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Consequences Of CNG Substitutions On Performance And Exhaust Emissions Of A Diesel Engine With Varying Compression Ratios

Rentala Girish Srivatsa[1*], Sarap Raghavendra[1]
[1](*Department of Mechanical Engineering, Lords Institute of Engineering & Technology, Hyderabad, Telangana, India)*

Abstract: *Compressed Natural Gas (CNG) is a hopeful alternative fuel as well as fuel additive to improve performance and emissions in CI engine, due to its lower carbon content and less knocking tendencies. CNG and Diesel dual fuel operation is regarded as one of the best ways to control emissions from diesel engines and simultaneously saving petroleum-based diesel fuel. Dual fuel engine is a conventional diesel engine which burn either gaseous fuel or diesel or both at the same time. This paper presents an experimental study on the effects of CNG substitutions on the performance and emission characteristics of CI engine. In the present work, experimental investigations were carried out by inducting CNG into the combustion chamber in conjunction with air as CNG –Diesel dual fuel mode. Experiments were conducted on different substitutions of CNG i.e. 2.5 LPM, 7.5 LPM, and 12.5 LPM at different compression ratios (CR) i.e. 16.5, 17.5, 18.5 respectively and the performance characteristics were calculated. The effect of CNG substitutions on emissions was measured at various CR's and reported.*
Keywords: *Compressed Natural Gas, CI Engine, Compression Ratio, Performance, Exhaust Emissions.*

I. Introduction

Internal Combustion Engines have become an integral part of our life without which the world would stop moving and will not meet its daily necessities. These engines act like the hearts of the majority of the prime movers. The fuel used by these engines are generally non-renewable, highly expensive and cause environmental pollution. This calls for the search for an alternative fuel, which promises to be harmonious in correlation with sustainable development, conservation, management, efficiency and environmental preservation. [1]. CNG is one such fuel which has been used as a fuel for spark ignition engine [2] and also for evolving compression ignition engine researchers as an alternative fuel.

Compressed Natural Gas (CNG) is a natural product. It improved from organic matter over millions of years ago. CNG is used in its primary gasiform state. Since it does not have to be transformed into any secondary fuel, it can be utilized directly without any occurrence of environmental pollution. Researchers have been investigating on many alternate fuels and a wide range of fuels were reviewed to substitute the vehicular fuels such as gasoline and diesel. In such a case, CNG becomes a candidate mainly because of its low emissions and abundant availability in the world. Much interest has centred on CNG due to its potential for low particulate and NO_X emissions. CNG and Diesel dual fuel operation is regarded as one of the best ways to control emissions from diesel engines and simultaneously saving petroleum-based diesel fuel. The introduction of CNG along with intake air and diesel changes the thermodynamic and chemical properties of the mixture in the cylinder and thus the dual fuel combustion has its own performance and emission characteristics. The diesel fuel which acts as a source of ignition is often referred to as pilot diesel [3].

In the present scenario, the infrastructure system of supplying, refuelling and its cost are the main problems for the commercialization of alternative fuels. When compared with other alternative fuels, CNG may possibly overcome these aspects if there is an increase in the production facilities and distribution networks, as they are available in most advanced countries.

Table 1. Typical Composition of Natural Gas [4]

Components	**Volume Percent (%)**	**Mass Percent (%)**
Methane	92.29	84.37
Ethane	3.60	6.23
Propane	0.80	2.06
Butane	0.29	0.99
Pentane	0.13	0.53
Hexane	0.08	0.39
Carbon Dioxide	1.00	2.52
Nitrogen	1.80	2.89
Water	0.01	0.01

II. CNG For CI Engines

There have been several fundamental studies on dual fuel engines. Abhishek Paul et al. [5] studied on the diesel-CNG and diesel ethanol blends. They investigated on the emission reduction characteristics of a CI engine fuelled with diesel-ethanol blends with CNG enrichment. The study revealed that the bio-ethanol blend increases the indicated mean effective pressure with an extension of the ignition delay and HC emission increased, CO emission decreased. The results of this study showed a great improvement in PM and NOx emissions with an increase in thermal efficiency. Chandra et al. [6] researched on gaseous fuel. In this experiment, CNG-Methane enriched biogas & raw biogas was used as gaseous fuels. For performing the experiments, CI engine was converted to SI engine with few modifications in ignition timing and compression ratio. They found that there is a power loss due to the conversion of the engine from CI to SI and are calculated as 31.8%, 35.6% and 46.3% for CNG, methane enriched biogas and raw biogas respectively. It is found that the power development rate in case of raw biogas was significantly decreasing when compared to CNG and methane enriched biogas. The comparative study resulted that the speed of the engine operating on biogas was low compared to CNG and methane enriched biogas. In case of diesel engine co-fuelling of diesel with LPG [7, 8], methane [9, 10], natural gas [11] and hydrogen–methane combination were studied. Most research in dual fuel engine has concentrated on defining the extent of dual fuelling and its effect on emissions and performance [12] use of additives to methane has been reported to be effective to promote combustion at homogeneous lean operation.

Table 2. Thermodynamic Properties of Diesel and CNG [13]

Thermodynamic Properties	Diesel	CNG
Stoichiometric Ratio	14.5	15.7
Density @25°C (kg/ m^3)	833-881	2.52
Flammability Limits (% vol. in air)	0.7-5	15.6

III. Experimental Method And Experimentation

The engine used in the present study is Kirloskar TV-1, single cylinder, water cooled, four stroke, variable compression ratio (VCR), and compression ignition diesel engine with specifications given in Table 3, while a schematic diagram of the test rig setup is shown in fig. 1. This engine is coupled to an eddy current dynamometer. Air temperature, coolant temperature and throttle position are connected to open electronic control unit which controls fuel injector, fuel pump and idle air. The load was varied from 0% to 100% at an interval of 25%. A digital shaft encoder was used to measure crankshaft position. The signals from piezo sensors and the crank encoder were acquired using national instruments logical card. Data acquisition was made using National Instruments Lab VIEW acquisition system developed in-house. Several series of experimental cycles were conducted with varying CNG substitutions at 2.5 LPM, 7.5 LPM, and 12.5 LPM. At each cycle, the engine was operated at rated injection opening pressure of 200 bar and the exhaust emissions was noted. All the experiments were carried out at full load with a constant speed of 1500 rpm and at different compression ratios of 16.5, 17.5 and 18.5 respectively. The injection timing was set to a value of 23° BTDC.

CNG flows were measured by using a specially designed flow meter. Initially, the CNG from the cylinder enters into the mixing chamber with the desired flow rate by using the flow meter. Here the CNG mixes with air. Because of the enrichment of CNG with air in the mixing chamber, proper atomization takes place with the diesel fuel and peak pressure was observed inside the combustion chamber. The diesel is used as a pilot fuel. When CNG supply was increased, the diesel injection was automatically decreased due to the governor mechanism of the engine to maintain a constant speed.

The exhaust gas analyser used is MN-05 multi-gas analyser (5 gas version) is based on infrared spectroscopy technology with signal inputs from an electrochemical cell. Non-dispersive infrared measurement technique used for the measurement of CO, CO_2, and HC gases. Each individual gas absorbs infra-red radiation that can be used to calculate the concentration of sample gas. The Gas Analyser uses an electrochemical cell to measure oxygen concentration. It consists of two electrodes separated by an electrically conducted liquid or cell. The cell is mounted on a polytetrafluorethene membrane through which oxygen can diffuse. The device, therefore, measures oxygen partial pressure. If a polarizing voltage is applied between the electrodes the resultant current is proportional to the oxygen partial pressure.

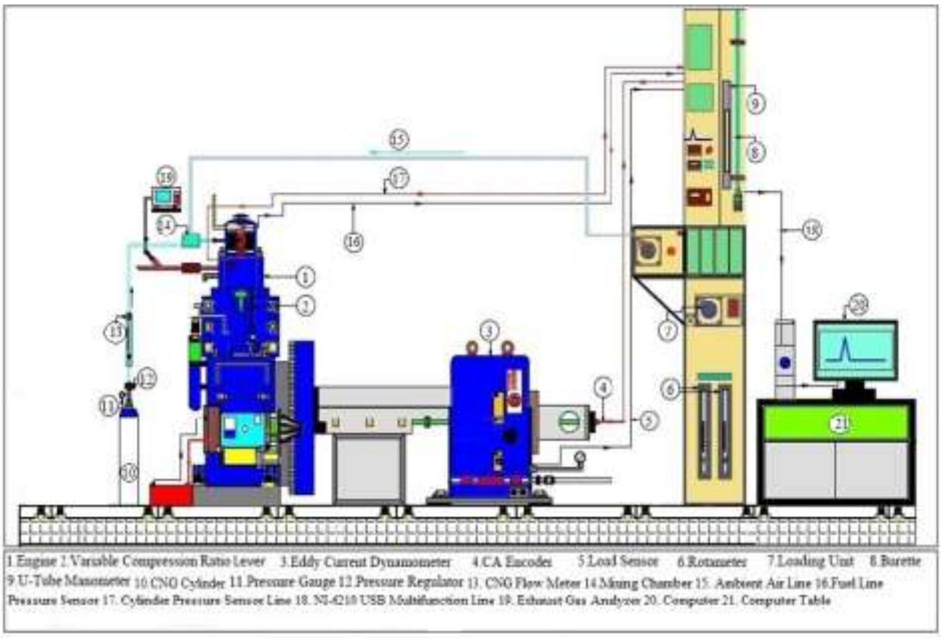

Fig.1. Schematic layout of CNG-Diesel dual fuel engine test rig

Table 3. Specifications of Test Engine

Particulars	**Specifications**
Type	Vertical, 4-Stroke Cycle, Totally Enclosed, Water Cooled
Make	Kirloskar Oil Engines
Model	TV-1
Type of Ignition	Compression Ignition
Rated Power (KW)	3.5
Constant Speed (rpm)	1500
Bore (mm)	87.5
Stroke (mm)	110
Connecting Rod Length (mm)	234
Variable Compression Ratio	12:1 to 18.5:1
Cylinder Capacity (cc)	661
Fuel Injection	Direct Injection
Injection Timing	23^o BTDC
Dynamometer	Eddy Current Type
Piston Bowl	Hemispherical
Starting	Auto Start
Injection Pressure (bar)	200

IV. Results And Discussions

An experimental investigation was carried out for performance and exhaust emissions of the engine by inducting CNG at different flow rates and various performance parameters and emission graphs have been drawn at full load with respect to compression ratio. The plotted graphs depict the comparative study of a diesel engine operating under pure diesel mode and dual fuel mode.

4.1 Effect of CNG Substitution on Performance Parameters

4.1.1 Brake Thermal Efficiency

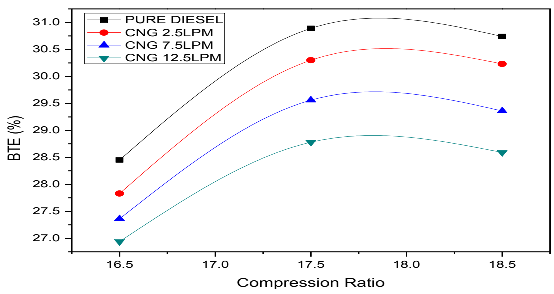

Fig. 2. Effect of CNG Substitutions on BTE at various Compression Ratios

Brake thermal efficiency is the measure of the performance of the engine calculated as the ratio of brake power generated to the heat input. The above fig. 2 shows the variation of brake thermal efficiency with respect to different compression ratios i.e. 16.5, 17.5 and 18.5 respectively. BTE was calculated at full load conditions at 2.5, 7.5 and 12.5 LPM CNG substitutions. It was observed that as substitutions of CNG increased, BTE decreased at all compression ratios because CNG possesses extreme low flame velocity. It was also noticed that as the compression ratio increased from 16.5 to 17.5, BTE increased and then slightly decreased at 18.5 CR. This is due to the fact that increase in compression ratio ensures a complete combustion due to injection of fuel in higher temperature and pressure compressed air, better air-fuel mixing and faster evaporation. The highest value of BTE was noticed at 17.5 CR for pure diesel i.e. 30.89% and then followed by CNG substitutions of 2.5, 7.5 and 12.5 LPM i.e. 30.3%, 29.56% and 28.78% respectively.

4.1.2 Brake Specific Fuel Consumption

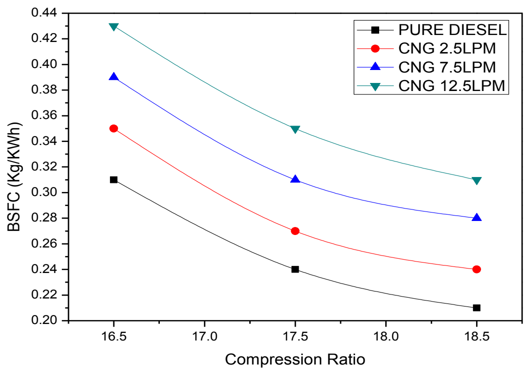

Fig. 3. Effect of CNG Substitutions on BSFC at various Compression Ratios

Brake specific fuel consumption is defined as the fuel flow rate per unit power output. Fig. 3 shows the variation of brake specific fuel consumption for different compression ratios and different substitutions of CNG when compared to that of pure diesel. It was observed that as the substitutions of CNG increased, BSFC increased at all compression ratios when compared to pure diesel mode. CNG when enriched with diesel fuel droplets, the mixture becomes lean which results in lower cylinder temperature and increase in brake specific fuel consumption. Also, the trend of BSFC decreased with increase in compression ratio for pure diesel as well as CNG substitutions as shown in the figure. This is due to the fact that increase in compression ratio reduces BSFC due to a reduction in dilution of charge by residual gases, which results in better BTE and lower BSFC. However, an increase in BSFC is observed with lower compression ratio due to low combustion pressure and temperature. The lowest value of BSFC was noticed at 18.5 CR for pure diesel i.e. 0.21 Kg/KWh and then followed by CNG substitutions of 2.5, 7.5 and 12.5 LPM i.e. 0.24, 0.28 and 0.31 Kg/KWh respectively.

4.1.3 Volumetric Efficiency

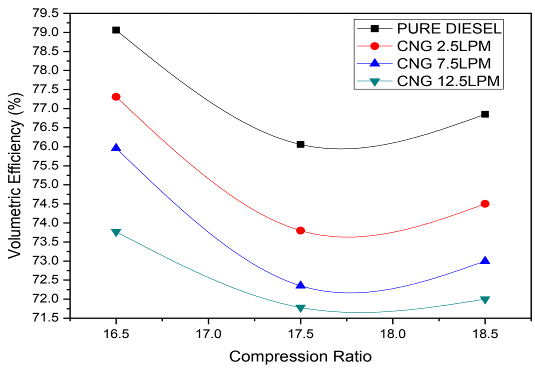

Fig. 4. Effect of CNG Substitutions on Volumetric Efficiency at various Compression Ratios

Volumetric efficiency is defined as the ratio of actual air capacity to ideal air capacity. The above fig. 4 shows the variation of volumetric efficiency for various CNG substitutions and at different compression ratios. It was noticed from the figure that as the substitutions of CNG increased, volumetric efficiency decreased at all compression ratios when compared to pure diesel mode. This is because heating up of inlet manifold due to higher exhaust gas temperatures and due to radiation heat transfer in VCR engine. Also, as the compression ratio increased from 16.5 to 17.5, volumetric efficiency decreased and then mildly increased at 18.5 CR. This is because the increase in compression ratio increases the cylinder pressure and inlet air temperature leading to less volumetric efficiency. The highest volumetric efficiency was noticed at 16.5 CR for pure diesel i.e. 79.06% and then followed by CNG substitutions of 2.5, 7.5 and 12.5 LPM i.e. 77.31%, 75.96% and 73.77% respectively.

4.1.4 Brake Specific Energy Consumption

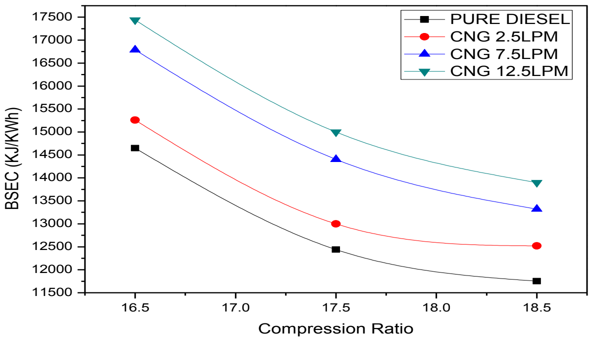

Fig. 5. Effect of CNG Substitutions on BSEC at various Compression Ratios

Brake specific energy consumption is an essential and ideal parameter for comparing engine performance of the fuels having different calorific value and density. Brake specific energy consumption in dual fuel mode is calculated from the brake specific fuel consumption and calorific value of the dual fuel. From fig. 5 it is clearly observed that as substitutions of CNG increased, BSEC also increased at all compression ratios when compared to pure diesel. This is due to lean air-fuel mixture which results in poor combustion efficiency leading to increasing in brake specific energy consumption. At a compression ratio of 16.5, BSEC was highest for all CNG substitutions and pure diesel mode followed by 17.5 CR and 18.5 CR. For CNG substitutions of 2.5, 7.5 and 12.5 LPM and at 16.5 CR, BSEC was 15260, 16789 and 17440 KJ/KWh respectively and for pure diesel, it was 14649 KJ/KWh.

4.2 Effect of CNG Substitution on Emission Parameters

4.2.1 CO Emissions

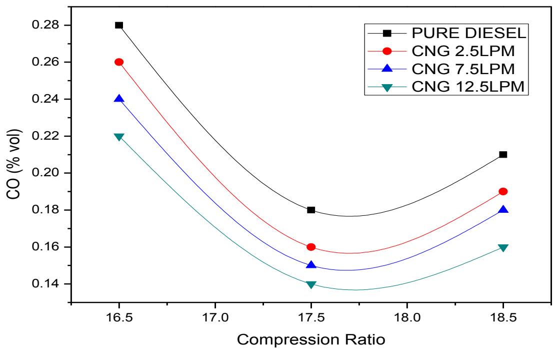

Fig. 6. Effect of CNG Substitutions on CO Emissions at various Compression Ratios

Exhaust emissions play a significant role to predict the engine behavior. Fig. 6 shows the variation of carbon monoxide for different compression ratios and different CNG substitutions. It was noticed that as the substitutions of CNG increased, CO emissions significantly decreased at all compression ratios when compared with pure diesel mode. 17.5:1 of compression ratio gives lowest CO emission as compared to all other compression ratios and pure diesel fuel. The lowest CO emission at 17.5 CR is observed for CNG substitution of 12.5 LPM i.e. 0.14% by volume whereas for pure diesel it is 0.18% by volume. This may be due to better combustion and less dilution of charge by residual gases accelerates the carbon oxidation reaction. At a lower compression ratio of 16.5 CR, the CO emissions are increased due to more dilution of fresh air with residual gases, lower compression temperature and poor mixing of fuel and air.

4.2.2 NO_X Emissions

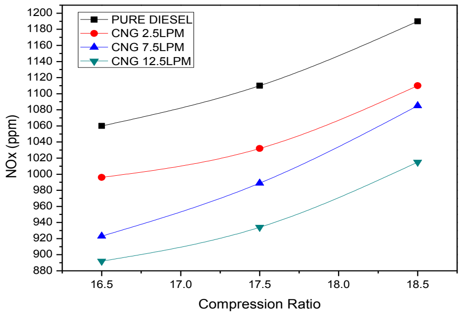

Fig. 7. Effect of CNG Substitutions on NO_X Emissions at various Compression Ratios

The above fig. 7 depicts the behavior of NO_X with respective compression ratios. It was observed that as the CNG substitutions increased NO_X emissions decreased. The addition of CNG to diesel causes a greater reduction in NO_X in comparison with pure diesel. This is because most of the dual fuel burnt under lean premixed conditions result in low local temperatures. Also, as the compression ratio increased from 16.5 to 18.5 CR, NO_X emissions gradually increased for all CNG substitutions as well as for pure diesel mode. The highest NO_X emission was noticed at 18.5 CR for pure diesel i.e. 1190 ppm and then followed by CNG substitutions of 2.5, 7.5 and 12.5 LPM i.e. 1110, 1085 and 1015 ppm respectively. This may be due to the fact that increase in compression ratio increases the combustion pressure and temperature which accelerates the oxidation of nitrogen to form NO_X emissions. At lower compression ratio, the combustion temperature and pressure decreases which leads to lower NO_X emissions.

4.2.3 UHC Emissions

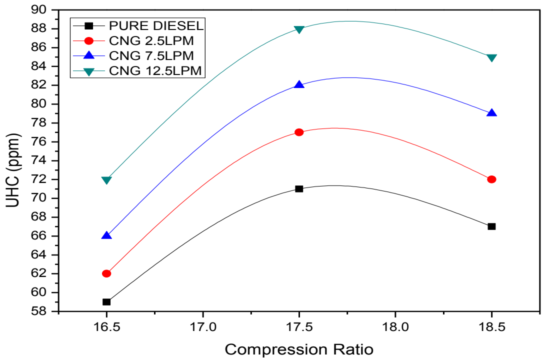

Fig. 8. Effect of CNG Substitutions on UHC Emissions at various Compression Ratios

The formation of unburnt hydrocarbons inside the engine cylinder and top of the piston head and across the piston rings was due to incomplete combustion. From the above fig. 8 it was depicted that as the CNG substitutions increased, UHC emissions increased at all compression ratios when compared to pure diesel mode. For CNG-diesel dual fuel mode, maximum brake thermal efficiency at all compression ratios was observed at pure diesel mode. Hence, the formation of UHC content for pure diesel will be less than that of all substitutions of CNG. The maximum UHC content was observed for 12.5 LPM of CNG substitution at 17.5 CR i.e. 88 ppm followed by 7.5 LPM and 2.5 LPM i.e. 79 ppm and 72 ppm respectively. Also, increase in UHC emission is observed with increase in compression ratio which is due to insufficient time for combustion process at higher compression ratios.

4.2.4 CO_2 Emissions

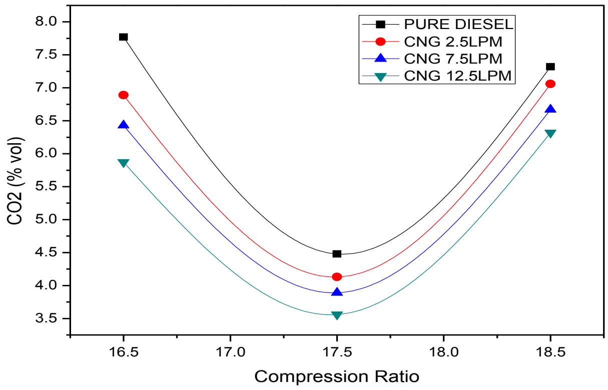

Fig. 9. Effect of CNG Substitutions on CO_2 Emissions at various Compression Ratios

The effect of carbon dioxide with compression ratio is explained in the above fig. 9. It was noticed that the content of CO_2 emissions was maximum under pure diesel mode compared to different substitutions of CNG at all compression ratios. As the compression ratio increased from 16.5 to 17.5, the CO_2 content decreased for all substitutions of CNG and pure diesel because more amount of diesel was injected as the load was increased for the same amount of CNG and from 17.5 to 18.5 CR, CO_2 emission rapidly increased. The minimum CO_2 content was observed at 17.5 CR when the engine was operating under pure diesel mode i.e. 4.48% by volume followed by 2.5, 7.5, 12.5 LPM of CNG substitutions i.e. 4.13, 3.89 and 3.56% by volume.

V. Conclusions

- Brake thermal efficiency decreased as the CNG substitutions increased because CNG possesses extreme low flame velocity. Also as the compression ratio increased, BTE increased because increase in compression ratio ensures a complete combustion due to injection of fuel at higher temperature and pressure, better air-fuel mixing and faster evaporation.
- Brake specific fuel consumption increased with increase in CNG substitutions because addition of CNG to diesel results in lean mixture leading to lower cylinder temperature and hence higher BSFC. Increase in compression ratio reduces BSFC due to a reduction in dilution of charge by residual gases, which results in better BTE and lower BSFC.
- Volumetric efficiency decreased with increase in CNG substitutions because of heating up of inlet manifold due to higher exhaust gas temperatures and due to radiation heat transfer in VCR engine. Also, as the compression ratio increased from 16.5 to 17.5, volumetric efficiency decreased and then mildly increased at 18.5 CR.
- Brake specific energy consumption increased with increase in CNG substitutions. This is due to lean air-fuel mixture which results in poor combustion efficiency leading to increasing in brake specific energy consumption. Also, as the compression ratio increased from 16.5 to 18.5 CR, BSEC gradually decreased.
- As the substitutions of CNG increased, CO emissions significantly decreased at all compression ratios. Also, CO emissions decreased with increase in compression ratio due to better combustion and less dilution of charge by residual gases that accelerates the carbon oxidation reaction.
- NO_X emissions decreased with increase in CNG substitutions because addition of CNG to diesel leads to the burning of dual fuel under lean premixed conditions that result in low local temperatures and hence less NO_X content. Furthermore, increase in compression ratio increases NO_X emissions due to increase in the combustion pressure and temperature which accelerates the oxidation of nitrogen to form NO_X emissions.
- UHC content increased with increase in CNG substitutions because BTE was low for all CNG substitutions when compared with pure diesel mode. Also, increase in UHC emission is observed with increase in compression ratio which is due to insufficient time for combustion process at higher compression ratios.
- It was noticed that the content of CO_2 emissions was maximum under pure diesel mode compared to different substitutions of CNG at all compression ratios. Also, as the compression ratio increased from 16.5 to 17.5, CO_2 content decreased and increased rapidly with increase in compression ratio up to 18.5.

Table 5. Nomenclature

CNG	Compressed Natural Gas
CI	Compression Ignition
CR	Compression Ratio
LPM	Liters per Minute
BTDC	Before Top Dead Center
BTE (%)	Brake Thermal Efficiency
BSFC (Kg/KWh)	Brake Specific Fuel Consumption
BSEC (KJ/KWh)	Brake Specific Energy Consumption
CO (% vol)	Carbon Monoxide
CO_2 (% vol)	Carbon Dioxide
NO_X (ppm)	Oxides of Nitrogen
UHC (ppm)	Unburnt Hydrocarbons
ppm	Parts per Million
% vol	Percentage by Volume

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