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Experimental Investigation of Load-Dependent Performance Characteristics of a Single-Cylinder Compression Ignition Engine

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Abstract*: Compression ignition (CI) engines performance evaluation continues to be a key issue in enhancing fuel efficiency and the nature of combustion under realistic operating conditions. The experiment in the present study was carried out in a detailed study of a single-cylinder, four-stroke diesel engine to examine the performance characteristics of the engine under a wide range of load conditions. Systematic measurements and assessments of key performance parameters, such as brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), and exhaust gas temperature (EGT) were performed. The experimental evidence suggests that at the lower loads, the brake thermal efficiency rises until there is an optimum operating range after which there is a slight decrease with higher loads caused by the rising fuel consumption and combustion constraints. On the other hand, it has a negative dependence on load, that is, brake specific fuel consumption reduces with increasing load, which indicates a high efficiency of fuel utilization. A steady increase in exhaust gas temperature with load is observed and this shows that more heat is released and more energy is lost through exhaust gases at high operating temperatures. The trends observed are a clear indication of how interdependent engine load and performance parameters are, and that there is an optimal range of engine load within which engine performance is optimal. The results of the current research not only help to understand the behavior of a diesel engine performance better but also leave a solid experimental base that may be used to validate the advanced computational models and further engine optimization research.

***Keywords*: Compression ignition engine; Diesel engine performance; Brake thermal efficiency; Brake specific fuel consumption; Exhaust gas temperature; Engine load variation.**

1. INTRODUCTION

Compression ignition (CI) engines remain predominant in transport, agricultural and industrial sectors because they are more fuel-efficient, have higher torque and better operational features. The effectiveness of converting chemical energy of fuel to useful mechanical work is the main factor that controls the performance of CI engines and it depends on various parameters including load conditions, fuel properties, and combustion behavior. Among the key performance indicators are the brake thermal efficiency, brake specific fuel consumption, and exhaust gas temperature which are the most common measures of engine performance because the summation of these indicators demonstrates the engine system energy conversion efficiency, fuel used, and thermal loss [1].

The performance of diesel engines at different operating conditions has over the years been the subject of extensive experimental studies. Much of this research has centered on the effect of alternative fuels like biodiesel, alcohol blends, and dual-fuel on engine performance and emission. Experimental studies have shown that fuel makeup and working conditions have a major influence on the nature of the combustion process thus determining efficiency and emissions [24]. Likewise, investigations with alternative fuel mixtures and dual-fuel combustion engines have noted differences in the performance parameters with alteration in the fuel properties and the combustion mechanisms [5–7].

Besides the study conducted on fuels, a number of review articles have underscored the significance of the nature of combustion, efficiency of thermodynamic processes, and mixing of fuels and air in the determination of engine performance. It is well known that better combustion results in increased thermal efficiency, as well as decreased specific fuel consumption, whereas incomplete combustion and increased heat loss have negative performance implications [8-10]. Moreover, experimental investigations of diesel engines running on fuel mixtures of various compositions have always revealed that engine load is a factor that is very important in regulating performance parameters, with higher loads tending to increase combustion efficiency because of the rise in-cylinder temperature and pressure [11-14].

More recent research has still been conducted to identify the diesel engine performance under different load conditions using conventional and alternative fuels. Such studies verify a positive correlation between the engine load and the optimal fuel consumption and combustion efficiency, leading to the enhancement of the brake thermal efficiency and the decrease in the brake specific fuel consumption [2,3,15]. Nonetheless, there are also higher load conditions resulting in higher exhaust gas temperatures, which means more thermal energy losses via exhaust gases. This action shows the trade off in the nature of conversion of energy and heat rejection in compression ignition engines.

Although there is a lot of literature, most of the research focuses on modified fuels, emission control measures or even on sophisticated ways of combustion. Despite the insightfulness of these studies, there is a dearth of studies that will seek to establish a clear and systematic baseline of knowledge on diesel engine performance when it operates under controlled conditions using the conventional diesel fuel. Such baseline experimental data will play an important role in learning how an engine behaves and to test computational models in highly engine simulations. There might be limitations in numerical and simulation-based approaches due to lack of standardized experimental data.

In this case, the ongoing study will aim at conducting a critical experimental study of a one-cylinder diesel engine in various load conditions. The exploration will be founded on simple performance factors i.e. thermal efficiency of the brakes, specific fuel consumption and exhaust gas temperature with the intention of ascertaining the association to engine load. The paper presents an organized and valid experimental data and an extensive overview of the performance patterns which can be used as a reference point in future modeling, validation and optimization research.

2. EXPERIMENTAL SETUP

In order to assess the performance characteristics of the diesel engine at different load conditions, an elaborate experimental setup was created and run under controlled laboratory conditions. It was set up in such a way that important engine performance parameters could be measured with precision such as brake power, fuel consumption and exhaust gas temperature.

2.1 Engine Specifications

The tests were carried out on a four-stroke, water-cooled compression ignition engine working at constant speed with a single-cylinder. The engine was chosen because it is simple, reliable, and can be used in controlled experimental studies. Table 1 presents the geometric and operating specifications of the test engine and gives important information needed to evaluate its performance.

Table 1. Specifications of the test diesel engine used for experimental investigation.

Parameter	Value
Engine Type	Single-cylinder, four-stroke CI engine
Cooling System	Water-cooled
Fuel	Diesel
Bore	95 mm
Stroke	110 mm
Displacement Volume	780 cm^3
Compression Ratio	15.5:1
Rated Power	5.9 kW
Rated Speed	1500–1600 rpm

2.2 Experimental Test Rig

The experimental was set up as diesel engine with an electrical dynamometer to load and measure load. The test rig was fitted with fuel supply system, cooling system as well as the instrumentation required to measure many operating parameters. The dynamometer made it possible to control the variation of load throughout the entire operating range of the engine and provided consistent and repeatable test conditions. Figure 1 shows the general arrangement and interrelationship of parts of the experimental set up.

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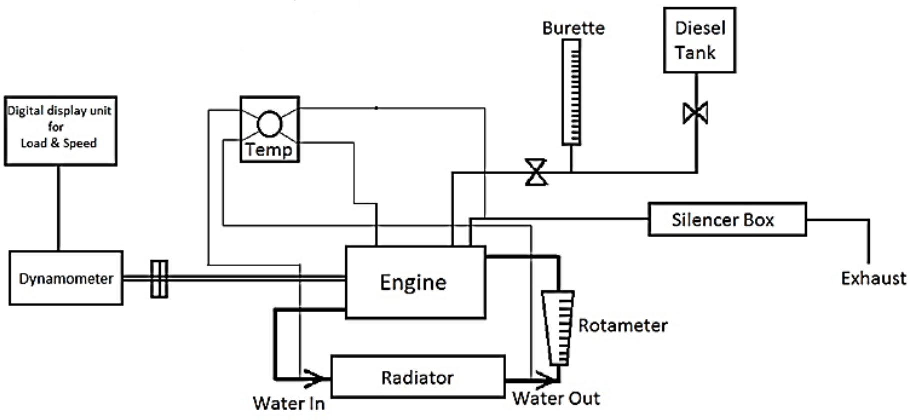

Figure 1. Schematic diagram of the experimental setup for diesel engine performance testing, showing engine, dynamometer, fuel system, and measurement instrumentation.

A photographic view of the actual experimental setup is shown in Figure 2, highlighting the physical arrangement of the engine, dynamometer, and instrumentation.

Figure 2. Photographic view of the experimental engine test rig illustrating the arrangement of dynamometer, fuel measurement system, and temperature sensing devices.

2.3 Instrumentation and Measurements

Parameters of the engine must be measured precisely in order to obtain credible performance measurement. The following instruments were used in the experiment:

- Load Measurement: A load was measured by using an electrical dynamometer on the engine. A systematic adjustment of the load was made and the voltage and current readings were taken with the objective of determining the brake power.
- Fuel Consumption Measurement: A calibrated burette was used to measure the fuel consumption. A stopwatch was used to measure the time taken to consume a certain amount of fuel that allowed the calculation of the fuel flow rate accurately.
- Speed Measurement: To make sure that the engine was working in the same manner throughout the experiment, we measured the speed of the engine with a non-contact digital tachometer.
- Temperature Measurement: Temperature at the exhaust was obtained with the help of a thermocouple attached to the exhaust manifold and it gave a clue about the loss of thermal energy.

2.4 System Operation

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The engine was run in steady-state and all measurements were made when the engine could be run to steady operating parameters. The cooling system ensured a constant engine temperature and reduced thermal changes throughout testing. The general configuration allowed the variation of the engine load to be under control, and the operating conditions could be maintained constant to provide an accurate evaluation of performance characteristics.

3. EXPERIMENTAL PROCEDURE AND DATA REDUCTION

3.1 Experimental Procedure

Experimental Procedure The experimental study was done under steady-state operating conditions to provide consistency and reliability of the measured values. A sufficient time to allow the engine to run at no-load conditions was allowed before the collection of the data. After reaching stable operating conditions, the engine was tested with a sequence of load variations with the help of the dynamometer. The no-load and full-load conditions were also gradually increased and decreased in small steps on the load to the engine. All load settings were then allowed to stabilize and corresponding measurements taken. Vital parameters like voltage, current, time of fuel consumption, and exhaust gas temperature were measured under each operating condition. To isolate the effect of load variation on performance characteristics, the engine speed was kept nearly steady during the experiment. This methodological procedure ensured that the test results were an authentic reflection of the working performance characteristic of the engine under the working limit.

3.2 Experimental Observations

The main measurements in the experiment were electrical output parameters, fuel consumption characteristics and exhaust gas temperature and speed of the engine. Table 2 includes all experimental observations made under varying load conditions and this is the starting point of the analysis of performance in the future.

Table 2. Experimental observations recorded at different engine load conditions.

Load (%)	Voltage (V)	Current (A)	Exhaust Gas Temperature (°C)	Fuel Volume (cc)	Time (s)	Speed (rpm)
2	217	0.49	72	10	43.0	765
6	223	1.31	82	10	42.5	762
10	228	2.12	88	10	42.0	762
14	228	2.66	90	10	35.0	758
20	234	4.15	96	10	35.0	759
40	238	8.38	105	10	27.81	752
60	239	12.47	126	10	21.35	745
80	237	16.47	147	10	17.82	739
94	233	18.84	142	10	12.71	729
100	226	21.20	153	10	12.00	718

3.3 Data Reduction and Performance Parameters

The recorded experimental data were processed to determine key performance parameters of the engine. These parameters provide insight into the efficiency of energy conversion, fuel utilization, and thermal behavior of the engine.

3.3.1 Brake Power (BP)

Brake power represents the useful mechanical power output available at the engine shaft. It was calculated using the electrical output measured from the dynamometer.

$$BP = \frac{V \times I}{1000} \quad (1)$$

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where:
V= Voltage (V) and I= Current (A).

3.3.2 Fuel Consumption Rate

The fuel consumption rate was determined by measuring the time required for a fixed volume of fuel consumption using a burette. The mass flow rate of fuel was calculated using:

$$M_f = \frac{X_{cc} \times \rho}{1000 \times t} \tag{2}$$

where:
X_{cc}= volume of fuel consumed (cc)
ρ= density of fuel (kg/m³)
t= time taken (s)

3.3.3 Brake Specific Fuel Consumption (BSFC)

Brake specific fuel consumption indicates the fuel efficiency of the engine and is defined as the fuel consumed per unit brake power output. It was calculated using the following relation:

$$BSFC = \frac{M_f \times 3600}{BP} \tag{3}$$

where:
M_f= mass flow rate of fuel (kg/s) and BP= brake power (kW).

The calculated performance parameters were validated against expected engine performance trends to ensure physical consistency of the results.

3.3.4 Brake Thermal Efficiency (BTE)

Brake thermal efficiency represents the effectiveness of converting the chemical energy of fuel into useful mechanical work. In the present study, brake thermal efficiency was calculated using brake specific fuel consumption and the calorific value of the fuel to ensure consistency with experimental measurements. The relation used is given by:

$$BTE = \frac{3600}{BSFC \times CV} \tag{4}$$

where:
CV= Calorific value of fuel (kJ/kg)

4. RESULTS AND DISCUSSION

The experimental investigation provides a detailed understanding of the variation of key performance parameters with engine load. The behavior of brake thermal efficiency, brake specific fuel consumption, and exhaust gas temperature is analyzed to interpret the combustion characteristics and energy utilization within the engine.

4.1 Variation of Brake Thermal Efficiency

The variation of brake thermal efficiency with engine load is presented in Figure 3.

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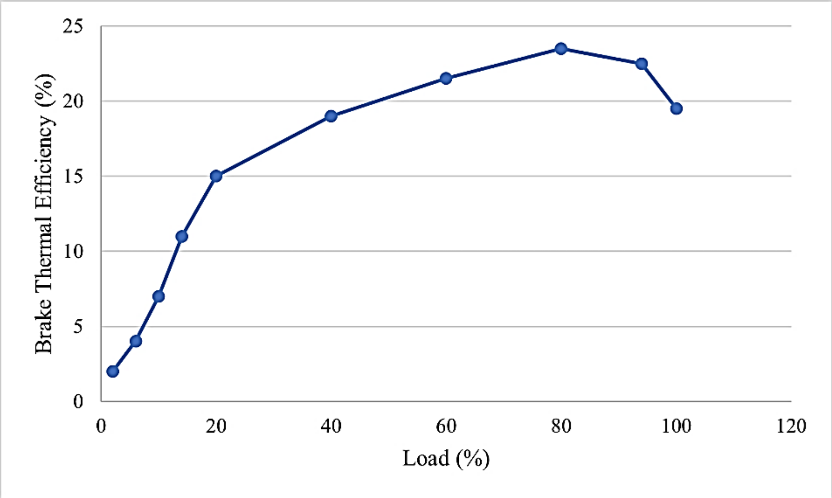

Figure 3. Variation of brake thermal efficiency with engine load, showing an increase up to an optimal load region followed by a slight decline at higher loads.

Brake thermal efficiency (BTE) is the efficiency of converting the chemical energy of fuel into useful mechanical work. The dependence on the engine load to vary BTE shows that it has a non-linear relationship, with the efficiency increasing with engine load and then approaching a slight decline as the load increases in high load conditions.

With the lower loads, the engine works at a relatively higher heat losses than the useful work output. The fuel provided in such conditions is not fully utilized in the generation of power because of insufficient combustion and inefficient use of thermal energy. With increasing load, the combustion process becomes enhanced because of the enhanced interaction between air and fuel, higher in-cylinder temperature, which leads to an enhanced conversion of energy and hence the corresponding increase in BTE.

But there is an optimum range of loads, after which the efficiency starts to decline marginally. This tendency may be explained by higher fuel injection rates that result in the formation of locally rich combustion zones, incomplete combustion, and increased thermal losses. Moreover, there are more restrictions on the availability of air at greater loads which decrease the efficiency of combustion, which subsequently impacts the overall energy conversion process.

4.2 Variation of Brake Specific Fuel Consumption

The variation of brake specific fuel consumption with engine load is shown in Figure 4.

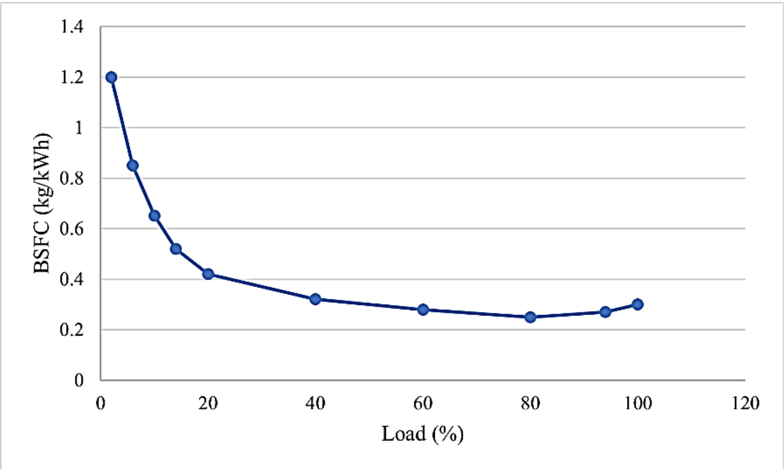

Figure 4. Variation of brake specific fuel consumption with engine load, indicating a decreasing trend with increasing load.

Brake specific fuel consumption (BSFC) is a ratio of the fuel needed to generate one unit of engine power output and is one of the important indicators of engine fuel efficiency. The experimental results show a decreasing trend in BSFC with increasing engine load.

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The engine burns a comparatively large amount of fuel per unit power output at lower loads as it burns inefficiently and experiences large relative heat losses. When this happens, a significant fraction of the fuel energy does not get transformed into useful work leading to increased BSFC values.

The higher the load, the better the conditions in which the engine will be operating, which results in better utilization of the injected fuel. The higher cylinder pressure and temperature increase the speed of combustion and energy expulsion and thus the quantity of fuel used per unit power output is less. This causes an ever-decreasing BSFC as load increases.

The negative correlation between BSFC and BTE in the results also confirms the fact that better fuel use is a direct result of increased thermal efficiency.

4.3 Variation of Exhaust Gas Temperature

The variation of exhaust gas temperature with engine load is illustrated in Figure 5.

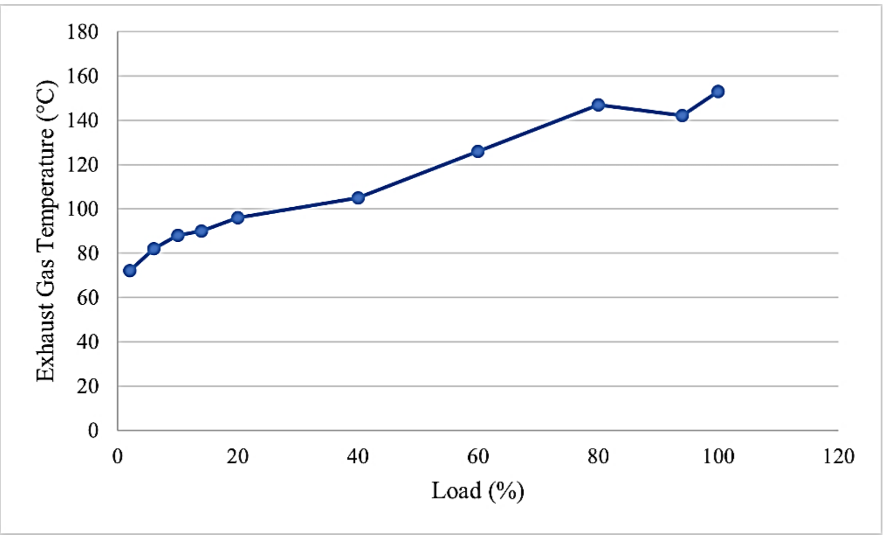

Figure 5. Variation of exhaust gas temperature with engine load, showing a continuous increase with increasing load.

The exhaust gas temperature (EGT) gives an indication of the amount of thermal energy the exhaust gases take out and the general intensity of the combustion in the engine. As indicated by the experimental results, the EGT is steadily rising with the increasing engine load.

The quantity of fuel being injected into the cylinder at lower loads is relatively low leading to less heat released during combustion and thus less exhaust gas temperatures. The supply of fuel increases with the load and this causes more energy to be released and the temperatures of combustion to rise. This leads to increased exhaust gas temperatures since it raises temperatures in the exhaust gases.

The steady increase in EGT with load also means that there is a rise in heat losses across the exhaust system. Although increased temperatures are linked with better combustion, they also indicate that some of the energy goes to waste instead of being converted to some useful work. Hence, EGT is a valuable parameter when it comes to measuring the performance of combustion and thermal losses.

4.4 Integrated Performance Analysis

The performance parameters are interdependent as the combined analysis of BTE, BSFC and EGT points to. With an increase in engine load, better combustion results in a greater brake thermal efficiency and reduced specific fuel consumption. Nevertheless, this has been matched by an increase in exhaust gas temperature, which implies that it has more thermal losses.

The fact that there is an optimum range of load, in which efficiency is maximized and fuel consumption is minimized, indicates the need to operate the engine under the right conditions of loading. Beyond this region, the marginal slowdown in the efficiency and additional increase in the exhaust temperature reflects the declining returns of performance due to combustion and thermal limitations.

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This concerted effort is a sign of the natural trade-off of an effective conversion of energy and thermal losses in compression ignition engines. The general trends which are observable in Figures 3-5 are a good reflection of the interdependence of the performance parameters with respect to engine load.

5. CONCLUSION

- The current experiment is an experimental assessment of the performance properties of a single-cylinder compression ignition engine in different load conditions in a systematic manner. Important parameters of performance that are measured like brake thermal efficiency, brake specific fuel consumption and exhaust gas temperature give useful data on the behavior of the combustion of the engine and its consumption of energy.
- The results indicate that the change in load is a major factor that affects engine performance and the definite improvement in combustion efficiency is noticeable as the load increases between low and moderate load levels. This is reflected in the enhanced thermal efficiency of the brakes and low specific fuel consumption that means that the fuel energy is more efficiently converted to useful work.
- Nevertheless, when the load is increased, the marginal decrease in efficiency points to the constraints related to air-fuel mixing and combustion completeness. The increase in the exhaust gas temperature with the load is indicative of the corresponding increase in the thermal losses, and indicates the inherent trade-off between combustion intensity and heat rejection. This move brings out the need to identify an optimum operating range where the engine is most efficient at minimum fuel consumption and tolerable thermal losses.
- Overall, the experiment establishes a certain relationship between engine load and performance characteristics that would be a good source of experimental data to investigate the behaviour of a baseline engine. The results are especially significant in terms of corroborating numerical models and advancing the future research that should be conducted to enhance engine efficiency and performance with the help of advanced combustion strategies and optimization methods.

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NOMENCLATURE

Symbol	Description	Unit
BP	Brake power	kW
BSFC	Brake specific fuel consumption	kg/kWh
BTE	Brake thermal efficiency	%
M_f	Mass flow rate of fuel	kg/s
(V)	Voltage	V
(I)	Current	A
(t)	Time taken for fuel consumption	S
X_{cc}	Volume of fuel consumed	cc
(CV)	Calorific value of fuel	kJ/kg
ρ	Density of fuel	kg/m^3
EGT	Exhaust gas temperature	°C
N	Engine speed	rpm