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Predictive Maintenance for MTU Marine Diesel Engine Using Lubrication Analysis

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الصيانة التنبؤية لمحرك ديزل بحري من نوع MTU باستخدام تحليل الزيت

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Abstract:
The predictive maintenance is very important in all mechanical machines, which will give more relatability of the machine. There are many types of predictive maintenance, such as, vibration monitoring. This type of maintenance will give many advantages, which will help the operations to avoid any sudden failure or shutdown. The present study focusses in an oil lubrication analysis using Arduino platform., when combined with physically sound models, can serve as an effective tool for predictive maintenance applications in marine diesel engines.

The results showed that the relation between the temperature and viscosity is the dominant governing factor in lubrication system performance, where increasing temperature leads to viscosity reduction and flow rate increase, potentially degrading the oil's ability to maintain an adequate lubrication film beyond design limits. In addition, the pressure flow relationship proved to be an effective indicator for early fault detection, such as filter clogging, pump degradation, or internal leakage. Integrating these relationships into a multi-level alarm system enabled the development of predictive maintenance model capable of issuing early warnings and progressive alerts up to critical shutdown, thereby reducing unexpected failures and improving operational.

Keywords: Predictive maintenance, Lubrication system, Marine diesel engine, Arduino UNO,

الملخص:
الصيانة التنبؤية لها أهمية كبيرة لاكتشاف الأعطال في الآلات الميكانيكية والتي من شانها أن تساعد على اكتشاف الأعطال قبل حدوتها، وهناك عدة طرق لهذه الصيانة مثل مراقبة الاهتزازات، لهذا النوع من الصيانة يساهم في استمرار العملية الإنتاجية بدون نوقف مفاجئ. تهدف هذه الدراسة إلى تطوير نموذج صيانة تنبؤية لمراقبة منظومة تزييت محرك ديزل بحري من نوع MTU باستخدام منصة Arduino UNO كنموذج محاكاة عملي.
وقد تم التركيز على دراسة السلوك الفيزيائي لزيت التزييت من خلال تحليل العلاقات بين درجة الحرارة، اللزوجة، معدل التدفق، والضغط، باعتبارها المتغيرات الأكثر تأثيرًا على كفاءة التزييت وسلامة المحرك. أظهرت نتائج الدراسة أن العلاقة بين درجة الحرارة واللزوجة تمثل العامل الحاكم الأساسي في أداء منظومة التزييت، حيث يؤدي ارتفاع درجة الحرارة إلى انخفاض اللزوجة وزيادة معدل التدفق، مما قد يؤثر سلبًا على قدرة الزيت على تكوين طبقة تزييت كافية عند تجاوز الحدود التصميمية. كما بينت النتائج أن العلاقة بين الضغط ومعدل التدفق تُعد مؤشرًا فعالًا للكشف المبكر عن الأعطال مثل انسداد المرشحات، ضعف المضخة، أو التسرب الداخلي.
ومكّن دمج هذه العلاقات ضمن نظام إنذار متعدد المستويات من بناء نموذج صيانة تنبؤية قادر على إصدار إنذارات مبكرة وتحذيرات متدرجة وصولًا إلى الإيقاف الحرج (Shutdown)، بما يساهم في تقليل الأعطال المفاجئة وتحسين موثوقية التشغيل، وتؤكد الدراسة أن استخدام متحكمات منخفضة

التكلفة مثل Arduino، عند دمجها مع نماذج فيزيائية قائمة على علاقات فيزيائية صحيحة، يمكن أن يشكل أداة فعالة في تطبيقات الصيانة التنبؤية للمحركات البحرية.

الكلمات المفتاحية: الصيانة التنبؤية، منظومة التزييت، محرك ديزل بحري، Arduino UNO

1. Introduction:

In recent years, there has been a growing interest in the development of predictive maintenance systems for marine machinery, particularly ship engines, relying on sensing technologies and signal analysis techniques. Vibration analysis has proven to be an effective diagnostic tool for early fault detection, as demonstrated by the systematic review presented by Wan Rahiman and Ghazali, which reported that such techniques are capable of detecting more than 82% of industrial faults without requiring operational shutdown [1].With the advancement of monitoring systems, research efforts have increasingly focused on integrating artificial intelligence and machine learning techniques to process the large volumes of data generated in modern operating environments. Several studies have shown that signal processing techniques such as FFT, STFT, HOS, WVD, and WT provide effective indicators for diagnosing faults in internal combustion engines, with wavelet transform (WT) showing superior performance in improving diagnostic accuracy and reducing false alarms [2]. In this context, Sardar et al. (2022) proposed a low-cost engine condition monitoring model using the Arduino UNO platform, highlighting the feasibility of employing low-cost systems in predictive maintenance applications [3]. Other studies have investigated the use of machine learning algorithms such as SVM, RF, and GBM to develop multi-level alarm models, where comparative results demonstrated the flexibility and efficiency of the GBM algorithm in complex operating environments [4]. From a practical application perspective, Coșofreț et al. (2022) examined the implementation of predictive maintenance on operational maritime vessels through a monitoring and alarm system based on sensor integration with a central processing unit via a CAN-BUS network. The results showed that the temperature–viscosity The system provided a software interface to alert crew members when critical operating limits were exceeded, contributing to reduced maintenance costs and improved operational readiness and safety despite the high initial implementation cost [5]. In the field of fault prediction, an artificial neural network (ANN)-based model was developed using real failure data collected under a DNV GL-approved planned maintenance system. The model demonstrated high predictive accuracy (R = 0.999) with a low error rate using the Levenberg–Marquardt algorithm [6]. Additionally, a decision support system (DSS) was developed to compare real-time monitoring data with historical data to support operational and maintenance decisions through a Java-based graphical interface [7]. Other comparative studies highlighted the importance of selecting the optimal algorithm to improve maintenance efficiency and reduce environmental impact, reporting a 33% reduction in pollution when such models were applied to an oil filter as a case study [8]. Further results confirmed the superior accuracy of the Random Forest algorithm, the effectiveness of SVM in reducing false alarms, and the flexibility of GBM in meeting diverse predictive maintenance requirements [9]. The application of predictive maintenance methodologies has also been extended to wireless sensor networks (WSN), using feedforward neural network (FFNN)-based models to predict operational conditions while reducing system complexity [10].
Accordingly, this study aims to develop a predictive maintenance model for monitoring the lubrication system of an MTU marine diesel engine using the Arduino UNO platform as a practical simulation system.

1.1. Lubrication System Layout of the Target MTU Engine:

The MTU MD 20V538TB91 engine is one of the marine diesel engines used in main marine propulsion systems, with an operating power range between 2250 and 3750 kW. This engine relies on a highly reliable lubrication system to ensure continuous operation under high-load conditions and harsh marine environments [11]. The lubrication system of this engine requires continuous monitoring of several fundamental physical variables, including oil pressure, temperature, oil viscosity, and flow rate, in order to maintain operational stability and enable early fault detection through an adopted predictive maintenance system [11,12].
Figure (1) illustrates the general technical layout of the lubrication system for the MTU marine diesel engine, prepared based on the MTU Marine Diesel Engines Technical Manual. The diagram shows the complete lubrication oil flow path and includes the oil pump, filters, oil passages, and the locations of pressure, temperature, and flow sensors, enabling continuous and accurate monitoring of system performance [11,13].

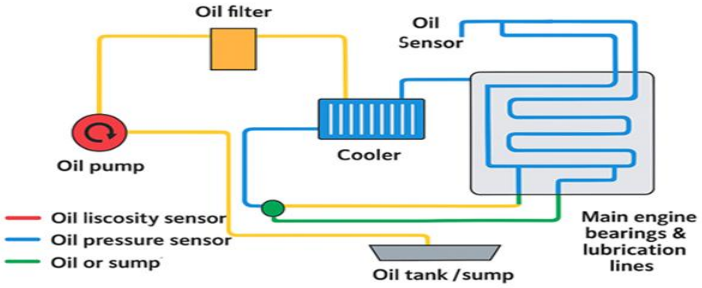

Figure (1): shows the overall technical block diagram of the lubrication system of an MTU marine diesel engine [11].

This study aims to develop a predictive maintenance model for monitoring the lubrication system of an MTU marine diesel engine using an Arduino UNO platform as a practical simulation tool. The research focuses on analyzing the physical behavior of lubricating oil by examining the relationships between temperature, viscosity, flow rate, and pressure, as these parameters critically affect lubrication efficiency and engine safety. The analyzes critical operational variables of lubricating oil to enable early fault detection and support proactive maintenance decision-making before reaching critical failure conditions.

3. Methodology:

3.1. Simulation Model:

An Arduino-based simulation model was developed to represent sensor readings, calculate oil viscosity as an exponential function of temperature, and compute flow rate based on pressure and viscosity, while considering a maximum flow rate limit (Q_max).

3.2. Experimental Setup:

Temperature range: 40 °C to 100 °C
Pressure range: 1 to 10 bar.
Oil tank capacity: 300 L.
The objective is to determine the relationships between temperature and oil viscosity, temperature and flow rate, and pressure and flow rate, and to establish decision rules for predictive maintenance systems.

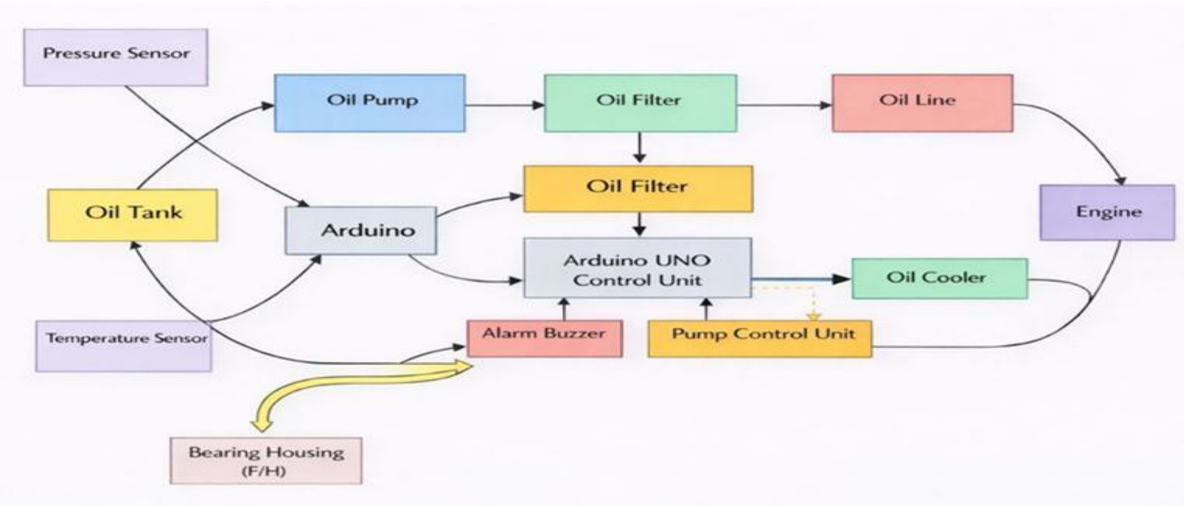

Figure (2): shows the Arduino UNO simulation schematic employed for analyzing the engine lubrication system.

3.3 Design Data and Operating Limits of the Lubrication System:

Based on the operational tables provided in the vessel technical manual (pages 3-6 to 3-9), and on the standard values adopted for the operation of marine diesel engines, the normal operating limits of the lubricating oil can be summarized as follows [14].

3.4 Lubricating Oil Pressure:

The normal operating range is approximately 5–9 bar, with oil pressure between 5–7 bar considered an indicator of stable operation under normal load conditions [14].

3.5 Lubricating Oil Temperature after the Cooler:

The recommended operating temperature range is approximately 55–80 °C, as temperatures exceeding this range lead to a significant reduction in oil viscosity and deterioration of the oil's ability to form an effective load-carrying lubricating film [15,16]. These design limits are used as the basis for calibrating the Predictive Maintenance System and defining critical alarm thresholds in the experimental model adopted in this study [17,18].

3.6 Functional Role of the Lubrication System in Marine Diesel Engines:

The lubrication system is a fundamental component in the operation of marine diesel engines, as it performs several vital functions that ensure the mechanical stability and operational efficiency of the engine. These functions include:

1.Reducing friction between moving components.

2.Cooling bearings and preventing localized temperature rise.

3.Removing particles and contaminants from oil passages, thereby limiting mechanical wear and preserving the integrity of internal components.

Recent studies have demonstrated that the effectiveness of these functions depends directly on the physical properties of the lubricating oil and the consistency of its flow within the system. Consequently, monitoring these variables constitutes a fundamental basis for predictive maintenance applications in marine diesel engines [19].

3.7 Physical Analysis Equations:

The modeling of the lubrication system in this study is based on a set of fundamental physical equations governing the behavior of lubricating oil within the system in terms of viscosity, flow rate, and pressure effects.

These equations were employed as a mathematical foundation to derive analytical relationships and correlate them with the experimental results obtained from the simulation using the Arduino UNO controller. This approach ensures consistency between the developed model and the established principles of fluid mechanics and engineering lubrication [20,21 and 22].

3.7.1. Kinematic Viscosity–Temperature Relationship:

The variation of lubricating oil kinematic viscosity with temperature is described using the following exponential relationship, which reflects the thermal behavior of hydrocarbon-based oils commonly used in marine diesel engines:

$$\nu = \nu_0 \cdot e^{(-k \cdot (T - T_0))} \quad (1)$$

where:

ν: Kinematic viscosity of the lubricating oil (cSt).

ν_0: Reference kinematic viscosity at the reference temperature T_0 (cSt).

T: Operating temperature (°C).

T_0: Reference temperature (°C).

k: Oil-dependent constant.

This equation reflects the nonlinear decrease in viscosity with increasing temperature, a behavior well documented in ASTM standards and engineering lubrication literature.[20,23,24].

3.7.2 Relationship Between Kinematic and Dynamic Viscosity:

Since hydraulic flow equations are based on dynamic viscosity, kinematic viscosity is converted to dynamic viscosity using the following relationship:

$$\mu(T) = \rho \cdot \nu(T) \quad (2)$$

where:

μ: Dynamic viscosity (Pa·s).

ρ: Lubricating oil density (kg/m³).

ν: Kinematic viscosity (m²/s).

Standard unit conversion:
1cSt = 1 × 10^{-6} m^2/s
This relationship is essential for linking the thermal analysis of lubricating oil with the hydraulic analysis of flow within the lubrication system21,22].

3.7.3 Governing Hydraulic Flow Equation:

To describe the flow behavior of lubricating oil within oil passages, the Hagen–Poiseuille equation was adopted, which relates flow rate to pressure difference and oil viscosity inside pipes[25].

$$\mathbf{Q = (\pi \cdot r^4 \cdot \Delta P) / (8 \cdot \mu \cdot L)} \qquad \mathbf{(3)}$$

where:
Q: Volumetric flow rate (m^3/s or L/min).
R: Pipe radius (m).
ΔP: Pressure difference (Pa).
μ: Dynamic viscosity (Pa·s).
L: Flow path length (m).

3.7.4 Pressure unit conversion:

ΔP (Pa) = ΔP (bar) × 10^5
This equation indicates that the flow rate is directly proportional to the pressure difference and inversely proportional to oil viscosity and flow path length, forming the physical basis for analyzing the pressure–flow relationship in marine lubrication systems [21, 25 and 26].

3.7.5 Smart Alarm Mechanism in the Lubrication System:

A smart alarm mechanism was developed within the proposed predictive maintenance system to enable early detection of abnormal operating conditions in the lubrication system of an MTU marine diesel engine.
This mechanism relies on analyzing real-time sensor readings of temperature, pressure, and flow rate, and comparing them with predefined reference and threshold values established according to manufacturer recommendations and marine lubrication performance standards [13].
Three alarm levels were defined based on the severity of deviation from nominal operating values for each system variable, as presented in table (1).

Table (1): Alarm Levels and Corresponding Actions.

Variable	Normal Range	Warning Level 1	Warning Level 2	Shutdown Level	Possible Fault	Recommended Action
Temperature(C°)	60- 80	≥ 85	≥ 90	≥ 95	Oil temperature rise due to blockage in oil passages or insufficient cooling system	Load reduction and inspection of cooling
Pressure (bar)	5- 8	< 5	< 4	< 3	Low oil pressure due to clogged filter internal leakage, or pump weakness	Oil pump inspection, filter cleaning lubrication system check
Viscosity (cSt)	> 10	< 10	< 8	< 6	contamination Degradation due to furl or Oil property water	Oil replacement and laboratory oil analysis
Flow Rate (Q)	Q≥ Qmax	Near Qmax	At Qmax	Q< Qmax	Partial blockage in oil supply lines or pump Performance degradation	Cleaning oil passages and inspection of oil pump

3.7.3 Alarm Mechanism within the Predictive Maintenance System:

The fault prediction mechanism is based on comparing real-time data (RTD) acquired from sensors with predefined threshold values. The data are automatically recorded on the Serial Monitor using the following abbreviations:

Temperature (tem), Pressure (pre), Flow rate (flo), Viscosity (vis).

The values are updated every second within the Arduino IDE environment, while warning signals are transmitted via an audible buzzer according to the severity level. In addition, a predictive control algorithm is activated to evaluate the overall trend of temporal data variations (Trend Analysis) in order to anticipate faults before their actual occurrence [21and 22]. This approach represents an embedded predictive logic application within modern ship control systems, enabling the crew to make rapid and accurate decisions to reduce downtime and improve operational efficiency [21,22 and 26].

Within the framework of designing a predictive maintenance system for the lubrication system of an MTU marine diesel engine, a multi-level smart alarm mechanism was developed based on real-time measurements of critical system variables, namely lubricating oil temperature, oil pressure, and flow rate. These variables are continuously acquired using sensors interfaced with the **Arduino UNO** controller .Alarm levels were defined based on the physical analysis of thermal and hydraulic relationships derived from the simulation results. An increase in oil temperature is considered a direct indicator of reduced viscosity and increased flow rate, which may lead to deterioration of the lubrication film and an increased risk of mechanical wear of moving components.

When the lubricating oil temperature reaches **85°C**, the system generates an early warning (Warning Level 1) to alert the operator to the onset of deviation from the safe operating range. If the temperature continues to rise to **90 °C**, a second-level warning (Warning Level 2) is activated, requiring immediate corrective actions such as load reduction or operational inspection. When the temperature exceeds **95 °C**, an Emergency Shutdown is executed to protect the lubrication system and prevent severe mechanical damage caused by a sharp reduction in oil viscosity or loss of effective lubrication capability.

A drop in oil pressure typically indicates reduced flow or partial blockage within the system. When the pressure falls below **5 bar**, an early warning is triggered, indicating the initial degradation of system performance. If the pressure decreases further below **4 bar**, a high-level warning is activated, necessitating intervention to inspect the pump and filters. When the pressure drops below **3 bar**, the system issues an immediate shutdown signal to protect critical components from insufficient lubrication and potential engine damage.

This system reflects the predictive maintenance approach by continuously monitoring real operating variables and implementing corrective actions before failures occur. The interdependence between critical variables is also considered, as increased temperature reduces oil viscosity and increases flow rate, whereas reduced pressure typically leads to decreased flow, adversely affecting lubrication efficiency and requiring prompt preventive measures.

The implementation of emergency shutdown as a protective measure upon exceeding safe operating limits is a widely accepted practice in marine diesel engine monitoring and protection systems. Industrial operation manuals emphasize the necessity of immediate intervention to prevent damage to vital engine components and to ensure overall system safety [11 and 13].

4. Results and Discussion:

4.1. Analysis of the Relationship Between Oil Temperature and Oil Viscosity:

Viscosity is one of the most significant physical parameters influencing the efficiency of lubrication systems, as it is directly related to oil temperature within the
System [24].

Through simulation of the lubrication system using the Arduino UNO controller, the operating data obtained are presented in Table 2.

Table (2): Operating data obtained from the Arduino UNO simulator for the lubrication system.

Visc (cSt)	Temp (°C)
100.0	40
74.08	50
54.88	60
40.66	70
30.12	80
22.31	90
16.53	100

Figure (3) shows the effect of temperature on the oil viscosity as can be seen, as the temperature increases the viscosity decreases with manner from 40℃ to 50℃, whereas, non-linear from 50℃ to 80℃ when the temperature increases.

A noticeable acceleration in viscosity reduction is observed beyond 80°C, which represents a critical thermal transition point. This behavior directly affects the thickness of the lubricating film and the oil's ability to operate within the hydrodynamic lubrication regime.

This observed trend is fully consistent with the analytical behavior predicted by Equation (1) and aligns with the recommendations reported in marine lubrication references or in accordance with the ASTM D341 standard, which is widely adopted in industrial and research applications [20,23 and 27].

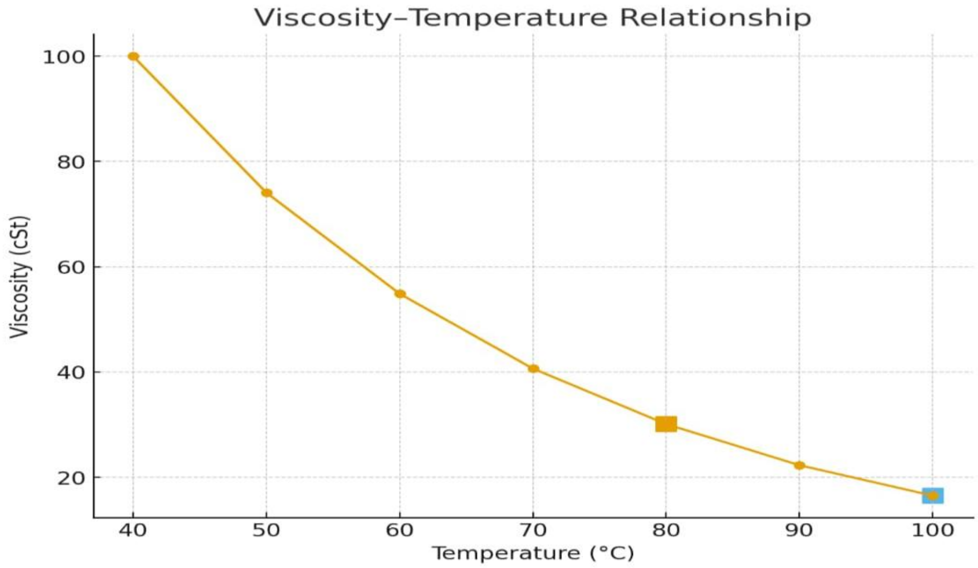

Figure (3): Relationship Between Temperature and Viscosity of the Lubrication System for an MTU Marine Diesel Engine.

4.2. Analysis of the Relationship Between Temperature and Flow Rate:

The lubricating oil flow rate is one of the most critical operational indicators in marine diesel engine lubrication systems, as both lubrication efficiency and cooling performance depend on the pump's ability to deliver an adequate oil flow under varying thermal conditions [22].

The flow rate is indirectly related to temperature through its direct influence on oil viscosity; as temperature increases, oil viscosity decreases, leading to reduced hydraulic resistance within the oil passages agree with [27,28].

Based on the simulation data obtained using the Arduino UNO controller, Table (3) presents the experimental relationship between oil temperature and flow rate in the lubrication system of the MTU marine diesel engine [11,13]. The curve indicates that the oil flow rate increases gradually with rising temperature, which is consistent with the fundamental hydraulic equations governing viscous fluid flow inside pipes [22,26].

Table (3): Operational Readings of the Temperature–Flow Rate Relationship for the MTU Lubrication System.

Flow Rate (L/min)	Temp (°C)
50.00	40
58.09	50
67.49	60
78.42	70
91.11	80
105.85	90
120	100

Figure (4) shows the flowrate behavior when the temperature raise, as can been seen, the temperature increases the flow rate increases in an approximately quasi-linear manner, until reaching a thermal saturation point at 100°C. This behavior can be attributed to either pump capacity saturation or the influence of internal leakage at elevated operating pressures [20 and 28]. Within the lower temperature range (40–60°C), the increase in flow rate is regular and stable, while oil viscosity remains within the safe range required for hydrodynamic lubrication. This range therefore represents the normal operating condition of the lubrication system [24]. At temperatures exceeding 80°C, the flow rate continues to rise while oil viscosity decreases significantly. This condition increases the likelihood of transitioning from hydrodynamic lubrication to mixed or boundary lubrication regimes, particularly in bearings subjected to high mechanical loads [20 and 28]. From a predictive maintenance perspective, an increased flow rate should not be interpreted as a positive indicator on its own. Instead, it must always be evaluated in conjunction with pressure and viscosity values, as a high flow rate accompanied by a pressure drop may indicate internal leakage or pump wear [21 and 27].

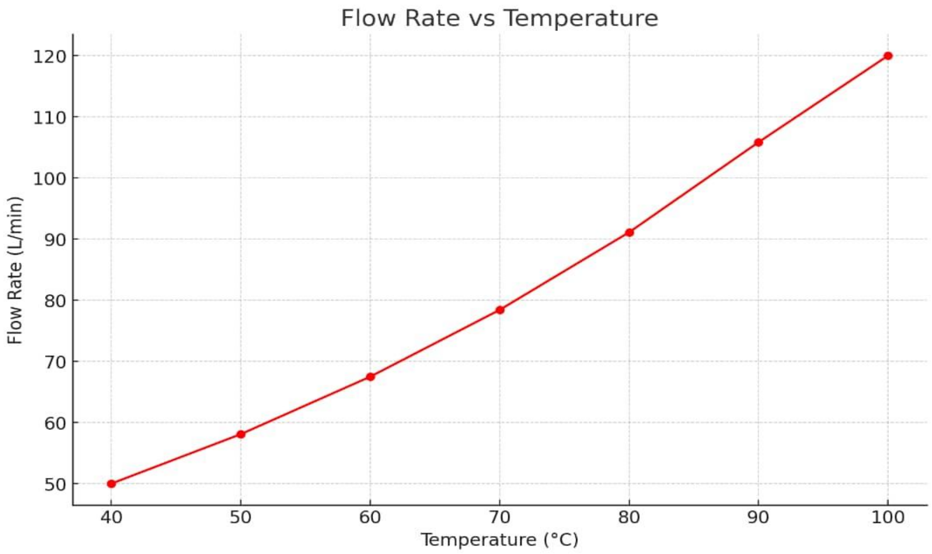

Figure (4): Relationship Between Temperature and Flow Rate for the Lubrication System of an MTU Marine Diesel Engine.

4.3. Analysis of the Relationship Between Pressure and Flow Rate:

Hydraulic pressure is a fundamental parameter that ensures the delivery of lubricating oil to all rotating and moving components within marine diesel engines, while remaining within the design limits recommended by the engine manufacturer [13]. The oil flow rate represents the volume of oil passing through the lubrication passages per unit time and is directly related to the pressure difference generated by the oil pump and the internal resistance of the system [22 and 26]. According to Equation (3), the flow rate is directly proportional to the pressure difference and inversely proportional to oil viscosity and flow path length. Consequently, an increase in pressure leads to a corresponding increase in flow rate until the system reaches a hydraulic saturation point, beyond which the rate of increase diminishes due to internal flow resistance [24 and 25].

Table (4) presents the experimental relationship between oil pressure and flow rate obtained from the simulation of the MTU lubrication system using the Arduino UNO platform [25].

Table (4): Operational Readings from the Arduino UNO Simulation for the Pressure–Flow Rate Relationship

Flow (L/min)	Press (bar)
13.50	1
27.00	2
40.50	3
53.99	4
67.49	5
80.49	6
93.49	7
106.49	8
119.49	9
120	10

The resulting curve demonstrates an approximately quasi-linear direct relationship between pressure and flow rate within the medium operating range (1–7 bar). This behavior is consistent with the Hagen–Poiseuille equation governing viscous fluid flow inside pipes [22 and 26].

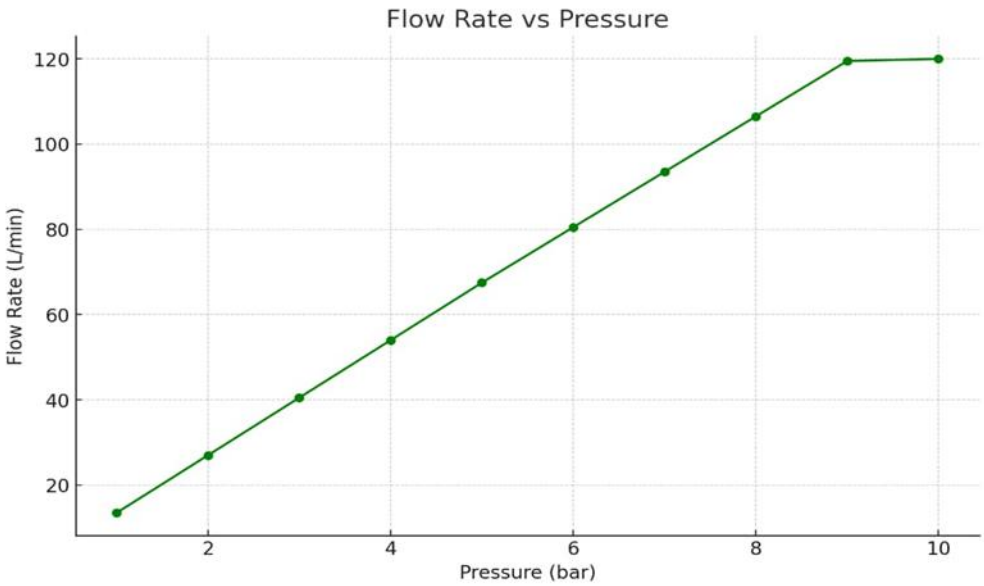

Figure (5): Pressure–Flow Rate Relationship in the Lubrication System of an MTU Marine Diesel Engine.

During the initial operating stages, the pressure increases in an almost linear manner with increasing flow rate. This behavior is attributed to the increase in the rotational speed of the lubrication oil pump, which raises the volume of oil delivered through the lubrication passages, thereby increasing the system pressure.

As the flow rate continues to increase, the pressure is observed to reach a quasi-steady state at higher values (starting from approximately 7 bar), despite the flow rate remaining at its maximum value (120 L/min). This phenomenon can be explained by the system reaching a state of hydraulic saturation, in which the pressure relief valves regulate and stabilize the pressure, preventing it from exceeding safe operational limits. Such behavior is considered normal in modern lubrication systems [13and 24].

This pressure–flow characteristic represents a key indicator in predictive maintenance applications, as deviations from the expected relationship can be used for the early detection of faults such as filter clogging or degraded oil pump performance [21 and 27].

5. Conclusion:

The results obtained from this study demonstrated that using the Arduino UNO platform as a practical simulation model provides an effective approach for implementing predictive maintenance in the lubrication system of an MTU marine diesel engine by analyzing the fundamental physical relationships governing lubricating oil behavior within the adopted thermal range (0–100°C). relationship is the primary governing factor affecting lubrication efficiency, as increasing temperature leads to reduced viscosity and increased flow rate, which weakens the oil's ability to maintain a stable lubrication film when design limits are exceeded. Accordingly, 85°C was adopted as the first warning level, 90°C as the second warning level requiring intervention, and 95°C as a critical threshold triggering a preventive engine shutdown before reaching 100 °C, in order to prevent the loss of the lubrication film and limit mechanical component damage.

Furthermore, the study demonstrated that the pressure–flow rate relationship is a critical operational indicator of system health. A reduction in oil pressure leads to decreased flow rate due to potential faults such as filter clogging or pump degradation. The results indicated that pressure below 5 bar marks the onset of abnormal operation, pressure below 4 bar represents an advanced degradation state, and pressure below 3 bar constitutes a critical condition requiring immediate preventive shutdown. Overall, integrating these physical relationships into a multi-level alarm system contributes to early fault detection, improved operational reliability, and enhanced support for predictive maintenance decision-making in marine diesel engine applications.

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