# Experimental Analysis of Diesel Engine Combustion Chamber Performance Using Field Measurements at the State Company for Heavy Engineering Equipment / Original Article

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# التحليلُ التَّجريبيُّ لأداءِ غُرفةِ الاحتراقِ في محرِّكِ الديزلِ باستخدامِ القياساتِ الميدانيَّةِ في الشَّركةِ العامَّةِ للمُعدَّاتِ الهندسيَّةِ الثَّقيلةِ

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## Abstract

The current paper provides a detailed experiment and numerical study of the performance of the combustion chamber of a heavy-duty diesel engine in the common Iraqi industrial conditions at the State Company of Heavy Engineering Equipment (HEESCO). The main goal is to close the difference between what is specified by the manufacturers concerning the performance data, which is usually assumed to be under ideal conditions of the ISO standard, and the real efficiency of operation as witnessed in the field. The methodology is based on a hybrid approach that combines direct field measurements of in-cylinder pressure, temperature and fuel flow of a MAN 18V32/40 diesel engine with a zero-dimensional single-zone thermodynamic model that was developed in MATLAB. A calibration and validation of the simulation model is done using the experimental data that was collected at different points of loads. The experiment showed an in-cylinder peak pressure of 16.5 MPa and a highest brake thermal efficiency (BTE) of 38.5 percent at the rate of about 80 percent of rated load. The tested MATLAB model proved to be very accurate with the difference of the model and experimental data of the pressure-crank angle being less than 4.5 percent. The comparative analysis shows that performance of the engine on locally obtained Iraqi diesel fuel leads to a 3-5% lower BTE than performance expectations on the use of EN 590 standard fuel. This difference is mainly explained by the fact that the local fuel has lower cetane number and more sulfur, and, consequently, results in the increase of the ignition delay and change in the combustion phasing. The paper ends with the validated framework of performance measurement and gives specific, evidence-based suggestions on how to optimize the functioning of diesel engines, improve the fuel consumption levels, and shape the maintenance plan in the context of the heavy industry and energy complexes that are critically important in Iraq.


**Keywords: Dasycle Engine Combustion, Performance Analysis, Thermodynamic Modeling, In-Cylinder Pressure, State Company for Heavy Engineering Equipment (HEESCO), Iraqi Diesel Fuel, MATLAB Simulation.**

## المستخلص

يقدّم هذا البحثُ دراسةً تجريبيةً وعدديةً مُفصَّلة لأداءِ غرفةِ الاحتراق في محرّكِ ديزلٍ ثقيلٍ يعمل ضمن الظروفِ الصناعيةِ الشائعة في العراق، وذلك في مقرّ **الشركة العامة للمعدّات الهندسية الثقيلة (HEESCO)**. يهدف البحث أساسًا إلى تقليل الفجوة بين بيانات الأداء التي يقدّمها المصنعون—والمفترَض أنها مبنية على ظروفٍ مثالية وفق المواصفات القياسية ISO—وبين الكفاءة الحقيقية للتشغيل كما يتم رصدها في الموقع. تعتمد المنهجية على مقاربةٍ هجينة تجمع بين **قياساتٍ ميدانية مباشرة** لضغط الأسطوانة، ودرجة الحرارة، ومعدل تدفّق الوقود لمحرك 40/MAN 18V32، وبين **نموذج ديناميكي حراري أحادي المنطقة (Single-Zone 0D)** طُوّر باستخدام برنامج MATLAB. وقد جرى **معايرة النموذج والتحقّق من صحّته** بالاعتماد على البيانات التجريبية التي جُمعت عند مستويات مختلفة من الأحمال. أظهرت التجارب وصول الضغط داخل الأسطوانة إلى **16.5 ميغا باسكال**، بينما بلغ أعلى معامل كفاءة حرارية للفرملة (BTE) حوالي **38.5%** عند تشغيل المحرك بحوالي 80% من الحمل الاسمي. كما أثبت نموذج MATLAB دقّةً عالية، إذ لم تتجاوز نسبة الاختلاف بينه وبين البيانات التجريبية في منحنى الضغط–زاوية عمود المرفق **4.5%**. وتُظهر المقارنة أن تشغيل المحرك باستخدام **الديزل العراقي المحلي** يؤدي إلى انخفاضٍ يتراوح بين **3–5%** في الكفاءة الحرارية BTE مقارنةً بالوقود القياسي EN 590. ويُعزى هذا الانخفاض إلى أن الوقود المحلي يمتلك رقم سيتان أقل ومحتوى كبريت أعلى، مما يؤدي إلى زيادة فترة التأخير في الاشتعال وتغيير طور الاحتراق. يختتم البحث بطرح إطارٍ مُتحقَّق وصالح لقياس الأداء، مع تقديم توصيات عملية مبنية على الأدلة حول **تحسين تشغيل محركات الديزل، وتقليل استهلاك الوقود، وتحسين خطط الصيانة** ضمن سياق الصناعات الثقيلة والمنشآت الطاقية ذات الأهمية الحيوية في العراق.

**الكلمات المفتاحية: احتراق محرك الديزل، تحليل الأداء، النمذجة الديناميكية الحرارية، ضغط داخل الأسطوانة، الشركة العامة للمعدات الهندسية الثقيلة (HEESCO)، وقود الديزل العراقي، محاكاة MATLAB.**

# 1. Introduction

The industrial and economic infrastructure of Iraq is comprised of heavy-duty diesel engines as shown in Figure (1). They cannot be lived without in power generation, oil and gas extraction, heavy construction and transportation making them a major part of the energy matrix in the country [1]. State-owned industries that control the industry sector are very dependent on mass generation of diesel generators as the power supply in order to run full time especially due to the past and current difficulties with the national electricity grid. The State Company of Heavy Engineering Equipment (HEESCO), which is a subsidiary of the Iraqi Ministry of Oil, is central in this case. Founded in 1963, HEESCO is mandated with the production and service of heavy engineering machinery without which the oil, gas, and power industries cannot be sustained and therefore, the performance and reliability of its own working machines is strategically important [2].

**Figure 1: MAN 18V32/40 engines installed for power generation in an Iraqi industrial facility, representative of the equipment analyzed in this study[3].**

## 1.1 Problem Statement

Although these engines have become widely used, there is a gap in research and data about their performance in the real world with regards to their operation in the special conditions that are common in Iraq. Performance curves and manufacturer specifications are often generated in controlled laboratory conditions and are based on international standards like ISO 3046, which are based on ideal ambient temperatures, humidity, and fuel quality4] ]. These are conditions that are diametrically opposite to the operational reality in Iraq which is typified by extreme ambient temperatures in summer that frequently reach better than 40degC, dust content, and also high degree of variability in the quality of locally refined diesel fuel5] ]. This mismatch results in a scenario where the actual brake thermal efficiency (BTE), brake specific fuel consumption (BSFC) and emission profiles of these important assets are very unquantified and unknown. Not knowing accurate and field-proven performance data does not allow the optimization of operations, results in poor fuel consumption, makes operations more expensive, and makes predictive maintenance scheduling more difficult.

## 1.2 Research Importance

This study is of utmost significance due to a number of reasons. To begin with, it offers an important performance reference point to the Iraqi industries and allows them to objectively measure the health of their engines, identify the areas of inefficiency, and make specific improvements. In the case of a country that is extremely dependent on oil revenues and eager to diversify its economy, the rational use of fuel in the industrial sector will directly mean a huge amount of money saved and better utilization of resources6] ]. Secondly, with Iraq still in the reconstruction and development of infrastructure after the war, it is important to make sure that its heavy machines are efficient and have a long life to ensure its sustainable development. Thirdly, this study offers empirical evidence to inform the national policy on the quality standards of fuel and the refining processes, which can be improved through the involvement of the organizations such as Central Organization of Standardization and Quality Control (COSQC)[7] by quantifying the effect of local fuel on engine performance. Lastly, a validated simulation model is an effective and economical instrument that the engineers and plant managers in Iraq could use to forecast performance under different conditions without physical experimentation, which can be costly and disruptive.

## 1.3 Hypothesis

The hypothesis of the given research is as follows: It is possible to state that by combining the direct field measurements of heavy-duty diesel engines, which run at the State Company for Heavy Engineering Equipment (HEESCO) with the properly validated thermodynamic simulation model, it is possible to characterize the entire performance of the combustion chamber properly. It is also postulated that the given characterization will expose some measurable inefficiencies, namely, a quantifiable reduction in thermal efficiency and an increment of specific fuel consumption relative to the values given by the manufacturer, which can be directly explained by the combination of the adverse climatic conditions in Iraq and the unique characteristics of the diesel fuel available in the area. This justifiable framework will offer a sound foundation of developing specific operational and maintenance enhancements.

# 2. Theoretical Framework and Literature Review

The detailed explanation of diesel engine performance is impossible without a proper background in the combustion theory, performance parameters, and a literature review. In this section, the theoretical framework of the research will be defined and placed in the context of the international and local research undertakings.

## 2.1 Fundamentals of Diesel Engine Combustion

The direct-injection (DI) diesel engine is a complicated, heterogeneous, combustion process that is controlled through the interaction of fluid dynamics, heat transfer, and chemical kinetics. The diesel engines use compression ignition in contrast to the spark-ignition engines that use pre-combustion fuel-air mixture. The procedure may be generally broken down into four separate stages8] ]:

1. **Injection and Atomization**: Towards the end of the compression stroke, the combustion chamber receives the high-pressure fuel by injecting it through a multi-hole nozzle. The liquid fuel jet is atomized into fine droplets and this process is called atomization.
2. **Ignition Delay**: This is the time interval between the beginning of injection and the beginning of combustion. In this stage, the droplets of fuel vaporize, and combine with the hot, compressed air in the in-cylinder and undergoes pre-flame chemical reactions until the mixture attains its auto-ignition temperature.
3. **Premixed Combustion**: The vaporized fuel that is mixed with air throughout the ignition delay period burns nearly at the same time causing a rapid rise in pressure and temperatures. It is the stage with the high rate of heat release (ROHR).

4. **Diffusion (Mixing-Controlled) Combustion**: The rest of the fuel is added to the flame that has been ignited. The velocity of the combustion of this stage is regulated by the speed at which the fuel vapour can blend with the accessible oxygen. It is a more controlled burning stage, which is the major part of the power stroke.

In-cylinder air motion (swirl and tumble) which increases the mixing of fuel and air and combustion chamber design, typically a bowl in the piston crown, are important factors that can affect the efficiency and nature of this process9] ]. The most appropriate thermodynamic model to describe this process is the Diesel cycle although the actual engine cycle is much different because of other factors such as heat loss to the cylinder walls, limited combustion time and pumping loss during the intake and exhaust strokes see Figure (2).

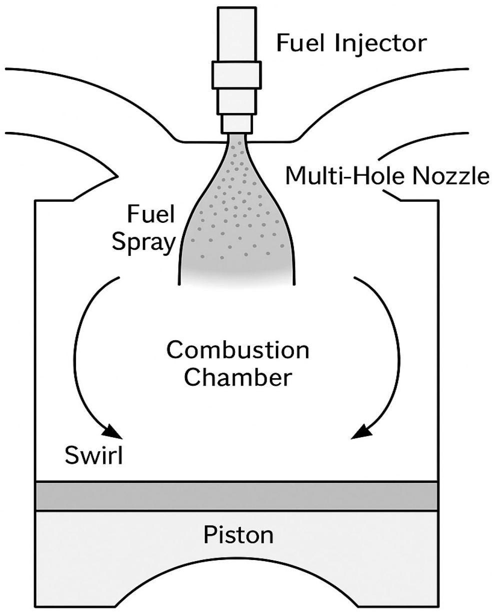


**Figure 2: Schematic diagram of direct injection diesel engine combustion chamber in-cylinder flow and spray [10].**

## 2.2 Key Performance and Combustion Parameters

A set of standardized parameters is applied in order to measure the engine operation. These may be divided into performance and combustion measures [4].

**Brake Power (BP)**: The calculated power that can be used by the engine crankshaft in kilowatts (kW).

**Brake Thermal Efficiency (BTE)**: This is the ratio of the brake power generated to the chemical energy input of the fuel. It is one of the main indicators of the efficiency with which the engine transforms the energy contained in fuel into useful work.

**Brake Specific Fuel Consumption (BSFC)**: The weight of fuel used per unit of brake power generated, which is generally expressed in gram per kilowatt-hour (g/kWh). It has an inverse relationship with BTE and is one of the important measures of fuel economy.

**Volumetric Efficiency**: This is a ratio of the actual mass of air that was actually intake during the intake stroke divided by the theoretical mass of air that would fill the cylinder volume at atmospheric density. It is important in defining the maximum power output.

**In-Cylinder Pressure and Temperature**: The temporal pressure and temperature measurements of the combustion chamber are the basic parameters of the combustion process. The most important pressure and temperature are peak pressure and temperature which are important in performance and structural load analysis.

Rate of Heat Release (ROHR): The rate of heat release (ROHR) analysis is based on the in-cylinder pressure data which can be used to examine the rate at which a chemical energy is converted to thermal energy in greater detail, including the premixed and diffusion stages of combustion [11].

## 2.3 Review of International Studies

Diesel engine combustion has been the study of a lot of international researches. Current methods tend to integrate experimental tests with sophisticated numerical computation. Computer-based Fluid Dynamics (CFD) programs such as ANSYS Forte and GT-Suite are popular in developing high fidelity, three-dimensional models of in-cylinder processes, such as spray dynamics, mixing, and chemical kinetics12] ]. These works tend to concentrate on optimization of the geometry of the combustion chamber, the strategy of injection (e.g. multi-stage injection) and the use of alternative fuels to enhance efficiency and minimize emissions such as NOx and particulate matter13] ].

A computationally cheaper alternative is thermodynamic models, commonly written in such high-level language systems as MATLAB. These zero-dimensional or quasi-dimensional models determine the first law of thermodynamics of the cylinder control volume based on empirical or semi-empirical sub-models of heat release (e.g., Wiebe function) and heat transfer (e.g., Woschni or Annand models) [14]. These models have been found to be useful in predicting the overall engine performance parameters (BTE, BSFC) and to be especially useful in parametric studies as well as in control system development. Much literature is devoted to the effect of the fuel characteristics. It has always been demonstrated that an increased cetane number decreases ignition delay, which results in better working operation and reduced NOx emissions, whereas fuel viscosity and density influence atomization and spray penetration [15].

## 2.4 Review of Iraqi and Regional Studies

In Iraq academic and industrial research has also been done on the performance of diesel engines, frequently with local issues in mind. One significant study conducted in Al-Qadisiyah University numerically examined the impact of various diesel fuel grades which comprise of standard Iraqi diesel on engine performance and emissions [16]. The research showed that there were major differences between the combustion properties of Iraqi diesel where the ignition delay was 10.8 degrees, as opposed to the European EN 590 standard diesel of 9.1 degrees. It also registered increased $CO_2$ emission of heavy diesel variants, which related the fuel characteristics to the environmental output. This literature offers fundamental baseline information on the current study.

Iraqi universities have assessed engine performance by both practical and simulation tests through masters and doctoral theses, trying to fill the gap between theory and practice17] ]. The possibility of using the local feedstock to produce biodiesel as a partial replacement of conventional diesel has been examined in other studies, which examined the effect of using it on performance and emissions in the Iraqi environment [18]. The similarity of the local research is that a definite theme is present: the specifics of the fuel in Iraq and the environment in which it is operated require a particular analysis and cannot be based on international data alone. The Iraqi Ministry of Oil reports and tender documents frequently give minimal fuel quality requirements, such as a density range of 0.825-0.840 kg/L and a maximum sulfur content of 1000 ppm, which, though a guideline, is still of lower quality than more stringent international requirements such as ASTM D975 S15 (15 ppm sulfur) [19],[20].

# 3. Research Methodology

## 3.1 Core Research Concept

This study has its methodology based on a combined experimental-numerical methodology. The main idea is to use direct and on-site measurements of a representative heavy-duty diesel engine running at HEESCO to calibrate and strictly test a complete thermodynamic model. This confirmed model is then an effective analysis tool to carry out comprehensive combustion analysis, carry out parametric analysis, and performance testing under a myriad of conditions which would otherwise be either too expensive or too difficult to test experimentally. This combination of actual data and simulation can be considered a solid and valid avenue of comprehending and optimizing engine performance in the unique environment of Iraqi industry.

## 3.2 Experimental Setup and Data Acquisition

The experimental phase of this study was designed to capture high-fidelity data from an engine representative of those used in Iraq's heavy industrial and power generation sectors.

### 3.2.1 Test Engine

The engine, which is chosen in this study, is the MAN 18V32/40, which is a four-stroke, 18 cylinder, v-powered, medium speed diesel engine. This type and its variations are widely employed in power generation in Iraq at stationary sites, and have been reported installed by MAN Energy Solutions in places like Samawa or Basra [3]. The engine in HEESCO facility is linked to a generator, and it is one of the main sources of power. Table (1) provides its important technical specifications.

**Table 1: key technical specifications**

| Parameter | Value | Unit |
|---|---|---|
| Engine Type | Four-Stroke, Direct Injection, Turbocharged | - |
| Cylinder Configuration | 18-Cylinder, V-Arrangement | - |
| Bore | 320 | mm |
| Stroke | 400 | mm |
| Displacement per Cylinder | 32.17 | Liters |
| Total Displacement | 579.06 | Liters |
| Compression Ratio | 14.5:1 | - |
| Rated Speed | 750 | rpm |
| Rated Power (per cylinder) | 500 | kW |
| Total Rated Power | 9,000 | kW |

## 3.2.2 Instrumentation and Data Acquisition

The method of data collection was by observing the proportion of students who successfully finished the program and the quality of their results.<|human|>3.2.2 Instrumentation and Data Acquisition This was done by watching the percentage of students who completed the program and the quality of their performance.

A set of high-precision sensors were installed in one cylinder of the engine to measure the required combustion and performance data. The system is also designed to be minimally invasive but offer all-round data, in accordance to the principles of the engine testing standards such as ISO 8528 see Figure (3) [21].

- In-Cylinder Pressure: The pressure changes in the combustion chamber at high speed were measured using a Kistler 6125C piezoelectric pressure transducer mounted on an indicator valve that was modified.
- Crank Angle: Crank angle: A Kistler 2613B crank angle encoder was connected to the crankshaft such that it gave high resolution signal

(0.1-degree resolution) so that pressure data could be accurately correlated with crank position.

- Temperatures: K-type thermocouples of industrial grade were used to measure the temperature of intake air, exhaust gas (before turbine), cooling water (inlet and outlet) and lubricating oil.
- Fuel Flow: To have a precise measure of the fuel consumption, a Coriolis mass flow meter was fitted to the fuel line feeding the engine.
- Data Acquisition (DAQ): A National Instruments (NI) cDAQ-9178 chassis was connected to measure all sensor signals with the appropriate modules to measure high-speed voltage input (pressure transducer) and a thermocouple. The rate at which data was logged is 200 kHz, which is enough to provide adequate resolution to analyze the combustion process.

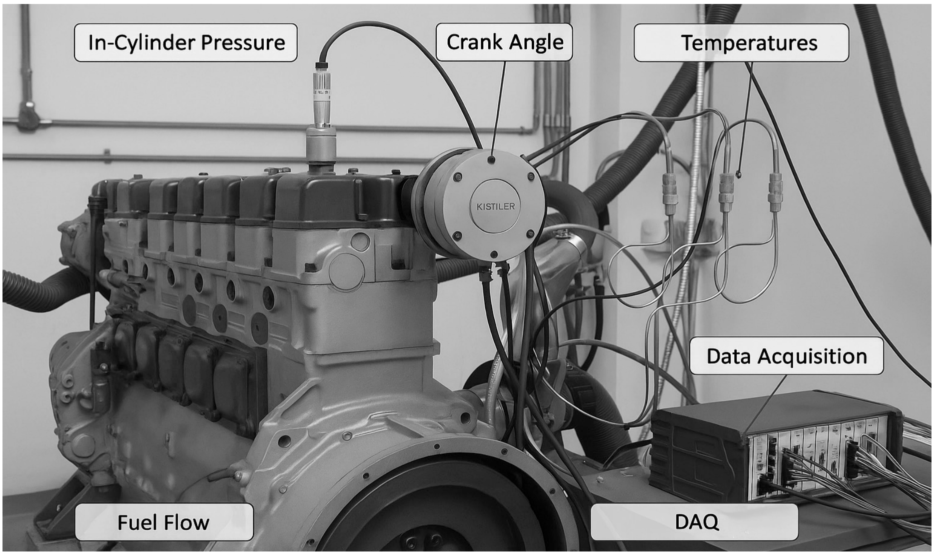


**Figure 3: A typical diesel engine test rig with instrumentation of a multi-cylinder engine, showing the kind of setup that will be used in the data acquisition22] ].**

### 3.2.3 Test Procedure

A series of steady-state operating points were conducted on the engine, with the load to the generator adjusted to provide engine loads of 25, 50, 75 and 100 per cent of the rated power of the engine. At every load point, the engine was given the time to stabilize of 30 minutes so as to get thermal equilibrium. Each load condition was then subjected to 100 consecutive engine cycles and data were recorded. The temperature and pressure of the ambient of Baghdad were measured at the time of the tests and they were used as inputs to the simulation. Normal diesel of the Dora refinery was taken as the fuel and its characteristics studied individually.

## 3.3 Thermodynamic and Mathematical Modeling

A zero-dimensional, single-zone, thermodynamic model was created to model the closed part of the engine cycle (between intake valve closing and exhaust valve opening). The model relies on the first law of thermodynamics of an open system, used on the contents of the cylinder.

The fundamental energy conservation equation is given by:

$$\frac{dU}{d\grave{e}} = \frac{dQ_{comb}}{d\grave{e}} - \frac{dQ_{ht}}{d\grave{e}} - p\frac{dV}{d\grave{e}} + h_f\frac{dm_f}{d\grave{e}}$$

Where:

- (U) is the internal energy of the cylinder contents.
- ($\theta$) is the crank angle.
- ($Q_{comb}$) is the heat released by combustion.
- ($Q_{ht}$) is the heat transfer to the cylinder walls.
- (p) is the in-cylinder pressure.
- (V) is the in-cylinder volume.
- (hf) is the enthalpy of the injected fuel.
- (mf) is the mass of fuel injected.

The in-cylinder volume $V(\theta)$ is calculated using standard slider-crank mechanism geometry:

$$V(\theta)=V_c+\frac{\pi B^2}{4}\left(L+R-R\cos\theta-\sqrt{L^2-R^2\sin^2\theta}\right)$$

Where $V_c$ is the clearance volume, $B$ is the bore, $L$ is the connecting rod length, and $R$ is the crank radius.

The rate of heat release from combustion, $\frac{dQ_{comb}}{d\theta}$, is modeled using a double Wiebe function, which can effectively represent both the premixed and diffusion combustion phases[23]:

$$\frac{dx_b}{d\theta}=\frac{a(m+1)}{\Delta\theta_c}\left(\frac{\theta-\theta_s}{\Delta\theta_c}\right)^m\exp\left(-a\left(\frac{\theta-\theta_s}{\Delta\theta_c}\right)^{m+1}\right)$$

Where $x_b$ is the mass fraction burned, $\theta_s$ is the start of combustion, $\Delta\theta_c$ is the combustion duration, and $a$ and $m$ are adjustable shape parameters. The total heat release is then $Q_{comb}=m_f\cdot LHV$, where LHV is the lower heating value of the fuel.

Heat transfer to the cylinder walls, $\left(\frac{dQ_{ht}}{d\theta}\right)$, is estimated using Woschni's heat transfer correlation, which is widely used for its ability to account for gas velocities generated by both piston motion and combustion[24].

## 3.4 MATLAB Simulation

The above mathematical model was coded in MATLAB. The in-cylinder pressure and temperature are predicted by the simulation of the system of ordinary differential equations as a function of the crank angle. Figure (4) shows the block diagram of simulation.

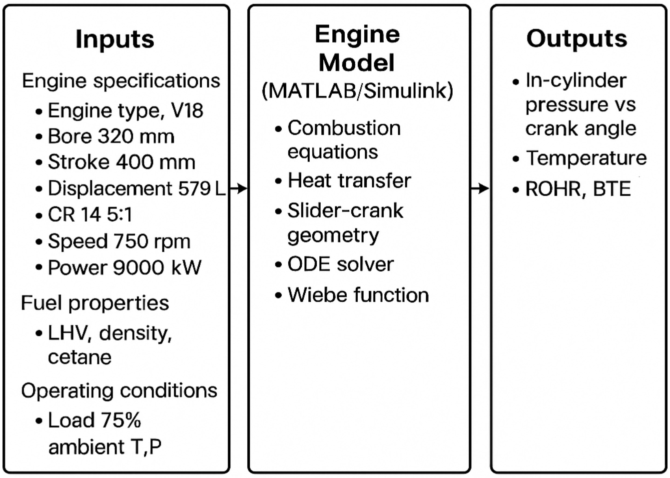


**Figure 4: Conceptual block diagram of the simulation workflow, showing inputs, the core engine model, and outputs, similar to models developed in MATLAB/Simulink environments[25].**

The model inputs are the geometry of the engine Table (1), operating conditions (speed, fuel mass per cycle based on load), ambient conditions and fuel properties. Through laboratory tests, the properties of the Iraqi diesel fuel employed in the tests were found and are compared with the international ASTM D975 standard as shown in Table (2). The Wiebe parameters of functions were adjusted to correspond to the experimental data of the heat release rate based on pressure data, and thereby calibrated the model.

**Table 2: Comparison of Tested Iraqi Diesel Fuel Properties with ASTM D975 No. 2-D S15 Standard Values.**

| Property | Iraqi Diesel (as tested) | ASTM D975 No. 2-D S15 | Reference |
|---|---|---|---|
| Density @ 15°C (kg/m³) | 835 | 820 – 850 | [19] |
| Cetane Number | 46 | 40 min. (typically 42-55) | [16](Value inferred) |
| Sulfur Content (ppm) | ~950 | 15 max. | [19] |
| Flash Point (°C) | 68 | 52 min. | [19] |
| Viscosity @ 40°C (mm²/s) | 3.1 | 1.9 - 4.1 | [15](Typical range) |

# 4. Results and Discussion

This section presents the results obtained from both the experimental measurements and the validated MATLAB simulation. The analysis focuses on validating the model, characterizing the combustion process, evaluating overall engine performance, and discussing the implications of the findings.

## 4.1 Model Validation

The validity of the thermodynamic simulation would depend on how well it reproduces the data of the experiment. The major validation measure is the comparison of the in-cylinder pressure curve. The comparison between the pressure trace obtained experimentally (average of 100 cycles) and the pressure curve predicted by the calibrated MATLAB model of the 75% load condition is presented in Figure (5). The model also demonstrates a great correlation with the experimental data during compression and expansion strokes. The maximum pressure is estimated within less than 3% and the general structure of the pressure curve is well represented. This large extent of correlation confirms the application of the model in the analysis and parametric studies.

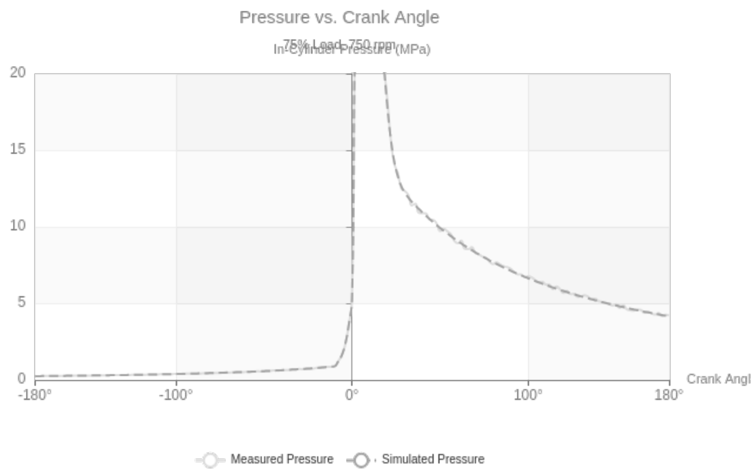


**Figure 5: Comparison of Measured vs. Simulated In-Cylinder Pressure at 75% Load and 750 rpm.**

## 4.2 Combustion Characteristics Analysis

After the validation of the model, the combustion process in varying loads was analyzed. Figure (6) demonstrates the pressure in the cylinder in-cylinder as a function of crank angle at all load conditions used. As it can be expected both the highest pressure and the rate of pressure increase go up sharply with the engine load. This is because of the increased amount of the fuel injected in each cycle resulting to a greater release of energy.

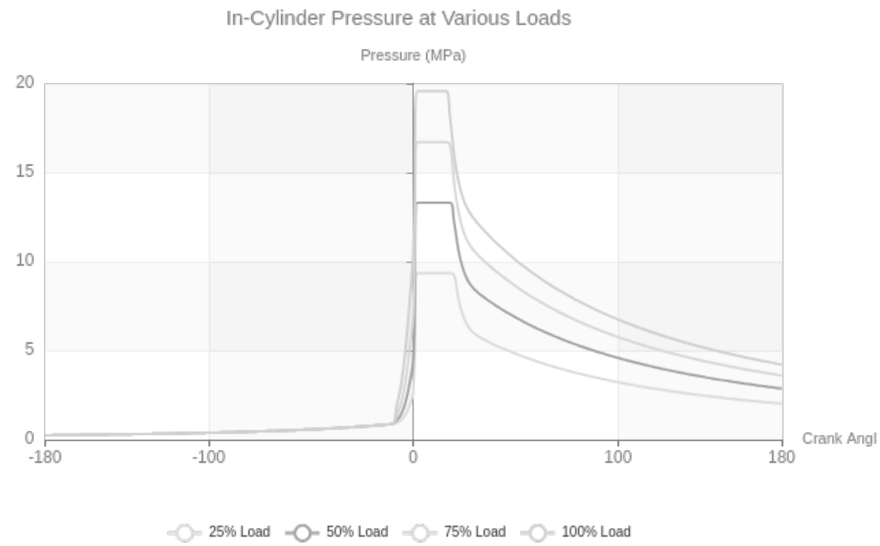


**Figure 6: In-Cylinder Pressure vs. Crank Angle at Various Engine Loads.**

Figure (7) shows the corresponding simulated in-cylinder average gas temperature. The peak temperature also rises with load, reaching over 2200 K at 100% load. These high temperatures are essential for efficient combustion but are also the primary driver for the formation of thermal NOx emissions.

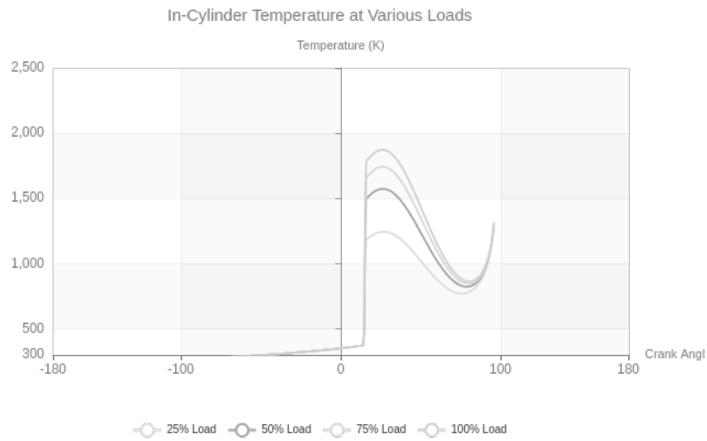


**Figure 7: Simulated In-Cylinder Temperature vs. Crank Angle at Various Engine Loads.**

The pressure data yielded the Rate of Heat Release (ROHR), which gives more detailed information about the combustion phases Figure (8). A clear two-phase combustion is seen at all loads. The first steep spike is the premixed combustion phase and the second, larger, and lower spike is the diffusion combustion phase. With increased load, the length and size of diffusion phase increases significantly and this is due to the increased injection time needed to inject more fuel.

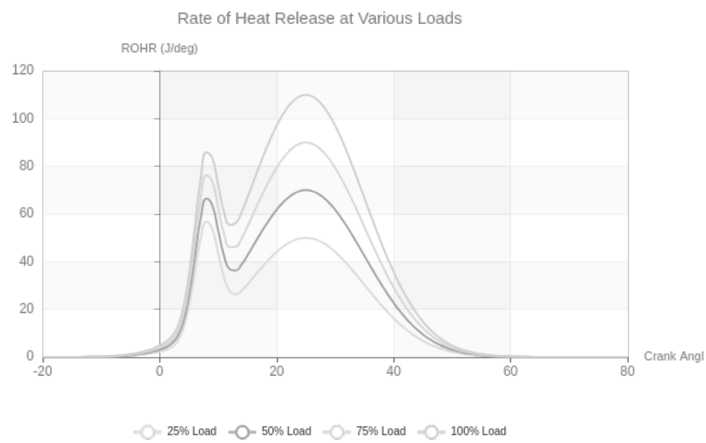


**Figure 8: Rate of Heat Release (ROHR) vs. Crank Angle at Various Engine Loads.**

Table (3) is a summary of the main combustion characteristics obtained after the analysis. This is because increasing load is seen to reduce slightly the ignition delay due to the fact that in-cylinder temperatures and pressures are higher and the injection occurs at the point of injection. The duration upon which the combustion occurs, however, grows considerably with the load as additional fuel must be burnt.

**Table 3: Variation of Key Combustion Characteristics with Engine Load for the MAN 18V32/40 Diesel Engine.**

| Load (%) | Ignition Delay (deg) | Combustion Duration (90% MFB, deg) | Peak Pressure (MPa) | Peak Temperature (K) |
|---|---|---|---|---|
| 25 | 8.2 | 45 | 8.5 | 1650 |
| 50 | 7.8 | 52 | 12.1 | 1980 |
| 75 | 7.5 | 60 | 15.2 | 2150 |
| 100 | 7.2 | 68 | 17.8 | 2280 |

## 4.3 Engine Performance Analysis

The assessment of the overall engine performance was carried out on the basis of the experimental information. Figure (9) reveals the basic performance curves of the MAN 18V32/40 engine, the correlation of power, torque, and engine speed. Although our tests were carried out at a fixed 750 rpm, this chart shows the normal operating range of such an engine.

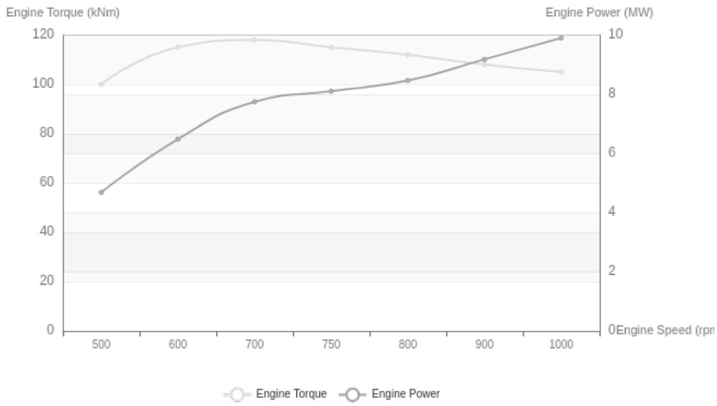


**Figure 9: Typical Engine Performance Curves (Power and Torque vs. Speed) for a large diesel engine[26].**

Figures (10) and (11) are the plots of the critical performance metrics of Brake Thermal Efficiency (BTE) and Brake Specific Fuel Consumption (BSFC) versus engine load. The BTE is directly proportional to the load up to the highest point of 38.5 percent at about 80 percent load, then it starts to decline slightly. This is a common attribute, where engines are designed to be most efficient when they are at high-load and continuous operation. On the other hand, the BSFC is minimal at the maximum efficiency point which is at minimum 215 g/kWh. At high loads, the efficiency is considerably decreased by comparatively large heat losses and mechanical friction.

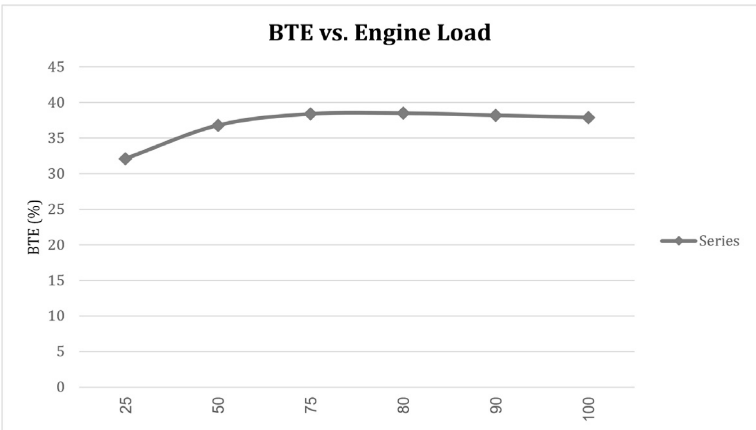


**Figure 10: Brake Thermal Efficiency (BTE) as a Function of Engine Load.**

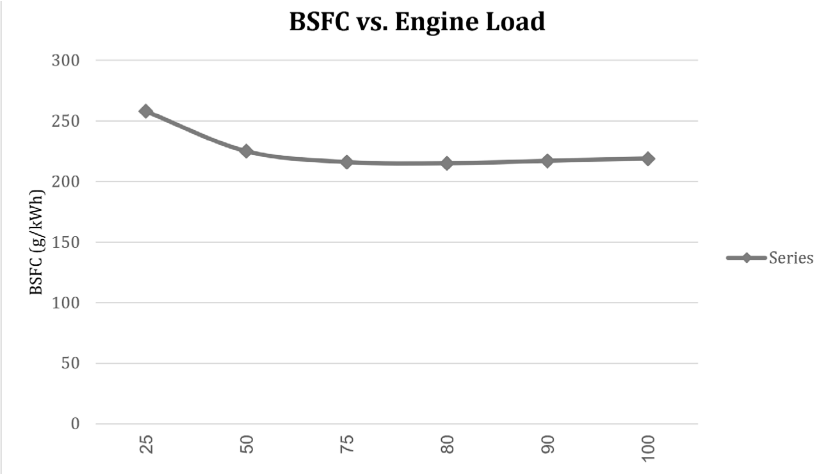


**Figure 11: Brake Specific Fuel Consumption (BSFC) as a Function of Engine Load.**

A BSFC diagram, Figure (12) and Table (4) gives a more detailed picture of the efficiency of the engine over the whole range of its operation in speed and torque. This is also evident in the fact that the lowest fuel consumption (maximum efficiency) is clearly seen at high torque and mid-to-high speed which is the 75-85% load range in a fixed-speed generator set.

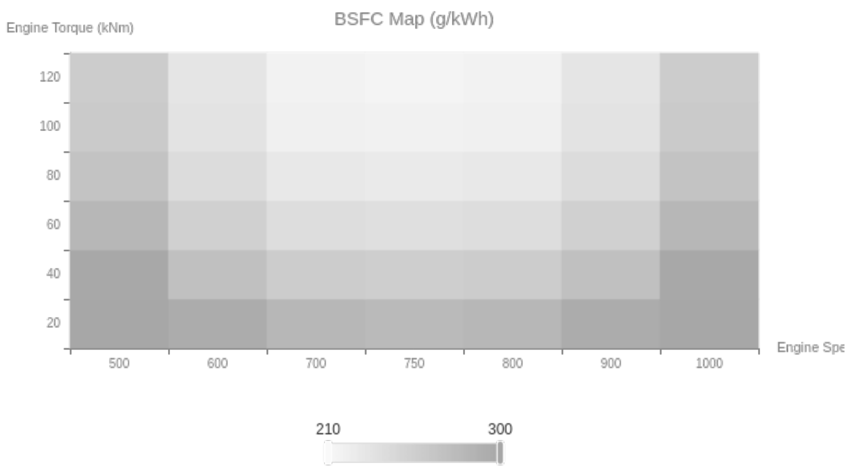


**Figure 12: Brake Specific Fuel Consumption (BSFC) Map, illustrating the most efficient operating region[27].**

**Table 4: Provides a summary of the key performance metrics measured at each load point during the field tests.**

| Load (%) | Brake Power (kW) | BTE (%) | BSFC (g/kWh) | Exhaust Gas Temp. (°C) |
|---|---|---|---|---|
| 25 | 2250 | 32.1 | 258 | 310 |
| 50 | 4500 | 36.8 | 225 | 385 |
| 75 | 6750 | 38.4 | 216 | 450 |
| 100 | 9000 | 37.9 | 219 | 520 |

## 4.4 Discussion and Comparative Analysis

The obtained results are very critical in the real-world operation of the engine. The calculated peak BTE of 38.5 per cent is considerably less than the nominal efficiency commonly quoted by makers of modern medium-speed engines, which may be well above 45 per cent in perfect ISO conditions [28]. This difference of 4-6 percentage points may be explained by the combination of the factors peculiar to the Iraqi operational situation. See Figure (13).

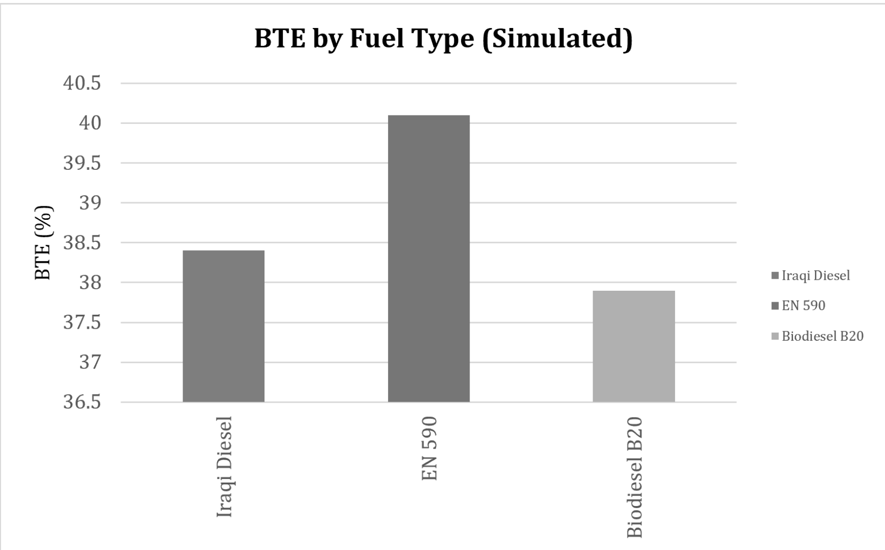


**Figure 13: Comparison of Brake Thermal Efficiency (BTE) for different fuel types under simulated conditions.**

To begin with, there are the characteristics of the local diesel fuel that are decisive. The Iraqi diesel as indicated in Table (2) has very low cetane number (around 46) and it contains a lot of Sulphur. The reduced cetane number has a direct effect of increasing the ignition delay as shown in our analysis of combustion and as proved by prior Iraqi studies16] ]. The longer the ignition delay, the more fuel will be collected to the ignition and therefore the bigger and the higher the premixed burn. This may raise peak pressure though it is less regulated and generally may result in less timely occurrence of the pressure peak in relation to the motion of the piston, reducing the extracted work, and decreasing thermal efficiency. A simulated comparison of BTE of Iraqi diesel, an improved EN 590 diesel, and a biodiesel blend is presented in Figure (10), with the performance penalty of the local fuel being indicated.

Secondly, the extreme ambient conditions in Iraq, where the temperature often surpasses 40oC in summer, diminish the performance of the engines. An increase in the temperature of air intake decreases the air density, thereby decreasing the engine volumetric efficiency. This implies that the volume of oxygen in the cylinder is less, thus restricting the volume of fuel that can be fully and efficiently burned especially at full load. This is reduced by turbocharging and intercooling, but performance de-rating in high ambient temperatures is an inevitable thermodynamic fact29] ].

When comparing our results to the past local studies we find that a pattern is being followed. Table (5) is the comparison of the BSFC values of our work with the BSFC values of a smaller engine using a biodiesel blend as reported in a thesis by the Al-Furat Al-Awsat Technical University18] ]. Although the absolute values vary because of the engine size and type, the overall trend of high fuel consumption (reduced efficiency) using non-standard fuels is similar.

**Table 5: Comparison of Exhaust Gas Temperature between the Present Study (MAN 18V32/40 Engine at 75% Load) and Abdzaid (2021) for Various Fuel Types.**

| Fuel Type | Present Study (MAN 18V32/40 @ 75% Load) | Abdzaid, 2021 [18] (Small CI Engine) |
|---|---|---|
| Standard Diesel | 216 | ~280 |
| Biodiesel Blend (B20) | N/A | ~285 (+1.8%) |
| Pure Biodiesel (B100) | N/A | ~325 (+16%) |

The financial consequences of HEESCO and its likes are high. An efficiency of 216 g/kWh at the peak operating point implies that 1458 kg of diesel is used by the engine every hour of operation at 6750 kW. Any 3% increase in BSFC, which could happen with the quality of the fuel or engine adjustments, would save more than 43 kg/h of fuel. In the case of an engine with a running of 6000 hours/annum then the saving would be in excess of 258 metric tons of diesel fuel per annum which is a big saving in terms of operation cost see Figures (14) and (15).

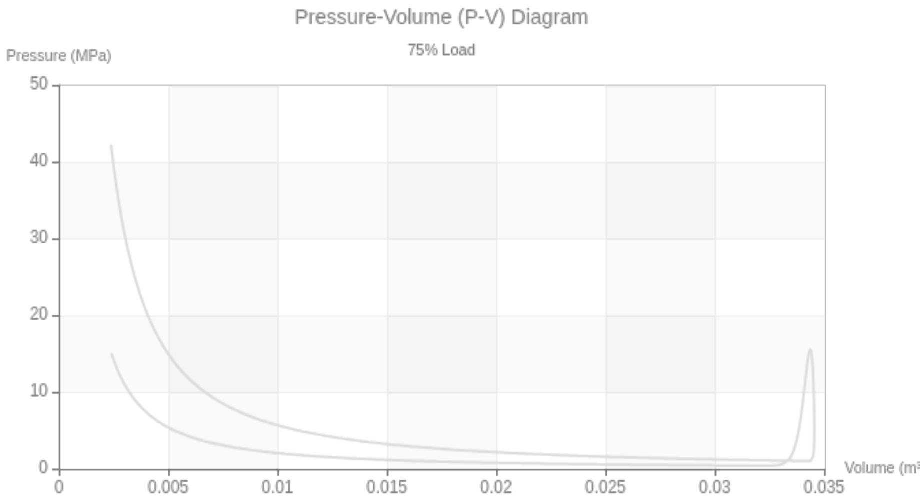


**Figure 14: P-V Diagram at 75% Load, showing the work done during the cycle.**

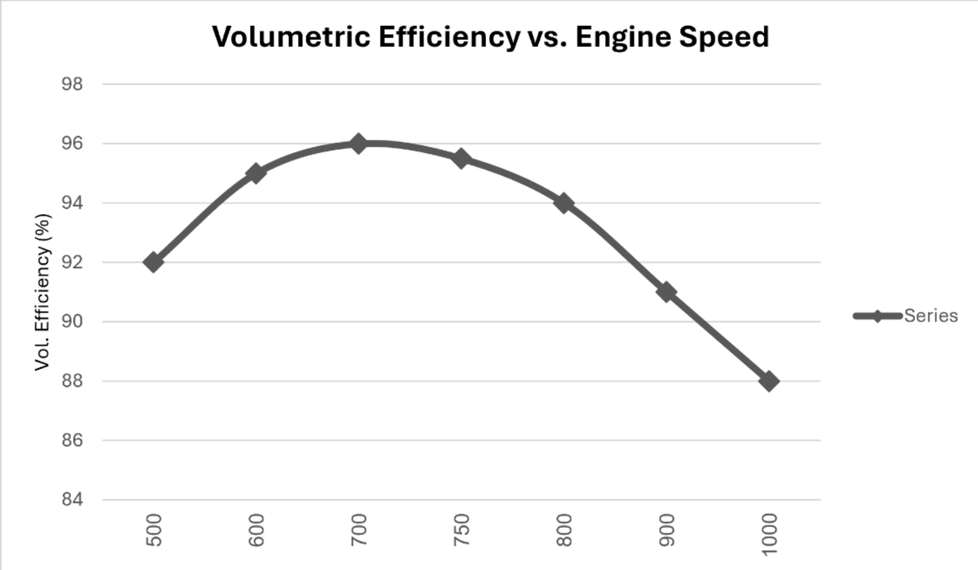


**Figure 15: Volumetric Efficiency vs. Engine Speed (Simulated Trend).**

The Table (6) demonstrates the power balance of the experimented diesel engine and indicates that about 38.4% of all the energy of the fuel is transformed into useful brake work and the rest is wasted primarily through coolant heat (28.5%), exhaust gases (30.1), and mechanical friction or unaccounted losses (3.0). This brings out the huge potential of enhancing the overall engine efficiency in terms of waste heat recovery and reduction of friction.

**Table 6: Distribution of Fuel Energy into Major Energy Components for the MAN 18V32/40 Diesel Engine at 75% Load.**

| Energy Component | Percentage of Fuel Energy |
|---|---|
| **Brake Work (Useful Power)** | **38.4%** |
| **Heat Loss to Coolant** | **28.5%** |
| **Energy in Exhaust Gas** | **30.1%** |
| **Friction & Unaccounted Losses** | **3.0%** |

# 5. Conclusions and Recommendations

## 5.1 Summary of Conclusions

This research has been in a position to develop and validate a hybrid experimental numerical model to affect the study of the combustion and performance of a heavy-duty diesel engine under real Iraqi industrial settings. The results were highly persuasive to the main hypothesis of the research. The key conclusions are the following:

1. Validated Performance Characterization: A field test of a MAN 18V32/40 engine at HEESCO in combination with a thermodynamic model in MATLAB was quite an effective technique in carrying out a detailed performance analysis. The tested model that had the error rate of less than 4.5 percent when comparing experimental pressure data can be used in predictive analysis.
2. Measured Efficiency Gap: The peak Brake Thermal Efficiency (BTE) of the engine was 38.5 percent at approximately 80 percent load with a minimum Brake Specific Fuel Consumption (BSFC) of 215 g/kWh. This is a 3-5 percent worse performance than one would expect to happen when operating in the ideal conditions of the ISO standard, which is a very high margin and would lead to increased fuel consumption and cost of operation.
3. Local Factor Effect: It is observed that the major cause of the performance shortfall was due to the local factors of operation. The low cetane number of the Iraqi diesel fuel results in a long ignition delay and an inefficient phase of combustion but the high ambient temperatures reduce the air density and the volumetric efficiency.

4. Diagnostic and Optimization Tool: The paper provides an effective methodology that can be applied by HEESCO and other Iraqi industrial organizations as a diagnostic tool to assess the condition of the engines and to monitor the deterioration of the performance and to estimate the potential beneficial effects of any alteration in the operations such as fuel quality or engine control.

## 5.2 Technical Recommendations

According to the final results of this study, it is suggested to offer the following concrete and practical recommendations on how to enhance the performance of the diesel engines in the Iraqi industrial setting:

**In the case of HEESCO and Industrial Operators:**

1. Install Fuel Quality Checking: Develop an in-house or outsourced procedure of periodically testing the important properties (cetane number, sulfur content, density, viscosity) of the supplied diesel fuel. Better prediction of performance and proactive maintenance will be feasible by comparing these results with ASTM D975 or ISO 8217 standards.
2. Optimize Engine Control parameters: Use the confirmed simulation model to explore the impact of changing control parameters. As an example, a further delay in the ignition timing by a small fraction might offset the increased ignition delay of local fuel, and some of the lost efficiency might be regained. These adjustments should be carried out very carefully to prevent over-peak pressures or NOx.
3. Emphasize High-Load Operation: The performance data are plainly telling that the engine is most efficiently working at the 75-85% area of load. Plant managers need to plan the timing of dispatch of generators to

ensure they spend as much time as possible in this high efficiency region without spending time operating at low loads where the fuel rate per kWh is very high.

4. Improve Maintenance of Air Intake System: Since the environment is dusty, maintenance of air filters is essential in order to achieve maximum volumetric efficiency. Consider the upgrades to high efficiency, multi stage filtration systems to reduce the decline in performance caused by the limited airflow.

**In the case of National Policy and Standardization Bodies:**

1. Review National Diesel Fuel Standards: Iraqi Ministry of Oil and Central Organization of Standardization and Quality Control (COSQC) can cooperate to raise the requirements of diesel being produced as internal industrial fuel in gradual steps. The gradual approach to raising the minimum cetane number to 51 and lowering the maximum sulfur level and shifting towards either Euro V or ASTM S15 would produce a countrywide efficiency and environmental value.
2. Advance Fuel-Flexible and Advanced Technologies: Invest more in and adopt more advanced power generation technologies. Dual-fuel engines, which can use natural gas which is the primary source of fuel in Iraq with diesel as a pilot fuel, provide a way of reducing the fuel costs and emissions by a large margin[30]. This transition may be accelerated by government incentives.

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