The effect of compression ratio on the performance and emission characteristics of C.I. Engine fuelled with corn oil biodiesel blended with diesel fuel.

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Abstract. The aim of this paper is to study the effect of changing the compression ratio on the performance and emission characteristics of single cylinder, 4-stroke compression ignition (CI) engine running with biodiesel and pure diesel fuel. Corn oil biodiesel blends were prepared viz. B5 (5%), B10 (10%), B15 (15%) and B20 (20%) (by volume). The tests were performed at full load, constant speed 1500 rpm and different compression ratios 14, 15, 16, 17 and 18 %. The engine performance like brake thermal efficiency (BTE), brake specific fuel consumption (BSFC) and emissions of CO, CO₂, HC, NOₓ and smoke opacity for all biodiesel blends were measured. The results showed that on increasing the compression ratios, the BTE increases and BSFC decrease for all types of fuel used, but it was found that for biodiesel blends B5, B10, B15 and B20, the BTE slightly decreased by 2, 4.2, 6.5 and 8.3 % and the BSFC increased by 3.3, 6.3, 9.4 and 13 % respectively, compared to the pure diesel fuel due to the high viscosity and density of biodiesels. With increasing the compression ratio and proportion of biodiesel blend, the emissions of CO, HC and smoke opacity were decreased, at the same time, the CO₂ and NOₓ emissions were increased. The highest reduction in the emissions of CO, HC and smoke was found in the B20 biodiesel blend, which was 30, 26 and 23.8 %, respectively, while the same blend showed the highest increase in emissions of CO₂ and NOₓ, which were 21 and 25.7 % respectively, compared to pure diesel fuel. Therefore, the biodiesel blend can be used at proportion up to 20 % and blend with diesel fuel in CI engines without any modifications.

Keywords: Corn oil biodiesel; Compression ratio; Compression ignition engine; Emissions; Brake thermal efficiency (BTE); Brake specific fuel consumption (BSFC).

1. Introduction:
Increasing use of diesel engines in many applications led to increasing the use of diesel fuel to run them, which in turn leads to the depletion of the fossil fuels day by day is the limited and non-renewable fuel [1]. Worldwide, fossil fuels contribute almost 80% of total energy [2]. On the other hand, the increased use of diesel engines has led to some environmental problems such as air pollution, due to the gases emitted from their exhausts as a result of the fuel combustion process inside the engine [3]. The gases emitted from these engines include Carbon monoxide (CO), Carbon dioxide (CO₂), Nitrogen oxides (NOₓ), Particulate matter (PM) and Unburned Hydrocarbons (HC) [4-5]. Therefore, due to the problems of fossil fuel depletion and environmental pollution, it is becoming necessary to search for alternative fuel for diesel fuel to run the diesel engines, and it has a harmonious correlation with environmental preservation, efficiency and energy conservation [6 - 8]. Biodiesel considered is the better alternative fuels for petroleum diesel to operating diesel engines, is a renewable, environmentally friendly and nontoxic fuel [9-10]. It is obtained through transesterifications of vegetable oils and animal fats [11]. But because of the high viscosity and density of biodiesel, it cannot be used directly as a fuel, leading
to some problems like poor spray characteristic, poor atomization and incomplete combustion [12-13]. So, one of the following methods: transesterification, blending, pyrolysis and microemulsion can be used, in order to reduce the higher viscosity of biodiesel and it's used as a fuel to run the engine without any modification [14][15]. Among the advantages of biodiesel are their high oxygen content and higher cetane number and both of them greatly improving the combustion process [16]. Several studies have been shown that when using biodiesel at different proportions and its blends with pure diesel fuel reduces the emissions of CO, SO₂, CO₂, PM and smoke, but at the same time increases the NOₓ emissions [17-19]. Numerically studied the characteristics of diesel engines at a constant speed and different loads using vegetable oil, alcohols, waste oil and animal fats [20]. The study showed that biodiesel has an ignition delay less and decrease more when the loads increased, and higher combustion duration. Studied the effect of fuel injection pressure on diesel engine using waste cooking oil biodiesel blends at proportions of 5 to 30 % (by volume) with diesel fuel at full load conditions and different engine speeds [21]. It found that on increasing the injection pressure, the thermal efficiency, brake power, CO₂ and NOₓ emissions increases, and the emissions of CO, HC and smoke reduces compared to the diesel fuel. Also, found that the best injection pressure for the fuel blends is 210 bars. They experimentally studied the use of algae oil biodiesel at 5 – 50 % (by volume) with diesel fuel in the VCR diesel engine at different loads and compression ratios [22]. They found that the minimum emissions of gases were at B30, where the HC and CO emissions decreased by 35.13 and 30 %, respectively, while the NOₓ, CO₂ and O₂ increased by 25 - 30 %, 9 - 20 % and 8 - 20 % respectively. The experimental study performed to the effect of changing the injection timing on the performance and emissions characteristics of a diesel engine at various loads and constant speed fuelled with fish oil biodiesel blends [23]. They found that the delay of injection timing led to a reduction in CO, NOₓ, HC emissions, ignition delay, duration of combustion, peak pressure and heat release rate for biodiesel compared with pure diesel fuel. [24] Experiments were carried out to study the performance and emissions characteristics of diesel engine using palm oil biodiesel (20 %) and its blend with diesel fuel at different compression ratios (16, 17 and 18). It was found that when increasing compression ratio 16, 17 and 18, the brake thermal efficiency increased by 28.9, 30.8 and 33.8 %, respectively. Also found the average reduction for the HC, CO and smoke emissions were 47.8, 41 and 35.7 %, respectively, while the NOₓ emission increased by 41.1 % when increasing the compression ratios 16 to 18. [25] They used the different ratios of exhaust gas recirculation (EGR) in a single cylinder diesel engine that works with Pongamia pinnata biodiesel and hydrogen at various flow rates in the intake manifold. They found that when using 10 % EGR, the CO, HC and NOₓ emissions decreased by 95.45, 10.52 and 2.22 %, also found the brake thermal efficiency (BTE) decreased by 1.31 %.

The present work aims to study the effect of changing the compression ratio on the performance and emission characteristics of a single cylinder, 4-stroke, compression ignition engine using different proportions of corn oil biodiesel and its blends with pure diesel. The experimental tests were performed at different compression ratios 14, 15, 16, 17 and 18, constant speed (1500 rpm) and full load conditions. The results of the experimental tests of performance and gas emissions for all biodiesel blends were discussed and compared with pure diesel fuel.

2. Materials and Experimental Methodology

2.1. Preparation of Corn oil Biodiesel and Properties:
The fuel blends were prepared by blending different volume ratios of the corn oil with varying volume proportions of diesel oil, following the literature procedure [26]. Corn oil was produced through the transesterification process with methanol (CH₃OH), to reduce its viscosity. The fuel blends were prepared by blending the corn oil biodiesel with volume proportions of 7 %, 15 % and 20 % in diesel fuel, and designated B7 and B15, B20, respectively. The reason for using such blends is to examine the effect of using the minimum amount of corn oil. The properties of the fuel used in this study were determined and listed in Table-1.
Table 1. Properties of pure diesel fuel and corn oil Biodiesel blends [26].

| Property                        | Diesel Fuel | B5  | B10 | B15 | B20 |
|---------------------------------|-------------|-----|-----|-----|-----|
| Density at 20 °C (kg/m³)        | 830         | 834.4 | 836.8 | 839.4 | 842 |
| Kinematic Viscosity @ 40 °C (cst) | 2.67       | 2.78 | 2.85 | 2.97 | 3.02 |
| Calorific Value (kJ/kg)         | 42920       | 42510 | 42265 | 41850 | 41280 |

2.2. Experimental Setup:
The engine used in this study consists of a single-cylinder, water cooled, 4-stroke, compression ignition engine and as illustrated its specifications in Table 2. The engine was connected with a rope brake dynamometer to apply the loads to it, and the schematic diagram of the experimental setup is illustrated in Figure-1. By changing the thickness of the cylinder head gasket, the compression ratio can be changed to a certain limit. The temperatures of exhaust were measured using thermocouples of type (K). Fuel consumption was calculated using a stopwatch and scalar cylinder installed in the fuel tank. The device of exhaust gas analyser of type (AVL DiGAS 444 with a Resolution Ratio 0.01 mg/m³) was used to measure the emissions each of carbon monoxide (CO, vol %), carbon dioxide (CO₂, vol %), unburned hydrocarbons (HC, ppm) and nitrogen oxides (NOₓ, ppm), in addition to, the smoke opacity (vol. %) was measured using a smoke meter device of type (AVL 437C), and both devices are supplied by AvI India Private Limited, India, and the Figure 2 (a) and (b) shows a devices image of exhaust gas analyser and smoke meter, respectively.

![Figure 1: A schematic diagram of the experimental setup.](image)

Table 2: Specifications of CI engine.

| Engine make                        | Kirloskar, 3.7 KW (5 HP) at 1500 rpm, Water Cooled, Bore 80 mm, Stroke 110 mm |
|------------------------------------|---------------------------------------------------------------------------------|
| Engine Type                        | Single Cylinder, 4-Stroke, Direct injection Diesel Engine                       |
| Type of ignition                   | Compression Ignition                                                           |
| Compression Ratio                  | 14:1, 15:1, 16:1, 17:1 and 18:1                                               |
| Dynamometer                        | Rope Brake Dynamometer                                                         |

2.3. Procedure:
Experimental tests were conducted on a compression ignition engine to study the performance and emission characteristics for different blends of corn oil biodiesel (B5, B10, B15 and B20) and pure diesel fuel under the effect of changing the compression ratios. Before the experiments start, all the biodiesel samples used for this study were prepared as well as pure diesel fuel. Also, before running the engine, the probes of the smoke meter and the exhaust gas analyser are installed properly in the engine exhaust pipe to ensure measure the emission values. Initially, the tank is filled with pure diesel fuel as a first fuel sample for testing. After that, the engine is started with a constant speed 1500 rpm and at no load, and is left to warm up for 15 minutes, and then the engine is gradually loaded by a rope brake dynamometer until it reaches the full load conditions, then the compression ratio is changed from (14, 15, 16, 17 and
18) by tilting the cylinder block arrangement which works to change the TDC position of the piston without engine stopping and changing in the geometry of combustion chamber. At each compression ratio, the engine is left to run for 3 minutes, and then the performance parameter values of brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) are recorded for every 10 ml of fuel consumption, as well as the values of CO, CO$_2$, HC, NO$_x$ emissions and the smoke opacity are recorded using the devices of exhaust gas analyser and the smoke meter respectively. Also, to obtain the optimal values, the test is repeated three times for each compression ratio. When completing the diesel fuel test, the remaining fuel in the tank is discharged and cleaned. After that, the engine is run again using the biodiesel samples used in this study B5, B10, B15 and B20, where for each sample of biodiesel, the same steps followed as in the diesel fuel test is used in terms of full load conditions, engine speed, changing of compression ratio and repeat the test to record the values of performance and emission.

2.4. Calculation of Engine Performance:

The parameters of engine performance such as fuel consumption, brake specific fuel consumption and brake thermal efficiency were calculated using the equations (1), (2) and (3) respectively [40, 41]:

$$
\dot{m}_f = \frac{v}{t} \times \rho \times 10^{-6} \left( \frac{kg}{sec} \right)
$$

$$
BSFC = \frac{\dot{m}_f}{\dot{B}P} \times 3600 \left( \frac{kg}{kW \cdot hr} \right)
$$

$$
\eta_{bth} = \frac{\dot{B}P}{\dot{m}_f \times C.V.} \times 100 \left( \% \right)
$$

3. Results and Discussion:

In this section, the results of the experimental tests obtained for the performance and emissions of CI engine at a constant speed (1500 rpm), full load condition and different compression ratios (14 - 18) were discussed. Different blends of biodiesel from corn oil B5, B10, B15 and B20 were used and compared with pure diesel fuel.

3.1. Performance Characteristics:

3.1.1 Brake Thermal Efficiency (BTE): Figure 2 shows the brake thermal efficiency (BTE) for all corn oil biodiesel blend and diesel fuel versus various compression ratios.

![Figure 2: The Brake Thermal Efficiency (BTE) of biodiesel 5, B10, B15, B20 and pure diesel fuel versus various compression ratios.](image)

Through the figure, it was observed that the BTE of the engine for all types of fuel used increases with increasing the compression ratio from 14 to 18. This is the fact that when increasing the compression ratio leads to higher temperatures, which in turn enhances the better combustion process and thus increases the BTE [27-28]. It was also noted that the BTE of all biodiesel blends were less than
the pure diesel, as well as at increasing the proportion of biodiesel in the blend, the BTE decreases. This reduction in the BTE for biodiesel blends is due to several reasons, including the high viscosity and density of biodiesel that causes poor atomization during combustion [29], the lower calorific value of biodiesel leads to a decrease in the brake power of the engine [30] and increasing the fuel consumption. The BTE decreased by 2, 4.2, 6.5 and 8.3% for biodiesel blends B5, B10, B15 and B20 respectively, compared to the diesel fuel.

3.1.2 Brake Specific Fuel Consumption (BSFC): The change of brake specific fuel consumption (BSFC) versus various compression ratios for biodiesel blends B5, B10, B15, B20 and pure diesel is illustrated in Figure-3. It was found through this figure that when increasing the compression ratio, the BSFC for biodiesel blends and diesel fuel decreases. This is the result of an improved fuel combustion process when increasing the compression ratios [31]. From the figure, it was observed that the corn oil biodiesel has a higher BSFC compared to pure diesel fuel, also, the BSFC increases more when the percentage of biodiesel in the blend increases. The reason for this increment is that the calorific value of biodiesel is less than diesel, which requires a larger amount of fuel in order to produce the same power output [32]. The BSFC for B5, B10, B15 and B20 increased by 3.3, 6.3, 9.4 and 13 %, respectively, compared to the pure diesel fuel.

![Figure 3. The Brake Specific Fuel Consumption (BSFC) of biodiesel B5, B10, B15, B20 and pure diesel fuel versus various compression ratios.](image)

3.2 Emission Characteristics:

3.2.1 Carbon monoxide emissions (CO): The variation of CO emission for different blends of corn oil biodiesel B5, B10, B15, B20 and diesel fuel versus various compression ratios is shown in Figure-4. It was observed from the figure that when the compression ratio increases, the CO emissions gradually decreased for all blends of biodiesel and pure diesel fuel. The reason behind this decrease is when the compression ratio increases, the air temperature inside the cylinder increases, which helps to better burn fuel and this gives a complete combustion process and thus reduces CO emissions [32]. Also, through the figure, it was observed that all blends of corn oil biodiesel have less CO emissions compared to the diesel fuel at all compression ratios. As well as, the reduction ratio of CO emissions increases when the blend proportions of corn oil biodiesel B5, B10, B15 and B20 increases. This is because the oxygen content existing in biodiesel greatly helps to the complete combustion of the fuel inside the combustion chamber, as well as the converting the largest amount of CO to CO₂ [34, 35]. It was found that the CO emissions for B5, B10, B15 and B20 decreased by 6, 13, 21 and 30% respectively, compared with pure diesel fuel.
3.2.2 Carbon dioxide emissions (CO$_2$): Figure 5 shows the CO$_2$ emissions resulting from B5, B10, B15, and B20 biodiesel blends and pure diesel fuel versus various compression ratios. Through the figure, it was found that the CO$_2$ emissions for all biodiesel blends and pure diesel fuel increase with the compression ratio increase. This is because that the increased compression ratio improves the combustion process of the mixture inside the cylinder as a result of high temperatures, which leads to an increase in the formation of CO$_2$ emissions. In all compression ratios, it was observed that the CO$_2$ emissions of B5, B10, B15, and B20 were higher than those in pure diesel fuel. Also, as the proportion of biodiesel blend increases, the CO$_2$ emissions increases. This is the fact that when increasing the percentage of oxygen content in biodiesel mixtures, it gives better and complete combustion of fuel, and thus increases the CO$_2$ emissions. It found that the CO$_2$ emissions increased by 4, 10, 15 and 21% for corn oil biodiesel blends B5, B10, B15 and B20 respectively, compared with those in pure diesel fuel.

3.2.3 Unburned hydrocarbon emissions (HC): Effect of compression ratio on the HC emissions for biodiesel blends B5, B10, B15 B20 and diesel fuel is shown in Figure 7. The main reason the HC emissions production is the insufficient temperatures inside the cylinder (i.e., low temperatures) to burn the fuel; this is an indication of incomplete combustion. For all types of test fuels used, it was noted that with increasing the compression ratio, the HC emissions decreases. This is due to that the increased of cylinder temperatures as a result of an increase in compression ratio, which facilitates the propagation of flame and enhances the complete burning of fuel, thus reducing the HC emissions [5][36]. The figure, also found that the HC emissions of corn oil biodiesel blends were lower in all compression ratios compared to the diesel fuel. In addition, when increasing the blend proportion (B5, B10, B15 and B20) of biodiesel reduces HC emissions. The main cause for this reduction is that the use of biodiesel blend significantly helps to improve the oxidation of fuel because of available oxygenated compounds in biodiesel, which enhances the complete combustion process of fuel and hence reduces HC emissions [19][37]. The HC emissions for blends B5, B10, B15 and B20 decreased by 4.5, 11.8, 20 and 26% respectively, compared to the diesel fuel.
Figure 5. The Carbon dioxide (CO2) emissions of biodiesel B5, B10, B15, B20 and pure diesel fuel versus various compression ratios.

Figure 6. The unburned hydrocarbon (HC) emissions of biodiesel B5, B10, B15, B20 and pure diesel fuel versus various compression ratios.

Figure 7. The NOx emissions of biodiesel B5, B10, B15, B20 and pure diesel fuel versus various compression ratios.
3.2.4 Nitrogen oxides emissions (NO\textsubscript{X}): Figure-8 illustrates the change of NO\textsubscript{X} emissions with various compression ratios for corn oil biodiesel blends B5, B10, B15, B20 and pure diesel. The high adiabatic flame temperatures, which are associated with the peak cylinder temperature, presence of oxygen during the combustion process, increased fuel amount entering and reduce ignition delay are considered the main factors that lead to increased NO\textsubscript{X} emissions in CI engines [22][38]. From the figure, it was observed that the NO\textsubscript{X} emissions for all tested fuels increases, with the compression ratio increases. The main reason for this increase is due to the fact that increasing the compression ratio causes to increase in the peak cylinder temperature, and this leads to more formation of NO\textsubscript{X} emissions. In addition to, there is another reason that when the compression ratio increases, the ignition delays as for all biodiesel blends, the NO\textsubscript{X} emissions were higher compared to pure diesel fuel in all compression ratios, and whenever the biodiesel proportion in the blend (B5, B10, B15 and B20) increases, the NO\textsubscript{X} emissions increases. The higher cetane number and presence of oxygen content in biodiesel have considered the two main reasons for increasing the combustion temperatures inside the cylinder and hence increased NO\textsubscript{X} emissions increases [38]. The NO\textsubscript{X} emissions increased by 5.5, 13, 19.3 and 25.7% of the corn oil biodiesel blend B5, B10, B15 and B20 respectively, compared with the pure diesel fuel.

3.2.5 Smoke opacity: Figure-8 shows the variation of smoke opacity for biodiesel blends B5, B10, B15, B20 and diesel fuel versus various compression ratios. The reasons for the production of smoke in CI engines are an incomplete combustion process of fuel, and can be related to: the lack of oxygen present in a sufficient quantity in the fuel, low the amount of air entering the engine, increasing the amount of fuel injected inside the combustion chamber and lower in-cylinder temperatures [21]. It was noted through the figure that the smoke opacity for all blends of biodiesel and diesel fuel gradually decreases, with compression ratio increases. This decrease is due to an increase in the temperatures inside the cylinder as a result of increasing the compression ratios, which facilitates the better and complete combustion process of fuel and therefore reduced the smoke. It was also observed that in all compression ratios, the biodiesel blend had a lower smoke opacity than diesel fuel. Since the proportions of biodiesel blend B5, B10, B15 and B20, the smoke opacity decreases, when the proportion of the blend increases. This is because of improving the combustion process of fuel in the case of using biodiesel blends as a result of it contains high oxygen content and thereby reduces the formation of smoke opacity. It was found that the smoke opacity for B5, B10, B15 and B20 biodiesel blends decreased by 6.3, 13, 19 and 23.8% respectively, compared with those in pure diesel fuel.

![Figure 8](image-url)  
**Figure 8.** The smoke opacity emissions of biodiesel B5, B10, B15, B20 and pure diesel fuel versus various compression ratios.
Table 3. The results of this study were compared with those obtained by other related articles that studied the effect of compression ratio on the performance BTE (%) and BSFC (kg/kW.hr) as well as the emissions characteristics of C.I. engine viz. HC, CO, smoke opacity (ppm) and NOX, and CO2 (%) fueled with different biodiesel blended with diesel fuel.

| Biodiesel %                     | Compression Ratio % | BTE (%) | BSFC (kg/kW.hr) | HC (ppm) | CO (ppm) | Smoke opacity (ppm) | NOX (%) | CO2 (%) | Ref. |
|---------------------------------|---------------------|---------|-----------------|----------|----------|---------------------|---------|---------|------|
| Corn oil/diesel (B20)           | (14→18):1           | Increases | Decrease        | -30.0    | -26      | -23.8               | +25.7   | +21     | *    |
| Palm oil/diesel (B20)           | (16→18):1           | Increases | -              | -47.8    | -41.0    | -35.7               | +41.1   | -       | (41) |
| Waste oil produced biodiesel (B50) | (14→18):1         | Increases | -              | -52.0    | -37.5    | NM                  | +36.84  | +14.28  | (42) |
| RUCO biodiesel/diethyl ether/diesel fuel | NM*                  | +16.06  | -4.12           | -34.69   | 20.41    | NM                  | -23.33  | NM      | (43) |
| Waste cooking oil methyl ester/diesel fuel (B50) | 50 %             | NM      | NM              | NM       | NM       | +                   | NM      | (44)    |
| Diesel oil only (16.5→19.0):1   | NM                  | Decrease | NM              | -19.0    | NM       | NM                  | NM      | (45)    |

*This work.;  BTE = Brake thermal efficiency; BSFC=Brake specific fuel consumption; **NM = Not mentioned in the article.

The results of this study were compared with those obtained by other related articles that studied the effect of Compression Ratio on the performance and the emission characteristics of C.I. engine fuelled with Corn oil biodiesel blended with diesel fuel (41-45). Table-3 showed some kind of compatibility with the current studies, but in a moderate and reasonable manner. We note that one of these studies gave unexpected value regarding the reduction of nitrogen oxides emissions associated with the compressibility increase.

4. Conclusion
The effect of changing the compression ratio on the engine performance and emissions was studied for all biodiesel blends and it is compared with pure diesel fuel. Increasing the compression ratio significantly improves fuel combustion as a result of the increase of the cylinder temperatures and this is an indication of the complete combustion process. With increasing the compression ratios, the BTE increases and BSFC decrease for all types of fuel used. For biodiesel blends B5, B10, B15 and B20, it found that the BTE slightly decreased by 2, 4.2, 6.5 and 8.3% and the BSFC increased by 3.3, 6.3, 9.4 and 13% respectively, compared to the pure diesel fuel. The complete combustion process of all corn oil biodiesel blend has resulted in a reduction in emissions of CO, HC and smoke opacity, but it increased the emissions of CO2 and NOX at all compression ratios, compared with diesel fuel. With increasing the proportion of corn oil biodiesel, an increase in the blended fuel, the emission ratio of CO, HC and smoke more decreases, at the same time the emission ratio of CO2 and NOX increases. The highest ratio of reduction in the CO, HC and smoke emissions were found in the corn oil biodiesel blend (B20), where it decreased by 30%, 26% and 23.8% respectively, compared with the pure diesel fuel. Also, at the same biodiesel blend (B20) it found the highest ratio of increase in CO2 and NOX emissions, where increased by 21% and 25.7% respectively, compared to the pure diesel fuel. Therefore, the CI engine can be operated using corn oil biodiesel at proportion up to 20% (by volume) with diesel fuel as an alternative fuel with the compression ratios ranging of (14 - 18) to get the best characteristics of emissions compared with the other blends and pure diesel without any modifications to the engine.

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**NOMENCLATURE:**

| Abbreviation | Description |
|--------------|-------------|
| BP           | Brake power, kW. |
| BSFC         | Brake specific fuel consumption, kg/kW.hr. |
| BTE          | Brake thermal efficiency, %. |
| CI           | Compression ignition. |
| CO           | Carbon monoxide, %Vol. |
| CO₂          | Carbon dioxide, %Vol. |
| CR           | Compression ratio. |
| C.V.         | Calorific value, kJ/kg. |
| EGR          | Exhaust gas recirculation. |
| HC           | Unburnt hydrocarbons, ppm. |
| m_f          | Fuel consumption, kg/sec. |
| NOₓ          | Nitrogen oxides, ppm. |
| O₂           | Oxygen. |
| PM           | Particulate matter. |
| ppm          | Parts per million. |
| r.p.m.       | Revolution per minute. |
| SO₂          | Sulfur dioxide. |
| TDC          | Top dead center. |
| t            | Time taken for fuel consumed, sec. |
| VCR          | Variable compression ratio. |
| V            | Volume of fuel consumed, cm³. |
| η_bth        | Brake thermal efficiency, %. |