© Applied Science Innovations Pvt. Ltd., India Carbon – Sci. Tech. 8/3(2016)52-59

Carbon – Science and Technology

ISSN 0974 – 0546

http://www.applied-science-innovations.com

RESEARCH ARTICLE *Received:10/03/2016, Accepted:15/04/2016*

Analysis of a combustion, performance and emission characteristics of a CNG-B20 fuelled diesel engine under dual fuel mode

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Abstract: The Carbon dioxide (CO_2) is one of the primary greenhouse gases emitted by various human activities. CO_2 is naturally present in the atmosphere as part of carbon cycle. Human activities are altering the carbon cycle by adding or removing CO_2 to the atmosphere. The main human activity that emits the CO_2 is combustion of fossil fuels for energy and transportation. Compression ignition (CI) engines emit high amount of CO_2 emission as it is the end product of complete combustion of hydro carbon fuels. Moreover, they emit higher NOx (nitrogen oxides) and PM (particulate matter) emissions and have higher fuel consumption. In the present study, experimental investigations were carried out on a CI engine under dual fuel mode with biodiesel as a pilot fuel and compressed natural gas (CNG) as a main fuel. The effects of 10 % and 20 % CNG energy shares on performance and emission characteristics of the engine at rated (100%) loads were studied. Experimental results indicate the beneficial of CNG addition on improvement in the engine efficiency, and reduction in NOx and CO_2 emissions. The NOx and CO_2 emissions decreased by 14.24 % and 30 % respectively at the rated load with biodiesel + CNG (20 % energy share) as compared to base diesel. No knocking combustion was observed during the tests which confirm the smooth operation. The dual fuel operation with combination of CNG-biodiesel is an effective method to reduce NOx and CO_2 emissions with an additional benefit of lower specific energy consumption.

Keywords: Compressed natural gas, dual fuel engine, combustion, emissions, compression ignition engine

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1 Introduction: Compression ignition engines are mainly used for power generation, mass and passenger transportation, agriculture and off-road applications due to higher thermal efficiency and torque as compared to spark ignition engine **[1-2]**. But diesel is nonrenewable source and it is available in fix quantity. Diesel fuel is becoming scare and costlier, hence there is need to preserve diesel for locomotive and agriculture uses only. Crude oil resource depletes at faster rate and there is also a huge demand-supply gap **[3]**. Furthermore, the compression ignition engine emits high level of particulate matter (PM) and NOx emissions due to heterogeneous combustion process **[4]**. CO_2 emission reduction gets more attention in worldwide due to global warming and climate change in order to avoid serious consequences. A suitable alternative fuel needs to be used to overcome these problems.

Biodiesel as a carbon neutral fuel could be a better alternative to diesel fuel in a compression ignition engine. The utilization of biodiesel in a compression ignition engines could lead to mitigate CO_2 emission as it will be recycled by the crop plant resulting in alleviating the climate change and global warming **[5]**. Moreover, biodiesel is a renewable fuel which can be derived from tree born plant crop such as Pongamia, Jatropha, Neem etc. Biodiesel has superior physico-chemical properties such as higher cetane number (> 58), flash point temperature (> 150 ºC), lubricity (350 μm), lower sulfur content (0.002 wt. %) and lower aromatics (almost zero) than that of conventional diesel fuel. Many study are reported in literatures on the benefits of biodiesel on compression ignition engine's emission reduction mainly CO, HC, and particulate matter **[3-8]**. However, specific fuel consumption (SFC) and NOx emission increase with biodiesel. SFC increased with biodiesel due to lower calorific value and longer combustion duration **[9]**. NOx emission mainly increased with biodiesel due to fuel containing oxygen (10 %), automatic advance in injection timing and its formation around spray periphery due to larger penetration distance **[10]**.

NOx emission can be reduced by creating dilution effect. The dilution effect can be created by inducting gaseous fuel through intake manifold to the combustion chamber. The compression ignition engine can be operated on gaseous fuel like liquid petroleum gas (LPG), compressed natural gas (CNG), and Hydrogen along with biodiesel fuel. But, LPG and Hydrogen has some operation problems along with biodiesel fuel under dual fuel mode operation in a compression ignition engine. At lower rate of LPG, the thermal efficiency is lower than neat diesel operation in a CI engine. The lean mixture of LPG-air can-not encourage to flame propagation results in incomplete combustion. At higher rate of LPG, the knocking take place results in reduction in thermal efficiency and bad engine running operation. In dual fuel mode with LPG at higher loads, the exhaust temperature increase with increase in LPG flow rate results in complete combustion **[11]**. Hydrogen utilization in a compression engine is still under research for safety point of view. Hence, CNG is only the best alternative as main fuel and biodiesel as pilot fuel to the compression ignition engine.

Lahane and Subramanian **[12]** have investigated that CO_2 emission decreases with CNG energy share. It is mainly due to less carbon to hydrogen (C/H) ratio i.e. 0.25 as compared to diesel i.e. 0.54. NOx emission decreases with increasing CNG substitution. Combustion start automatically due to methane has higher self-ignition temperature. CO and HC emissions are increase with substitution but it can control easily by using catalytic convertor **[12]**.

At different percentages of load the NOx emission decreases with increasing the CNG substitution in compression ignition engine. At the rated load, 15.2 % decrease in NOx was observed. Volumetric efficiency is reduced with increasing the CNG substitution because of lower density gas is blocking the air in flow **[13]**. CNG utilization in a compression ignition engine results in higher CO and HC emissions. However, it decreases with increasing the diesel quantity in the dual fuel mode and there are 82% reductions of smoke in dual fuel with CNG than 100 % diesel operation **[14]**.

The increase in torque measured and reduction in specific fuel consumption was observed with CNG utilization in a compression ignition engine under dual fuel mode which results in higher brake power and higher thermal efficiency of the engine. However, the decrease in exhaust temperature was observed with CNG utilization **[15]**. CO_2 reduction around 15 % was observed under dual fuel mode with CNG as main fuel and diesel as pilot fuel **[16]**.

One of the main objectives in worldwide to improve the combustion process of internal combustion engine is to find the effective ways to reduce the exhaust emission. The rapid expansion and plenty availability of natural gas is one of the areas to drive intense cost benefits over diesel fuel. The preparation of natural gas is a very economical. A dual fuel engine can operate either on 100 % diesel fuel or the substitution mixture of diesel and natural gas but it cannot operate on natural gas alone. Dual fuel engines technology has significant potential. Potential advantages of dual fuel engines include diesel like efficiency and brake mean effective pressure with much lower emissions of oxides of nitrogen (NOx), and particulate matter. Hence, the reduction of oxides of nitrogen and carbon dioxide is achieved by running the compression ignition engine under dual fuel mode with CNG as main fuel and biodiesel as pilot fuel.

2. Methodology:

The engine used in the present study is a Kirloskar AV-1, single cylinder direct injection, water cooled compression ignition engine. The flow of air which is sent to the inlet manifold along with the flow of CNG is calculated through CNG flow meter that is rotameter. A dual fuel engine is based on CI engine; with the addition of dual fuel specific hardware when the engine is operating in dual fuel mode natural gas is introduced into the intake system. The air-natural gas mixture from the intake is drawn into the cylinder, just as it would be in a spark ignited engine, but with a leaner air-fuel ratio. Near the end of compression stroke, the diesel fuel is injected just as it would be in CI engine. The diesel fuel ignites, and the diesel combustion causes the natural gas to burn. Emissions of the engine CO, CO_2, HC, NOx were measured by using exhaust gas analyzer. The diesel fuel is injected with a nozzle hole of size 0.15 mm. The engine is coupled to a dc dynamometer. In first phase the results of performance and emission characteristics with neat diesel at different load condition that is 25 %, 50 %, 75 %, and 100 % were taken and in second phase the CNG fuel was injected with different energy share along with biodiesel.

3. Experimental set-up:

The experiments have been conducted on the single cylinder, water cooled compression ignition engine with 3.7 kW rated power. The specification of engine is given in Table 1. The layout and experimental setup of compression ignition engine under dual fuel mode with CNG as shown in Figure 1-2. The flow of CNG which is provided to the inlet manifold along with flow of air is calculated by using rotameter. The emission is measured by using external gas analyzer. The physico-chemical properties of diesel, biodiesel (B20) and CNG are given in Table 2.

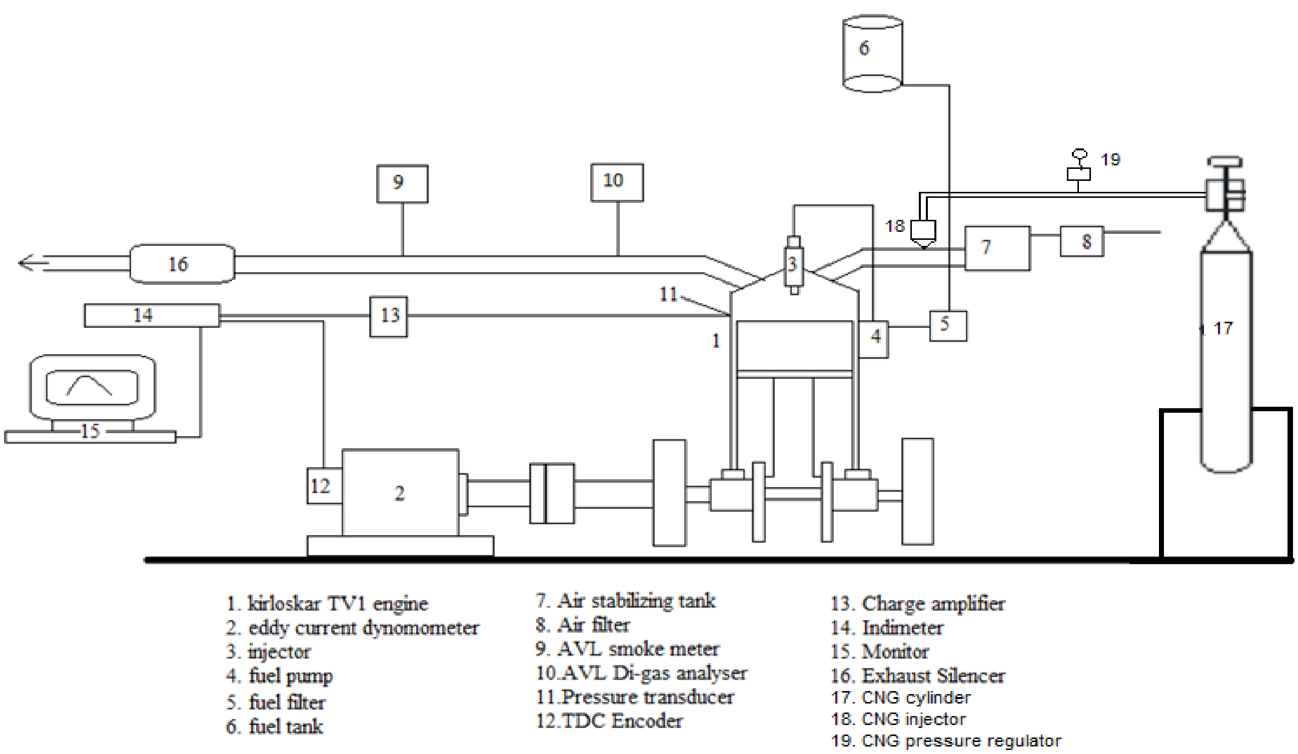


Figure (1): Schematic layout of diesel engine.

Table (1): Engine specifications.

Parameter	**Specification**	**Parameter**	**Specification**
Make	Kirloskar	C.R.	16.09:1
Model	AV1	Fuel	Diesel
Speed	1500	Cooling	Water cooled
Bore	80 mm	Starting	Hand Cranking
Stroke	110 mm	Injection pressure	205 bar
Cylinder	1 cylinder 4 Stroke CI engine	BHP	5 H.P./3.7KW

Figure (2): Experimental set-up.

Table (2): Fuel properties.

Property	**CNG**	**Diesel**	**B20**
Methane (CH_4)	88 - 98 %v/v	$C_{16}H_{34}$	$C_{18}H_{38}O_3$
Calorific Value	43.56 MJ/kg	44	42.6
Cetane number	--	49	51
Energy content	25 %	--	--
Auto ignition temperature	450 ºC	220	--
Stoichiometric ratio	17.3	14.4	--
Density	0.717 kg/m^3	821	835.6

4. Results and discussion:

Diesel engine is the most efficient combustion engine today and it plays an important role in transport of goods and passengers on road and on high seas. Figure 3 shows the variation of in-cylinder pressure with crank angle for diesel, B20 biodiesel, B20+CNG 10% and B20+CNG 20 % energy share at 1500 rpm and at the rated load conditions. In-cylinder pressure verse crank angle data is very important to optimize the performance and emission characteristics of the engine. In-cylinder pressure verses crank angle data over the compression and expansion strokes of the engine operating cycle can be used to obtain quantitative information on the progress of combustion. It is clearly from the figure that the peak in-cylinder pressure is increased with B20 biodiesel whereas it decreased with both the CNG energy share. The higher peak in-cylinder pressure with B20 is due to higher bulk modulus of biodiesel tends to automatic advance in dynamic injection timing and shorter ignition delay due to higher cetane number. In-cylinder pressure is decreased with both the CNG energy share due to its octane property results in retardation of start of combustion of the engine. The in-cylinder peak pressure is increased from 43.7 bar with diesel to 44.86 bar with B20 biodiesel and decreased to 43.1 bar with B20+CNG 10 % and 42.75 bar with B20+CNG 20% energy share. However, the combustion process of the test fuels is similar, consisting of a phase of premixed combustion following by a phase of diffusion combustion. Premixed combustion phase is controlled by the ignition delay period and spray envelope of the injected fuel. Therefore, the viscosity and volatility of the fuel have very important role to increase atomization rate and to improve air fuel mixing formation.

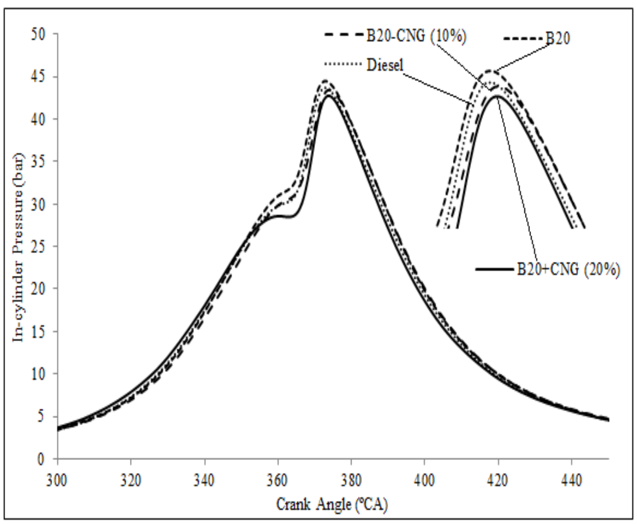


Figure (3): Variation of in-cylinder pressure.

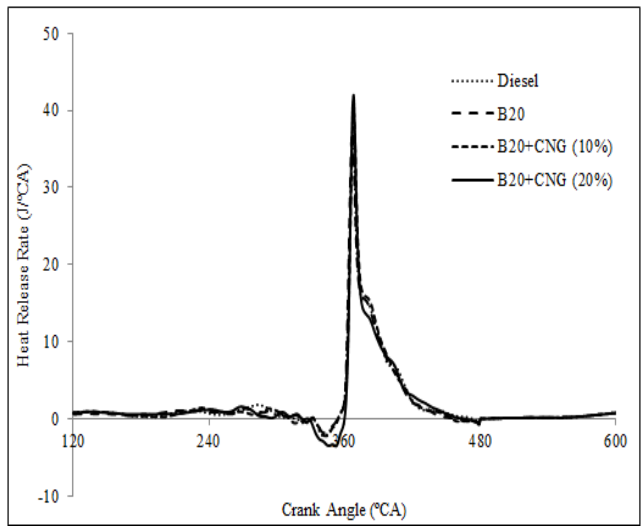


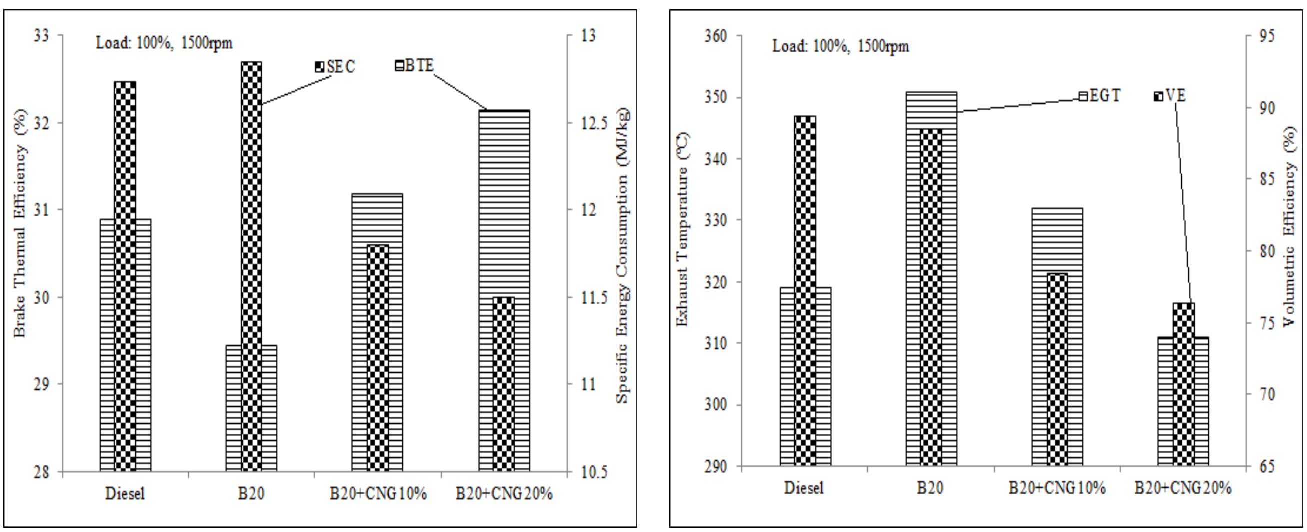
Figure (4): Variation of heat release rate.

The heat release rate is used to identify the start of combustion, the fraction of fuel burned in the premixed mode, and differences in combustion rates of fuels. Analyses of cylinder pressure data to obtain the heat release rate for diesel, B20 biodiesel, B20+CNG 10 % and B20+CNG20 % were conducted as shown in Figure 4. The start of combustion is advanced with B20 due to automatic advance in dynamic injection timing and shorter ignition delay. However, it retarded with both the CNG energy share due to longer ignition delay and octane fuel. The start of combustion is the cumulative effect of differences in the start of injection and changes in the ignition delay period. The ignition delay in a diesel engine is defined as the time between the start of fuel injection and the start of combustion. The physical and chemical properties of the fuels will affect the ignition delay period, and researchers have stressed that chemical properties are much more important than physical properties. The ignition quality of a fuel is usually characterized by its cetane number. Higher cetane number generally means shorter ignition delay.

The output of any engine is measured in terms of brake thermal efficiency. The brake thermal efficiency (BTE) is increased from 30.89 % with base diesel and 29.45 % with B20 to 32.15 % with B20+20 % CNG energy share (Figure 5a). The increase in brake thermal efficiency is mainly due to CNG utilization in higher compression ratio of a compression ignition engine operation (16.09:1). Another reason for the higher brake thermal efficiency could be due to higher cumulative heat release rate with B20+CNG energy share. Specific energy consumption (SEC) decreased with CNG energy share could be another reason for increase in brake thermal efficiency (Figure 5a).

As some air quantity was replaced by CNG, the volumetric efficiency (VE) decreased with CNG energy share (Figure 5b). The lower density of CNG is obstructing the air inflow. However, it doesn't effect on emissions of compression ignition engine which operates at lean mixture or excess air.

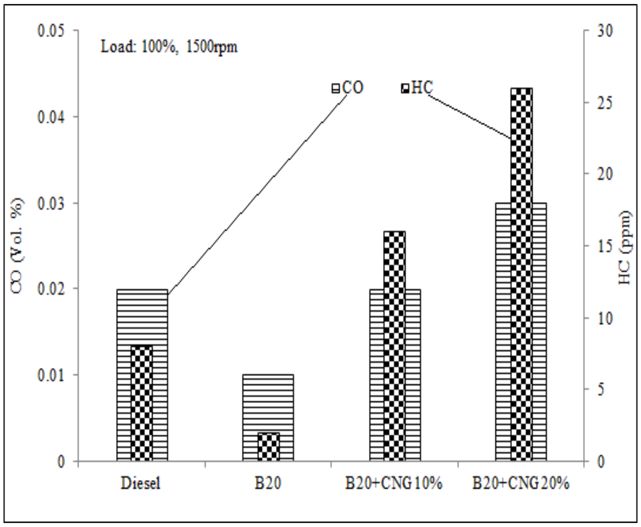
Exhaust gas temperature (EGT) decreased with CNG energy share (Figure 5b). It may be due to low temperature combustion with CNG energy share as a result of dilution effect. The decrease in exhaust gas temperature may be one of the reasons for decrease in NOx emission which discussed in latter. However, exhaust gas temperature increased with B20 blend. It mainly due to biodiesel has higher bulk modulus results in automatic advance in dynamic injection timing. Automatic advance in dynamic injection timing (DIT) achieve higher combustion temperature results in higher exhaust gas temperature.



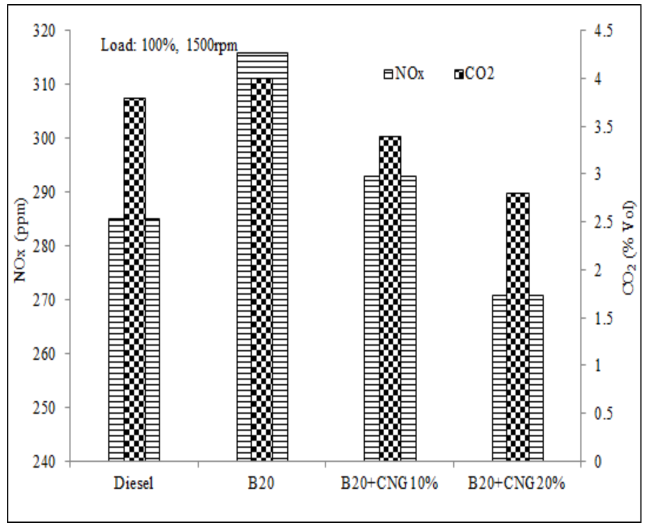
(a) (b)

Figure (5): (a) Comparison of BTE and SEC for diesel, B20 and CNG share.
(b) Comparison of EGT and VE for diesel, B20 and CNG share.

CO and HC emissions decreased with B20 fuel as compared to base diesel (Figure 6a). It is mainly due to automatic advance in dynamic injection timing and higher cetane number of biodiesel results in higher combustion temperature. Higher combustion temperature results in better and complete combustion further results in lower CO and HC emissions. However, CO and HC emissions increased with CNG energy share due to lower in-cylinder/combustion temperature.



(a)



(b)

Figure (6): (a) Comparison of CO and HC emissions for diesel, B20 and CNG share.
(b) Comparison of NOx and CO_2 emissions for diesel, B20 and CNG share.

NOx emission decreased with increase in CNG energy share (Figure 6b). It is mainly due to low in-cylinder temperature and charge dilution by compressed natural gas. However, it increased with B20 due to advance in DIT, higher spray penetration and in-cylinder temperature **[17]**. The NOx forms through three routes such as thermal NO, prompt NO and fuel bound NO. The thermal NO mechanism is based on the extended Zeldovich mechanism as given in equations (1-3), which involves atmospheric nitrogen and occurs during combustion thereafter in the post-flame gas region.

$$N_2 + O \leftrightarrow NO + N \text{............(1)}$$
$$N + O_2 \leftrightarrow NO + O \text{............(2)}$$
$$N + OH \leftrightarrow NO + H \text{..........(3)}$$

The carbon to hydrogen ratio for CNG is the least about 0.25 as compared to all carbon fuels. It indicates that CO_2 emission decreases significantly (Figure 6b). It could also be a carbon neutral fuel if it will produce from bio-resources such as biogas, producer gas and agro-waste. Moreover, it mixes homogeneously with air, resulting in better combustion and considerable reduction of emissions in the exhaust gas. As India is a diesel driven economy, CNG utilization in CI engine would give multiple advantages in terms of lower cost electrical power generation and lesser emission (NOx and CO_2) as compared to a 100 % diesel fuelled compression ignition engines.

5 Conclusions: The following conclusions are drawn based on the experimental investigations/results of 10 % and 20 % CNG energy shares with B20 as pilot fuel under dual fuel mode with comparison of base diesel and biodiesel blend (B20).

- Peak in-cylinder pressure is higher with B20 and lower with CNG share as compared to diesel.
- Start of combustion is advanced with B20 due to shorter ignition delay and retarded with both CNG share due to octane fuel as compared to diesel.
- Brake thermal efficiency is higher with both CNG energy shares than base diesel and B20 at rated load. The brake thermal efficiency increased from 30.89 % with base diesel to 31.19 % and 32.15 % with 10 % and 20 % CNG energy shares respectively.

- NOx emission decreased drastically with both CNG energy shares. NOx emission decreased from 285 ppm with diesel and 316 with B20 to 293 ppm and 271 ppm with 10 % and 20 % CNG energy shares respectively.
- CO_2 emission decreased significantly due to higher thermal efficiency and fuel containing lesser carbon. However, CO and HC emission increased significantly.

NOx emission is a major problem of biodiesel fuelled compression ignition engine. The dual fuel combination (B20-CNG) in a compression ignition engine gives reduction in CO2 and NOx emissions with tangible outcome of higher brake thermal efficiency.

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