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(ARTICLE)

# An Operational-Relationship-Based Diagnostic Model for Evaluating Fuel Injector System Performance in a Marine Diesel Engine Within a Predictive Maintenance Framework

**Abdul Salam Al-Rashidi[1]*, Ayoub Ibrahim[2] , Nuri Eshoul[3] , Reyad Qaddoura[4]**

[1-4] Department of Marine Engineering, Floating Platforms Branch, Faculty of Engineering, University of Tripoli, Tripoli, Libya

# نموذج تشخيصي قائم على العلاقات التشغيلية لتقييم أداء منظومة حاقن الوقود في محرك ديزل بحري ضمن إطار الصيانة التنبؤية

**عبدالسلام علي الراشدي[1]*، أيوب ابوبكر إبراهيم[2] ، نوري محمد الشول[3] ، رياض ابوبكر قدورة[4]**

**قسم الهندسة البحرية و المنصات العائمة، كلية الهندسة، جامعة طرابلس، طرابلس، ليبيا**

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**Abstract:**
The fuel injector system is one of the most critical systems in marine diesel engines, as it directly controls the amount of fuel injected into the combustion chamber, thereby affecting combustion stability and engine performance efficiency. This study aims to develop a diagnostic and operational simulation model based on a condition-based predictive maintenance methodology to analyze injector-system performance and detect operational faults at an early stage before complete equipment failure occurs. The study was conducted using a diagnostic model based on the fuel injector system of an MTU 20V538 TB91 marine diesel engine. The proposed methodology can be generalized to marine diesel engines with similar injection systems. The analysis focuses on the effects of key operational variables, including inlet fuel pressure (OP), fuel pressure factor (FP), and internal injector leakage (LEAK), on the effective injected fuel quantity (DQ_eff). A simulation model was developed using the Arduino UNO platform to measure operational variables and acquire data through the Serial Monitor interface. The data were then analyzed to derive the physical relationships governing injection-system behavior. The simulation results showed a clear positive relationship between inlet pressure and effective fuel quantity, whereas increasing internal injector leakage reduces the injected fuel quantity because part of the fuel is lost through leakage paths. Based on the reference effective fuel quantity, a diagnostic indicator, the fuel quantity deviation (ΔDQ), was defined as the difference between the actual effective injected quantity and the reference value used for diagnosis. This indicator was used to classify the operational condition of the injector system into four main operating zones: Normal, Warning, Critical, and Shutdown. The results indicate that injector-performance degradation occurs gradually rather than abruptly, allowing operational deviations to be detected at an early stage before complete failure is reached. The study also demonstrates that integrating physical-relationship analysis of the injection system with low-cost measurement technologies, such as Arduino-based embedded systems, can provide an effective tool for implementing predictive maintenance in marine engines, improving operational reliability, reducing unexpected failures, and lowering maintenance costs.

**Keywords**: Predictive Maintenance, Fuel Injector System, Marine Diesel Engines, Condition-Based Monitoring, Fuel Quantity Deviation, Arduino UNO Platform.

**الملخص**
تصنف منظومة حاقن الوقود من أهم الأنظمة الحيوية في محركات الديزل البحرية، حيث تتحكم بشكل مباشر في كمية الوقود المحقونة داخل غرفة الاحتراق، مما يؤثر على استقرار عملية الاحتراق وكفاءة أداء المحرك، تهدف هذه الدراسة إلى تطوير نموذج تشخيصي ومحاكاة تشغيلية يعتمد على منهجية الصيانة التنبؤية المعتمدة

* Corresponding author: Abdul Salam Al-Rashidi1(abdo.86alrashdi@gmail.com)

Department of Marine Engineering, Floating Platforms Branch, Faculty of Engineering, University of Tripoli, Tripoli, Libya

على الحالة لتحليل أداء منظومة الحاقن والكشف المبكر عن الأعطال التشغيلية قبل حدوث الفشل الكامل للمعدة.تم إجراء الدراسة اعتمادًا على نموذج تشخيصي مبني على منظومة حاقن الوقود لمحرك ديزل بحري من نوع
MTU 20V538 TB91، مع إمكانية تعميم المنهجية المقترحة على محركات الديزل البحرية ذات أنظمة الحقن المماثلة، وقد ركز التحليل على دراسة تأثير مجموعة من المتغيرات التشغيلية الأساسية، والتي تشمل ضغط دخول الوقود Inlet Pressure (OP)، و معامل ضغط الوقود Fuel Pressure Factor(FP) و التسريب الداخلي للحاقن( Internal Leakage (LEAK, على الكمية الفعالة للوقود المحقونة (Effective Fuel Quantity (DQ_eff. تم تطوير نموذج محاكاة باستخدام منصة Arduino UNO لقياس المتغيرات التشغيلية واستخراج البيانات من خلال شاشة الرسائل Serial Monitor، ثم تحليل هذه البيانات لاشتقاق العلاقات الفيزيائية التي تحكم سلوك منظومة الحقن, وقد أظهرت نتائج المحاكاة وجود علاقة طردية واضحة بين ضغط الدخول والكمية الفعالة للوقود، في حين يؤدي ازدياد التسريب الداخلي للحاقن إلى انخفاض كمية الوقود المحقونة نتيجة فقدان جزء من الوقود داخل مسارات التسريب. وبالاعتماد على القيمة المرجعية للكمية الفعالة للوقود تم تعريف مؤشر تشخيصي يتمثل في انحراف الكمية الفعالة للوقود Fuel Quantity Deviation (ΔDQ)، والذي يمثل الفرق بين الكمية الفعلية المحقونة والقيمة المرجعية المستخدمة في التشخيص، وقد تم استخدام هذا المؤشر لتصنيف الحالة التشغيلية لمنظومة الحاقن ضمن أربع مناطق تشغيلية رئيسية هي التشغيل الطبيعي (Normal) و الإنذار المبكر (Warning) و الحالة الحرجة (Critical) و الإيقاف الوقائي (Shutdown). تشير نتائج الدراسة إلى أن تدهور أداء الحاقن يحدث بصورة تدريجية وليس بشكل مفاجئ، مما يتيح إمكانية اكتشاف الانحرافات التشغيلية في مرحلة مبكرة قبل الوصول إلى مرحلة الفشل الكامل. كما توضح الدراسة أن دمج تحليل العلاقات الفيزيائية لمنظومة الحقن مع تقنيات القياس باستخدام الأنظمة المدمجة منخفضة التكلفة مثل Arduino يمكن أن يوفر أداة فعالة لتطبيق أنظمة الصيانة التنبؤية في المحركات البحرية، مما يساهم في تحسين موثوقية التشغيل وتقليل الأعطال المفاجئة وخفض تكاليف الصيانة.

**الكلمات المفتاحية:** الصيانة التنبؤية، منظومة حاقن الوقود، محركات الديزل البحرية، المراقبة المعتمدة على الحالة، انحراف كمية الوقود، منصة Arduino UNO.

**Introduction**

Marine diesel engines are the primary power source for most commercial and military vessels because of their high operating efficiency and ability to operate for long periods under harsh conditions. The efficiency of these engines is strongly related to fuel-injection-system performance, which directly affects combustion, power generation, and fuel consumption, making monitoring of its operating condition essential for maintaining engine reliability and reducing failures [1]. Disturbances or faults in the fuel injection system cause changes in engine performance, which may increase fuel consumption and reduce operating efficiency. Early detection is particularly important in marine engines, where sudden failures during operation may have serious operational consequences. Accordingly, modern maintenance approaches have moved toward monitoring and analyzing operational variables to detect early degradation indicators before failures occur [2,3]. Assessment of the fuel injection system condition also relies on monitoring key operational indicators, including fuel pressure and internal leakage rate and their effects on the injected fuel quantity; these variables are directly associated with the performance of the fuel-supply system in marine diesel engines [4,5]. Recent studies have focused on diagnostic models and analysis of relationships among operational variables in marine diesel engines, together with low-cost measurement and monitoring technologies and embedded control platforms such as Arduino UNO, enabling practical methods for monitoring marine-system performance and detecting operational changes [6,7]. Previous applications of predictive maintenance for marine diesel engines also indicate that operational relationships among physical variables can be incorporated into diagnostic models based on monitoring and analysis, supporting early detection of operational deviations and improved maintenance decision-making [8,9].

Accordingly, this study aims to analyze the main operational relationships in the fuel injector system of a marine diesel engine and develop a diagnostic mathematical model linking fuel pressure (OP), fuel pressure factor (FP), internal injector leakage (LEAK), and effective fuel quantity (DQ_eff), using an Arduino UNO-based simulation model to classify injector operating conditions and identify degradation indicators within clearly defined warning levels.

## 2. Description of the Fuel Injector System:

The fuel injector system in marine diesel engines consists of several main components, including the fuel pump, fuel transfer lines, injector, and internal leakage paths. The system delivers fuel at high pressure to the injector nozzle, where it is injected into the combustion chamber as a fine spray that promotes effective fuel–air mixing and stable combustion inside the cylinder. Part of the unused fuel returns through the return line [4,5].

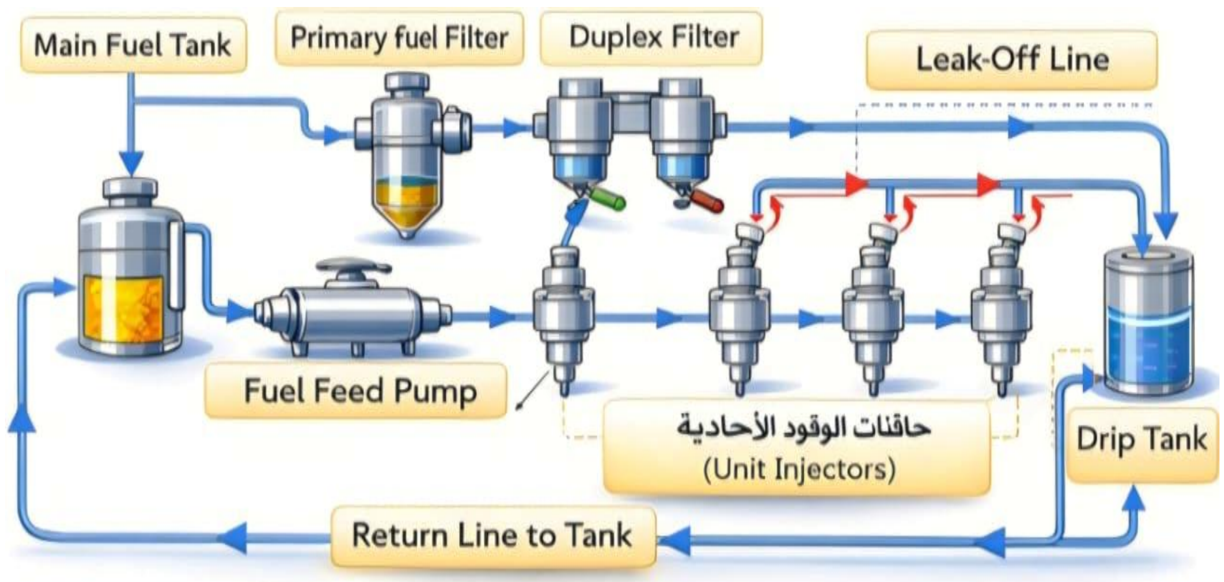


Figure (1): Schematic diagram of the Unit Injector Fuel System for an MTU marine diesel engine [4].

## 3. Simulation and Monitoring Methodology:

A simulation model of the injector system was developed using the Arduino UNO platform to represent system operating behavior under different operating conditions. A set of operational variables representing the main factors affecting the injection process was used:

**1. Inlet fuel pressure (OP).**

**2. Fuel pressure factor (FP).**

**3. Internal injector leakage (LEAK).**

Operational readings were obtained through the Serial Monitor interface and then exported in CSV format for analysis, graphical representation, and derivation of operational relationships among the different variables.

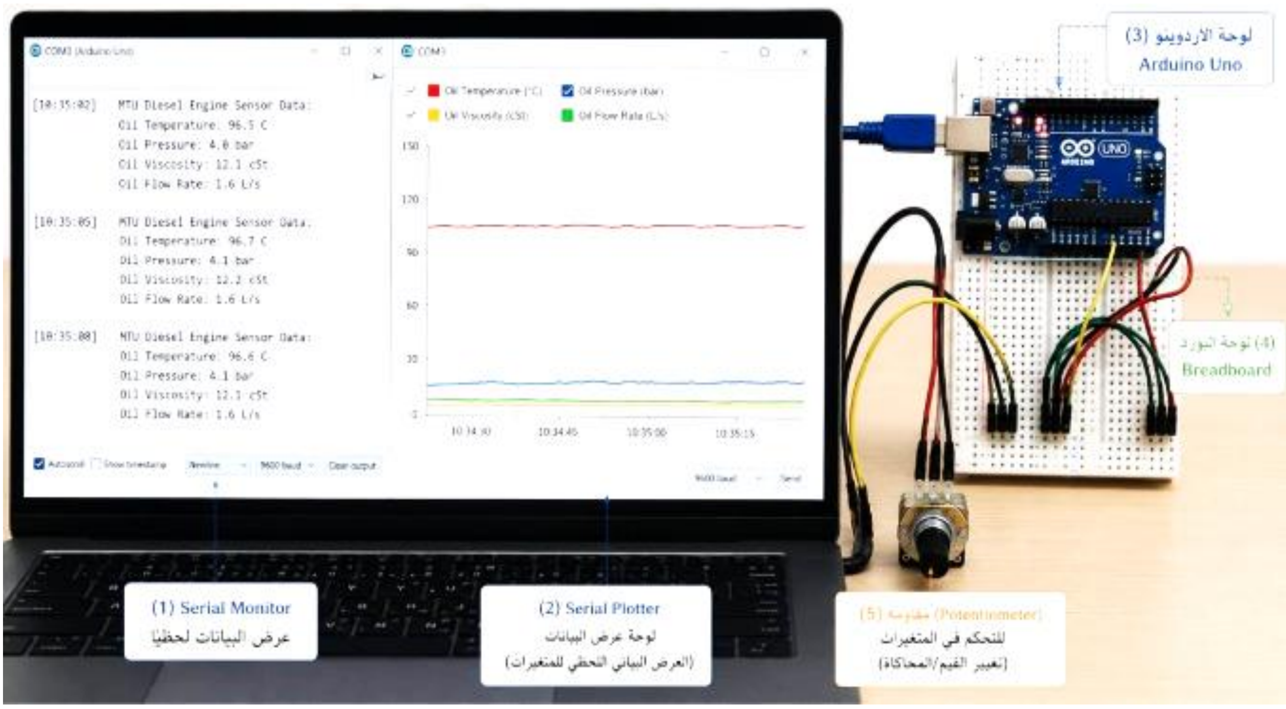


Figure (2): Monitoring-system interface and data display (Serial Monitor) and model components [8,9].

## 4. Physical Basis of the Fuel Injection Process:

High-pressure fuel injection in marine diesel engines is based on fluid flow through a small nozzle under a large pressure difference between the fuel line and the combustion chamber. This flow is governed by fluid-mechanics principles, and the theoretical flow rate is proportional to the square root of the effective pressure difference across the nozzle [1].

The volumetric flow rate through the injector nozzle can be represented by the following relationship:

$$Q = Cd \times A \times \sqrt{2\Delta P / \rho} \quad [1] \quad \text{.......} \quad (1)$$

where:

Q: Volumetric flow rate ($m^3/s$).

Cd: Discharge coefficient.

A: Nozzle cross-sectional area ($m^2$).

ΔP: Pressure difference across the nozzle ($Pa = N/m^2$).

ρ: Fuel density ($kg/m^3$) [1].

Physically:

An increase in ΔP increases the fuel exit velocity.

A decrease in density ρ increases the flow rate for the same pressure difference.

The coefficient Cd reflects the effects of internal losses, friction, and contraction [1].

Since injection occurs during a limited injector opening time, the injected fuel quantity per stroke becomes:

$$DQ = Q \times t \quad [1] \quad \text{.......} \quad (2)$$

where:

DQ: Injected fuel quantity per stroke ($m^3$/stroke).

t: Injector opening time (s).

For this study, DQ is converted to:

DQ ($mm^3$/stroke)

where:

$1\ m^3 = 10^9\ mm^3$

For the nominal condition of the MTU 20V538 TB91 study engine, the following reference value was adopted:

$$DQ\_ref = 630\ mm^3/\text{stroke} \quad \text{.......} \quad (3)$$

This value represents the normal operating point used by the predictive-maintenance algorithm as the basis for comparison [4].

## 5. Diagnostic Mathematical Model of the Injector System:

Based on the physical foundation described above, a simplified mathematical model was developed to convert the physical relationships into diagnostic indicators applicable to an Arduino-based monitoring system.

The purpose of the model is not to reproduce the complete injection dynamics, but rather to establish performance-deviation-sensitive relationships that can be used for early fault detection [2,3].

The model is based on four main relationships, designated R1 through R4.

### 5.1. Relationship (R1) between Internal Leakage (LEAK) and Effective Fuel Quantity (DQ_eff):

This relationship describes the effect of internal leakage on the effective fuel quantity injected per stroke.

When internal leakage occurs due to needle wear or excessive clearance inside the injector, the effective pressure available for injection decreases, resulting in a reduction in the actual injected quantity [1,4].

This behavior was represented by the following linear relationship within the studied operating range:

$$DQ\_eff = DQ\_ref - kL \times LEAK \quad \text{.......} \quad (4)$$

where:

DQ_eff: Effective fuel quantity ($mm^3$/stroke).

DQ_ref: Reference fuel quantity ($mm^3$/stroke).

kL: Additional-leakage effect coefficient, with units of ($mm^3$/stroke)/($cm^3$/5 min).

LEAK: Internal leakage rate ($cm^3$/5 min), and LEAK_base = 0.20 $cm^3$/5 min is the baseline leakage limit adopted in the simulation model.

Physically:
An increase in LEAK leads to:
**1. A reduction in actual injection pressure.**
**2. A reduction in injected quantity.**
**3. An imbalance in the air–fuel ratio.**
**4. An increase in exhaust-gas temperature.**
The term kL × max(LEAK − LEAK_base, 0) represents the loss attributed to leakage exceeding the baseline limit, and this relationship is used to estimate gradual degradation in injector performance within the simulation range [2].

**5.2. Relationship (R2) between Inlet Pressure (OP) and Effective Fuel Quantity (DQ_eff):**

From Equation (1), the theoretical flow is proportional to:

$$Q \propto \mathrm{sqrt}(\Delta P) \quad (5)$$

Based on the physical basis of fluid flow through nozzles, the flow rate is proportional to the square root of the pressure difference [1].
However, within the limited operating range studied (100–160 kg/cm²), the relationship can be approximated linearly for modeling and control purposes [4].

$$DQ\_eff = a \times OP + b \quad [1] \quad (6)$$

where:
OP: Inlet pressure (kg/cm²).
a: Slope coefficient (mm³/stroke)/(kg/cm²).
b: Equation constant (mm³/stroke).
This approximation was adopted to simplify software implementation in the actual measurement environment without losing diagnostic sensitivity within the studied range [3].

## 5.3. Relationship (R3) between Fuel Pressure Factor (FP) and Inlet Pressure (OP):

To evaluate the effect of changes in inlet pressure relative to the nominal value, the fuel pressure factor was defined as follows:

$$FP = OP / OP\_nom \quad [1] \quad (7)$$

where:
FP: Fuel pressure factor.
OP: Actual inlet pressure (kg/cm²).
OP_nom: Nominal pressure (kg/cm²).
OP_nom = 130 kg/cm² [4].
Accordingly, the effective quantity becomes as given in Equation (8):

$$DQ\_eff = DQ\_ref \times FP \quad (8)$$

This relationship represents a relative measure of performance deviation from the nominal condition and is more stable than relying on absolute values alone [2,3].

## 5.4. Relationship (R4): Effective Quantity Deviation from the Reference Value (ΔDQ):

The deviation variable ΔDQ is the most important indicator in the predictive-maintenance logic because it combines the effects of all preceding relationships into a single evaluable value [2].
It is defined as shown in Equation (9):

$$\Delta DQ = DQ\_ref - DQ\_eff \quad (9)$$

ΔDQ: Deviation of the effective quantity from the reference value (mm³/stroke).
Using Equation (4), we obtain:

$$\Delta DQ = kL \times \max(LEAK - LEAK\_base, 0) \quad (10)$$

This relationship shows that leakage-induced deviation is directly related to the portion of internal leakage exceeding the baseline limit. In general, ΔDQ is the central diagnostic indicator in the model because it represents the difference between the reference and effective fuel quantities injected per stroke.
To generalize the model and avoid restricting it to absolute values only, the percentage deviation was defined as follows:

$$\Delta DQ\% = (\Delta DQ / DQ\_ref) \times 100 \quad (11)$$

where:
ΔDQ%: Percentage deviation (%).
ΔDQ: Effective fuel quantity deviation ($mm^3$/stroke).
DQ_ref: Reference fuel quantity ($mm^3$/stroke).
This definition converts the deviation into a relative indicator independent of nominal injection capacity, making the model applicable to engines with different capacities without major modification to the diagnostic structure [2,3].
Considering that the reference quantity in the studied case is approximately:
DQ_ref ≈ 630 $mm^3$/stroke [4]
the adopted absolute deviation limits are:
10 $mm^3$/stroke, 20 $mm^3$/stroke, and 30 $mm^3$/stroke.
These correspond approximately to the following relative deviations:
≈ 1.6%, ≈ 3.2%, and ≈ 4.8%, respectively.
These percentages represent hypothetical decision limits within the simulation model and are not manufacturer-established limits for the engine unless supported by field tests or an explicit technical document.
Accordingly, gradual classification limits were adopted within the simulation model to transition from normal operation to warning, then to the critical condition, and finally to preventive shutdown at a deviation of approximately 5% of the reference quantity. These limits require operational validation through experimental testing on the actual engine.

## 6. Acceptance Limits and Operational Classification (Alarm Logic):

For the fuel injector system, the simulation model uses three operational indicators: inlet fuel pressure (OP), internal injector leakage rate (LEAK), and effective fuel quantity deviation (ΔDQ). The classification limits below were established from the simulation results and model logic; therefore, they must be field validated before being used as engine protection limits.
These limits divide the operating range into four main zones: NORMAL operation, WARNING, CRITICAL condition, and SHUTDOWN. This classification reflects the predictive-maintenance philosophy of early fault detection, staged warning, and intervention before complete system failure [1,4].

**Table (1): Acceptance limits and operational classification of fuel-injector-system variables in the diagnostic monitoring system.**

| Variable | Symbol | Unit | Normal | Warning | Critical | Shutdown |
|---|---|---|---|---|---|---|
| Operating pressure | OP | kg/cm² | 125 to 135 | 120 to less than 125, or greater than 135 to 140 | 110 to less than 120, or greater than 140 to 150 | Below 110 or above 150 |
| Internal leakage | LEAK | cm³/5 min | Less than 0.20 | 0.20 to less than 0.30 | 0.30 to less than 0.40 | 0.40 or greater |
| Effective quantity deviation from reference | ΔDQ | mm³/stroke | Less than 10 | 10 to less than 20 | 20 to less than 30 | 30 or greater |

## 6.1. Operational Classification Limits Based on Effective Quantity Deviation (ΔDQ):

Based on condition-based maintenance principles and the simulation and measurement results, the operating limits were determined as shown in Table (2) [2,3].

**Table (2): Operating limits adopted in the simulation model based on effective fuel quantity deviation.**

| Deviation condition | Operating condition |
|---|---|
| **ΔDQ is less than 10** | Normal |
| **ΔDQ is from 10 to less than 20** | Warning |
| **ΔDQ is from 20 to less than 30** | Critical |
| **ΔDQ is 30 or greater** | Shutdown |

These limits reflect the predictive-maintenance philosophy based on:

1. Early detection.
2. Staged warning.
3. Intervention before failure.
4. Preventive shutdown when necessary.

This is consistent with the principles of Condition-Based Maintenance [2].

## 7. Results and Discussion:

### 7.1. Relationship between Internal Leakage (LEAK) and Effective Fuel Quantity (DQ_eff):

Table (3) presents simulation readings extracted from the Arduino platform through the Serial Monitor interface and exported in CSV format. The speed was fixed at 800 RPM and the inlet pressure at OP ≈ 130 kg/cm² throughout this series to isolate the effect of LEAK on DQ_eff.

Table (3): Operational readings of the relationship between internal leakage and effective fuel quantity for the fuel injector system of an MTU marine diesel engine.

| Speed RPM (rpm) | Operating pressure OP (kg/cm²) | Internal leakage LEAK (cm³/5 min) | Reference quantity DQ_ref (mm³/stroke) | Effective quantity DQ_eff (mm³/stroke) | Operating condition |
|---|---|---|---|---|---|
| 800 | 130 | 0.00 | 630.0 | 630.0 | Normal |
| 800 | 130 | 0.05 | 630.0 | 630.0 | Normal |
| 800 | 130 | 0.10 | 630.0 | 630.0 | Normal |
| 800 | 130 | 0.15 | 630.0 | 630.0 | Normal |
| 800 | 130 | 0.20 | 630.0 | 630.0 | Normal |
| 800 | 130 | 0.25 | 630.0 | 617.5 | Warning |
| 800 | 130 | 0.30 | 630.0 | 605.0 | Critical |
| 800 | 130 | 0.35 | 630.0 | 592.5 | Shutdown |

Figure (3) shows three main features representing the effect of increasing internal injector leakage (LEAK) on the effective injected fuel quantity (DQ_eff), within the injector-system operating classification limits, as follows:

**1. Normal operating zone (LEAK ≤ 0.20 cm³/5 min):**

Within this range, the effective injected fuel quantity remains:

DQ_eff ≈ DQ_ref

Within this range, DQ_eff is approximately equal to the reference value of 630 mm³/stroke because the model assumes a baseline leakage (LEAK_base) representing design clearances and does not subtract it from the reference quantity.

Accordingly, LEAK values not exceeding 0.20 cm³/5 min do not cause a reduction in DQ_eff within the simulation model. This modeling assumption requires experimental validation before being generalized to the actual engine.

**2. Warning zone (0.20 < LEAK < 0.30 cm³/5 min):**

When the baseline leakage limit (LEAK_base) is exceeded, additional leakage (LEAK_extra) begins to appear, increasing the amount of fuel lost outside the effective injection path. Consequently, the effective fuel quantity begins to decrease gradually:

$$DQ\_eff = DQ\_ref - kL \times (LEAK - LEAK\_base) \quad \text{.........} \quad (12)$$

According to Equation (4).

Physically, increasing internal leakage means that an increasing portion of the fuel returns through the return line instead of participating in the injection process inside the combustion chamber. This is consistent with the definition of leakage in injection systems as recirculated flow outside the effective injection path [1].

At this stage, the system is in an early-warning condition indicating the beginning of injector-performance degradation, requiring inspection or preventive maintenance, such as injector testing or needle-sealing inspection, before the fault develops further.

**3. Critical and Shutdown zones (LEAK ≥ 0.30):**

As internal leakage continues to increase, the effective injected fuel quantity decreases until the system reaches the CRITICAL zone and then the SHUTDOWN zone at high leakage values. Physically, this leakage level is often associated with:

1. Wear of sealing surfaces inside the injector.
2. Increased clearance between the needle and its seat.
3. Wear of injection-system components [1].

This increases the equivalent leakage orifice area and, consequently, the leakage flow rate according to orifice-flow relationships associated with the pressure difference [3].

Injector-fault-diagnosis literature also confirms that internal leakage is one of the most important indicators used to determine injector condition and its degree of operational degradation [1].

In marine applications, reaching the shutdown zone should be linked to a protection procedure approved by the operating authority and engine manufacturer, because the current limits originate from the simulation model and are not a substitute for manufacturer protection instructions.

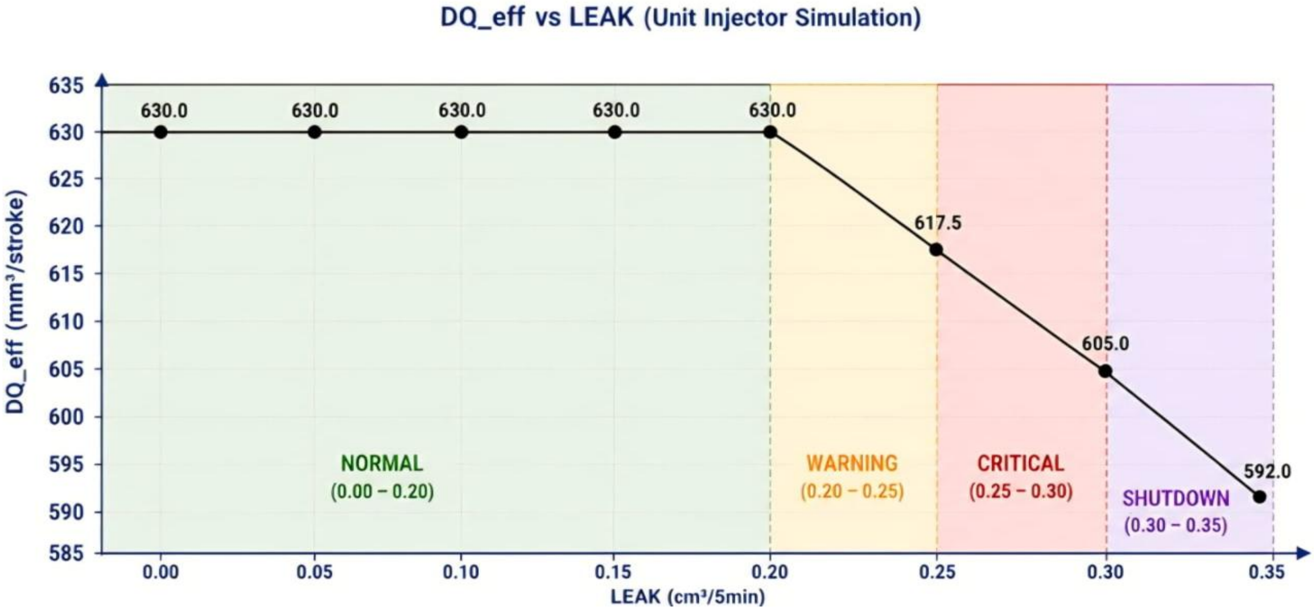


Figure (3): Relationship between internal leakage (LEAK) and effective fuel quantity (DQ_eff) in the simulation model, with the different operating zones.

## 7.2. Relationship between Inlet Pressure (OP) and Effective Fuel Quantity (DQ_eff):

Table (4) presents operational readings extracted from the Arduino UNO simulation showing changes in effective injected fuel quantity (DQ_eff) resulting from changes in injector inlet fuel pressure (OP). The data were obtained from the Arduino Serial Monitor outputs.

These readings represent different operating conditions covering the full operating range of the injector system, from very low-pressure Shutdown conditions through Critical and Warning ranges to the Normal operating range, and then beyond it toward high pressures. This distribution allows evaluation of the effect of inlet pressure on effective fuel quantity within a diagnostic framework supporting Condition-Based Maintenance.

Table (4): Operational readings of the relationship between inlet pressure and effective fuel quantity for the fuel injector system of an MTU marine diesel engine.

| Speed (rpm) | Inlet pressure OP (kg/cm²) | Effective fuel quantity DQ_eff (mm³/stroke) | Operating condition |
|---|---|---|---|
| 800 | 100 | 606.0 | Shutdown |
| 800 | 110 | 614.0 | Critical |
| 800 | 115 | 618.0 | Critical |
| 800 | 120 | 622.0 | Warning |
| 800 | 125 | 626.0 | Normal |
| 800 | 130 | 630.0 | Normal |
| 800 | 135 | 634.0 | Normal |
| 800 | 140 | 638.0 | Warning |
| 800 | 145 | 642.0 | Critical |
| 800 | 150 | 646.0 | Critical |
| 800 | 155 | 650.0 | Shutdown |

Figure (4) shows a clear positive relationship between inlet pressure (OP) and effective fuel quantity (DQ_eff), where the injected fuel quantity increases gradually as the fuel inlet pressure to the injector increases. This behavior is associated with the physical basis of injection, since fuel flow through the injector nozzle depends on the pressure difference between the supply pressure and the combustion-chamber pressure. The volumetric flow rate through the nozzle can be expressed as:

$$Q = C_d \times A \times \sqrt{2\Delta P / \rho} \quad (13)$$

where:

Q: Fuel flow rate through the injector nozzle.

Cd: Discharge coefficient.

A: Nozzle cross-sectional area.

ΔP: Pressure difference across the nozzle.

ρ: Fuel density.

This relationship shows that the flow rate is proportional to the square root of the pressure difference; therefore, increasing inlet pressure increases the flow rate and consequently increases the fuel quantity injected during the same injection duration [1].

The operational readings clearly agree with this physical behavior. When inlet pressure decreases to OP = 100 kg/cm², the effective fuel quantity decreases to DQ_eff = 606.0 mm³/stroke; it then increases gradually to 610.0 mm³/stroke at OP = 105 kg/cm² and to 613.2 mm³/stroke at OP = 109 kg/cm². This reduction in injected quantity reflects insufficient injector supply pressure, which may lead to reduced actual engine power or unstable combustion inside the cylinder [1].

As inlet pressure gradually increases, the effective-fuel-quantity curve begins to rise in an approximately linear manner within the studied operating range. At OP = 120 kg/cm², DQ_eff = 622.0 mm³/stroke, increasing to 628.4 mm³/stroke at OP = 128 kg/cm² and reaching 630.0 mm³/stroke at OP = 130 kg/cm². These values represent the normal operating range, where inlet pressure is between 125 and 135 kg/cm², providing stable injection and suitable combustion performance for the engine [3].

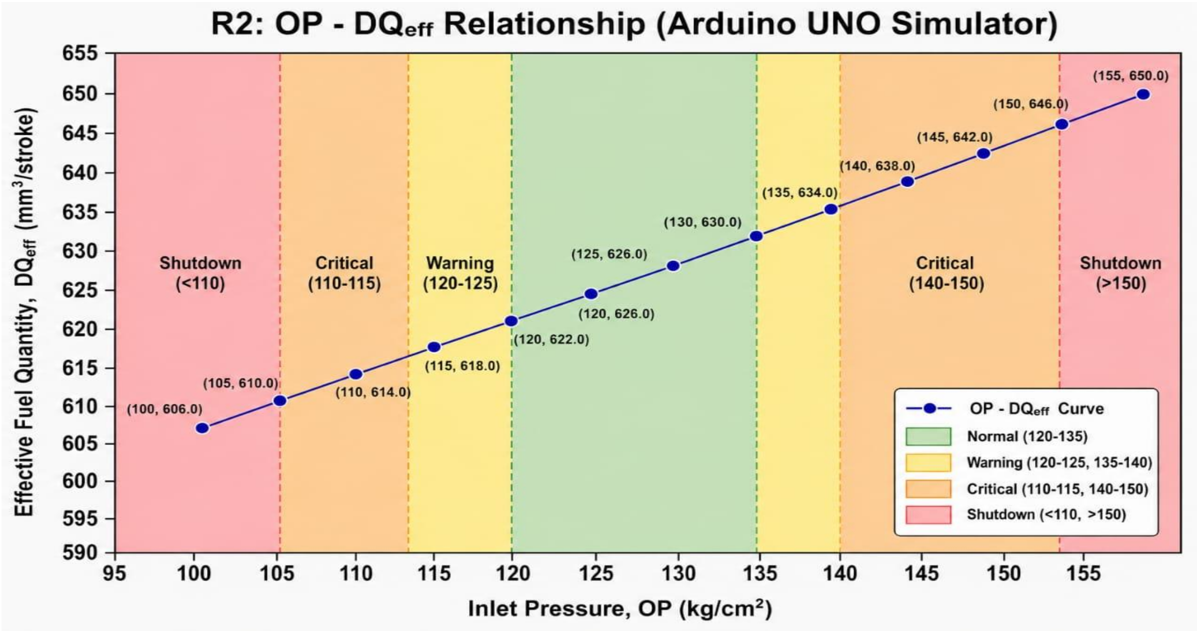


Figure (4): Relationship between injector fuel inlet pressure (OP) and effective injected fuel quantity (DQ_eff).

## 7.3. Relationship between Fuel Pressure Factor (FP) and Effective Fuel Quantity (DQ_eff):

Table (5) presents Arduino UNO simulation readings for the effect of the fuel pressure factor (FP) on effective fuel quantity (DQ_eff). The engine speed was fixed at 800 rpm, inlet pressure at 130 kg/cm², and internal leakage at 0.10 cm³/5 min to isolate the effect of FP according to the simulation-series setup.

The readings were obtained from the Arduino Serial Monitor outputs in CSV format and arranged in descending order of FP to show the physical trend between the fuel pressure factor and effective fuel quantity. These data represent gradual changes in relative fuel pressure around the system reference condition, allowing analysis of injection-system sensitivity to gradual pressure reduction within a predictive-maintenance framework.

**Table (5): Operational readings of the relationship between fuel pressure factor and effective fuel quantity.**

| Fuel pressure factor FP | Effective fuel quantity DQ_eff (mm³/stroke) | Operating condition |
|---|---|---|
| 1.00 | 630.0 | Normal |
| 0.99 | 628.7 | Normal |
| 0.98 | 627.5 | Normal |
| 0.96 | 625.0 | Normal |
| 0.94 | 622.4 | Normal |
| 0.92 | 619.9 | Warning |
| 0.90 | 617.4 | Warning |
| 0.88 | 614.9 | Warning |
| 0.86 | 612.4 | Warning |
| 0.84 | 609.8 | Critical |
| 0.80 | 604.8 | Critical |
| 0.76 | 599.8 | Shutdown |

Figure (5) shows a nearly linear positive relationship between fuel pressure factor (FP) and effective fuel quantity (DQ_eff): increasing FP increases the injected fuel quantity, whereas decreasing FP produces a gradual reduction in effective fuel quantity. This behavior reflects the physical basis of injection, in which fuel flow through the injector nozzle depends on the pressure difference acting on the fuel; lower pressure reduces the flow rate and therefore reduces the quantity injected during the same injection duration [1].

The simulation results show that the injection system reaches the reference operating condition at FP = 1.00, where the effective fuel quantity is 630.0 mm³/stroke, the reference value used in the diagnostic model. As the fuel pressure factor decreases, the effective fuel quantity gradually decreases, reaching 628.7 mm³/stroke at FP = 0.99 and 627.5 mm³/stroke at FP = 0.98, and continuing to 622.4 mm³/stroke at FP = 0.94, which remains within the normal operating range.

At FP = 0.92, the effective fuel quantity decreases to 619.9 mm³/stroke, representing the first exceedance of the warning limit adopted in the predictive-maintenance model (DQ_ref − 10). This point therefore marks the beginning of the Warning zone and is important for early diagnosis because the predictive-maintenance system can detect injector-system performance deviation before it reaches more severe levels [2].

As the fuel pressure factor continues to decrease, the reduction in effective fuel quantity increases, reaching approximately 612.4 mm³/stroke at FP = 0.86, indicating clear degradation in injection-system performance due to reduced effective fuel pressure.

To illustrate the complete diagnostic limits of the system, the curve was extended into lower ranges using the linear relationship derived from the data. The estimated values indicate entry into the Critical zone at approximately FP = 0.84, where effective fuel quantity is about 609.8 mm³/stroke, and, if pressure continues to decrease, entry into the Shutdown zone at approximately FP = 0.76, where effective fuel quantity decreases to about 599.8 mm³/stroke.

This gradual diagnostic sequence represents the essence of Predictive Maintenance, allowing fault-development stages to be identified in a clear sequence beginning with the Normal condition, followed by Early Warning, the Critical stage, and finally Shutdown before complete equipment failure is reached [2,3].

Data analysis also showed that the relationship between FP and DQ_eff within the studied range can be approximated by the following linear equation:

DQ_eff = 125.89 × FP + 504.10 (within the studied data range).

This equation represents an empirical linear approximation of the simulation data within the studied range and should not be extrapolated beyond this range without additional validation.

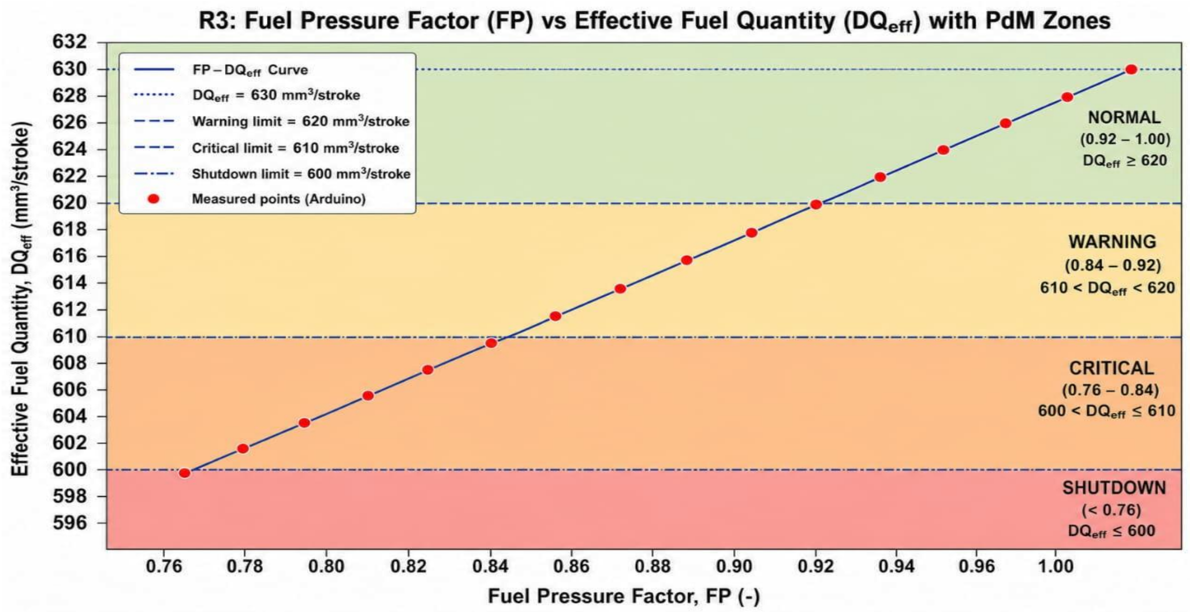


Figure (5): Relationship between fuel pressure factor (FP) and effective fuel quantity (DQ_eff), showing the operating zones according to the predictive-maintenance logic.

### 7.4. Relationship between Internal Leakage (LEAK) and Effective Fuel Quantity Deviation (ΔDQ):

Table (6) presents Arduino UNO simulation readings for the effect of internal leakage (LEAK) on ΔDQ, with speed fixed at 800 rpm, inlet pressure at 130 kg/cm², and fuel pressure factor at FP = 1.00. The data were arranged in ascending order of leakage.

This is one of the most important diagnostic relationships in the predictive-maintenance model for the injector system because internal leakage is a direct indicator of degradation of the needle and sealing surfaces inside the injector [1,2]. When leakage exceeds a certain limit, the effective injected fuel quantity begins to decrease below the reference value, appearing as an operational deviation ΔDQ that can be used to define transitions among the Normal, Warning, Critical, and Shutdown conditions [2].

Table (6): Operational readings of the relationship between internal leakage and effective fuel quantity deviation.

| **Internal leakage LEAK (cm³/5 min)** | **Effective quantity DQ_eff (mm³/stroke)** | **Deviation ΔDQ (mm³/stroke)** | **Operating condition** |
|---|---|---|---|
| 0.00 | 630.0 | 0.0 | Normal |
| 0.05 | 630.0 | 0.0 | Normal |
| 0.10 | 630.0 | 0.0 | Normal |
| 0.15 | 630.0 | 0.0 | Normal |
| 0.20 | 630.0 | 0.0 | Normal |
| 0.25 | 617.5 | 12.5 | Warning |
| 0.30 | 605.0 | 25.0 | Critical |
| 0.35 | 592.5 | 37.5 | Shutdown |

Analysis of the values in Table (6) shows that effective fuel quantity deviation ΔDQ remains approximately zero over the initial range of internal leakage and then begins to increase gradually after a certain leakage limit.

Figure (6) shows that ΔDQ remains approximately zero for internal leakage values from 0.00 to 0.20 cm³/5 min, while the effective injected fuel quantity remains equal to DQ_eff = 630.0 mm³/stroke. This behavior indicates that the injector can internally compensate for this level of leakage without an observable effect on the injected fuel quantity, representing an allowable operating margin before clear performance degradation begins.

At LEAK = 0.20 cm³/5 min, the system reaches the end of the internal-compensation stage. Beyond this point, additional leakage begins to directly affect the effective fuel quantity. This point is important in predictive maintenance because it represents the boundary between operationally acceptable leakage and leakage that begins to produce a measurable deviation in injection-system performance.

After this limit is exceeded, the deviation curve increases approximately linearly with increasing internal leakage. At LEAK = 0.25 cm³/5 min, ΔDQ = 12.5 mm³/stroke, placing the system directly in the Warning zone and indicating that the injector has begun to lose part of the fuel that should participate in the actual injection process. This suggests the beginning of degradation of the needle or internal sealing surfaces [5,4]. As leakage continues to increase, ΔDQ reaches 25.0 mm³/stroke at LEAK = 0.30 cm³/5 min, which falls within the Critical zone and reflects advanced injector degradation because the fuel-quantity loss has become large enough to directly affect combustion stability and engine efficiency. From a diagnostic perspective, this point requires urgent maintenance action to prevent fault escalation [3,2].

When internal leakage increases to LEAK = 0.35 cm³/5 min, effective fuel quantity deviation rises to ΔDQ = 37.5 mm³/stroke, placing the system in the Shutdown zone.

Physically, increasing internal leakage means that an increasing portion of the fuel returns through leakage paths or the return line instead of contributing to the actual injection process. Consequently, DQ_eff decreases and ΔDQ increases directly. For this reason, LEAK is one of the most important diagnostic variables associated with injector condition, while ΔDQ is the central diagnostic indicator that converts this degradation into a numerical value suitable for classification and decision-making [1,4].

This relationship clearly shows that internal leakage does not lead directly to sudden failure; rather, it progresses through gradual stages beginning with internal compensation, followed by early warning, the critical condition, and preventive shutdown. This sequence represents the essence of the Predictive Maintenance philosophy, enabling early fault detection and allowing an appropriate technical action to be taken before the fault reaches a level that threatens system safety or causes damage to injector components and engine efficiency [2,3].

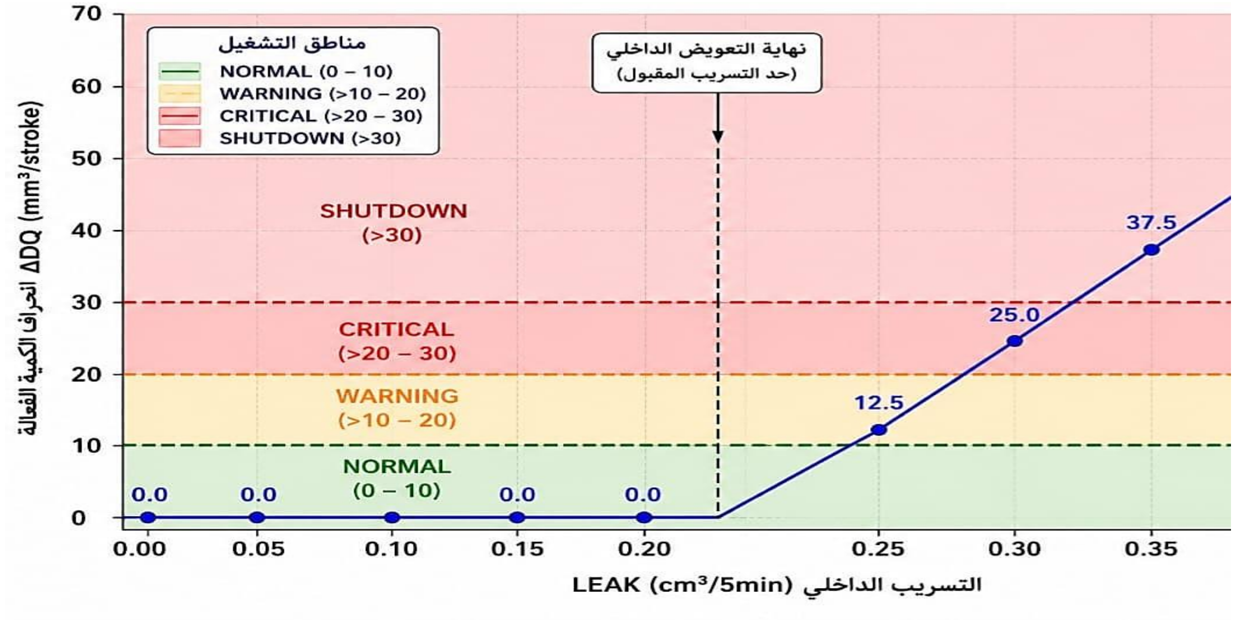


Figure (6): Relationship between internal fuel leakage (LEAK) and effective fuel quantity deviation (ΔDQ) for an MTU marine diesel engine.

## 8. Diagnostic Integration of Operational Relationships in the Injector System:

The study adopted four interconnected operational relationships to construct a diagnostic model supporting predictive maintenance. The analysis was based on simulation data extracted from the Arduino UNO platform, with variables not under study fixed at the specified reference values for each series.

The four relationships in the model were arranged as follows:

R1: Effect of internal leakage (LEAK) on effective fuel quantity (DQ_eff), according to Equation (4).

R2: Effect of inlet pressure (OP) on effective fuel quantity (DQ_eff), according to the linear approximation in Equation (6).

R3: Definition of the fuel pressure factor (FP = OP/OP_nom) and its relationship with effective quantity, according to Equations (7) and (8).

R4: Definition of effective fuel quantity deviation (ΔDQ = DQ_ref − DQ_eff) and its use as a diagnostic indicator for classification, according to Equations (9) and (11).

Through the interconnection of the four relationships, the main physical variables of the injector system can be identified as:

**1. Inlet pressure (OP).**

**2. Fuel pressure factor (FP).**

**3. Internal leakage (LEAK).**

These variables directly affect the effective injected fuel quantity (DQ_eff), which in turn represents the central variable reflecting injection-process performance. Comparing this quantity with the reference value used for diagnosis yields the effective fuel quantity deviation (ΔDQ), which is the primary diagnostic indicator used to determine the injector-system operating condition.

Based on ΔDQ, the operating condition is classified into four decision zones: Normal, Warning, Critical, and Shutdown.

This classification represents the essence of the predictive-maintenance methodology, which relies on continuous monitoring of operating performance and periodic measurement and analysis of the key variables through a Condition-Based Maintenance approach. The system therefore allows continuous monitoring of operating variables and detection of gradual deviations before complete equipment failure [2,3].

Accordingly, the four relationships are not separate analyses; together they form an integrated diagnostic model for the injector system. Diagnosis begins by measuring the system's fundamental physical variables, then analyzing their effects on effective fuel quantity, and finally converting this effect into a quantitative diagnostic indicator through which the appropriate maintenance decision can be made at the appropriate time before actual failure occurs.

Figure (7) presents a diagnostic diagram showing the integration of these four relationships within a unified framework for the proposed predictive-maintenance system of the fuel injector system.

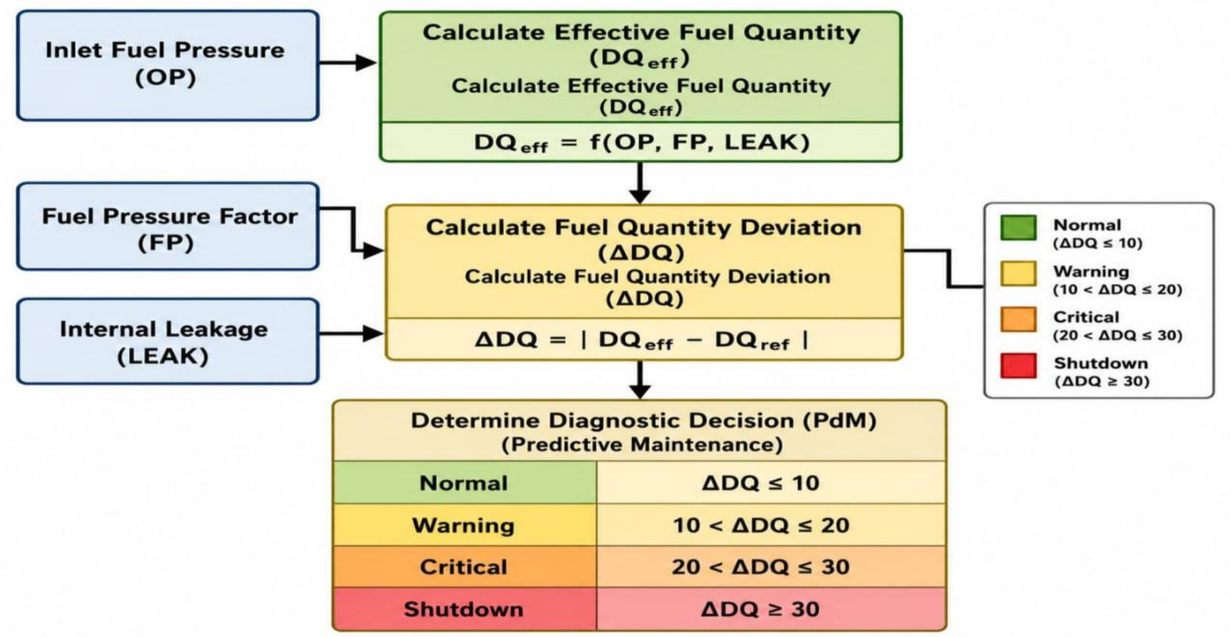


Figure (7): Integrated diagnostic diagram of the predictive-maintenance system for the fuel injector system.

## 9. Conclusions:

This study aimed to develop a predictive-maintenance diagnostic model for the fuel injector system of marine diesel engines by simulating the effects of inlet pressure (OP), fuel pressure factor (FP), and internal leakage (LEAK) on effective fuel quantity (DQ_eff) using the Arduino UNO platform.

The simulation results showed a positive relationship between inlet pressure and effective fuel quantity within the studied range, and an inverse relationship between internal leakage above the baseline limit and effective fuel quantity. These results represent the behavior of the computational model and require experimental validation before being generalized to the actual engine.

The study also showed that analysis of the fuel pressure factor can provide an additional indicator for evaluating injector-system performance and diagnosing changes in fuel-pressure characteristics within the injection system. Analysis of the different operational relationships allowed a diagnostic indicator based on deviation of effective fuel quantity ($\Delta DQ$) from the reference value to be derived for determining injector condition.

Based on $\Delta DQ$, the model condition was classified into four zones (Normal, Warning, Critical, and Shutdown). The limits used are simulation decision limits and are not manufacturer protection limits unless documented through tests or approved technical instructions.

The results indicate that integrating physical-relationship analysis of the injection system with low-cost monitoring systems based on embedded measurement platforms such as Arduino can provide an effective tool for implementing predictive maintenance in marine diesel engines. This approach can improve the operational reliability of marine propulsion systems, reduce unexpected failures, and improve maintenance planning. A published study by the authors also supports the applicability of this approach to a marine cooling system using Arduino UNO.

The proposed diagnostic model can provide a basis for developing intelligent monitoring systems for fuel injection systems in marine diesel engines, supporting predictive-maintenance strategies, improving operational reliability, and reducing unexpected failures.

This study also represents a scientific contribution to predictive maintenance of marine diesel engines through development of a diagnostic model based on analysis of fundamental operational relationships within the injector system. The proposed model can convert different physical variables into a unified quantitative diagnostic indicator that can be used to evaluate injector operating condition and support appropriate maintenance decisions before critical failures occur.

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