Archives of Environmental Protection
Vol. 49 no. 1 pp. 79–84

PL ISSN 2083-4772
DOI 10.24425/aep.2023.144740

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Environmental impact evaluation of diesel engine fuelled with CNG

Neeraj Kumar*, Bharat Bhushan Arora, Sagar Maji

Delhi Technological University, Delhi, India

*Corresponding author's e-mail: neev37@gmail.com

Keywords: Diesel; CNG; Dual fuel; Emissions

Abstract: The uncertainty in the supply of crude oil, increasing the number of vehicles and rising air pollution, especially in urban areas, has prompted us to look for alternative fuels. It is understood that using Compressed Natural Gas (CNG) in IC engines could be a mid-term solution to these problems. It is well established that CNG has better combustion characteristics and low emissions compared to conventional gasoline and diesel fuel. In the present study, an experiment was conducted to evaluate the engine performance and exhaust emissions using various percentages of CNG in dual fuel mode. CNG was mixed in the intake manifold's air stream, and diesel was injected after the compression of the CNG air mixture. This paper presents experimental results of 40%,60%, and 80% CNG in the air stream. Engine performance and emissions are presented and discussed at a speed of 1200 rpm to 1500 rpm in steps of 50 rpm. The results of the experiments showed that adding CNG to diesel engines in dual-fuel combustion significantly impacted performance and emissions. Compared to single diesel fuel combustion, dual fuel combustion increases brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) at all CNG energy shares and engine speeds. Carbon monoxide (CO) and hydrocarbon (HC) emissions were increased, while nitrogen oxide (NO_X) and smoke opacity were decreased in dual fuel combustion compared to single diesel fuel.

Abbreviations:

BSFC	Brake Specific fuel consumption
BTE	Brake Thermal Efficiency
CO	Carbon monoxide
CNG	Compressed natural gas
DF	Dual Fuel
HC	Hydrocarbon
IC	Internal Combustion
NO_X	Nitrogen oxide
rpm	Revolution per minute
VCR	Variable compression ratio

Introduction

The applications of compression ignition engines are widely employed in several automotive, power generation, and agriculture sectors because of their supreme fuel conversion efficiency (Kalghatgi 2014). Due to the rapid depletion, increased crude petroleum prices, and stringent environmental legislation, it is necessary to use environmentally friendly fuels in the existing compression ignition engines, partially or completely replacing conventional fuels. Ignition of conventional fuels produced pollutants such as HC, CO, NOx, CO_2 and smoke in addition to producing acoustic sound (Zwierzchowski and Wrońska 2021). These pollutants cause adverse environmental and human health effects such as impaired lung function, respiratory symptoms, cardiovascular diseases, and premature death (Wyrwa 2010).

Implementing CNG in the CI engine via dual fuel technique is a better alternative to the present fuel trouble and atmospheric air pollution reduction. CNG is recognized for its better combustion properties, high calorific value, lower greenhouse gas emission, high knock resistance, and high octane number, which can utilize the engine at higher compression ratios (Shim et al. 2018, Cowan et al. 2005).

Many experimental studies were performed on combustion characteristics and emissions of dual fuel CI engines with CNG and diesel fuel with various operational parameters such as engine load, injection strategy, diesel fuel quantity, gas substitution ratio and other combustion parameters (Johnson et al. 2017, Stelmasiak et al. 2017, Wang et al. 2021, Wei et al. 2016, Yousefi et al. 2018, Rai et al. 2021, Bari et al. 2019, Stelmasiak et al. 2017 and Pathak et al. 2021).

Gharehghani et al. (2015) investigate the comparison between single diesel and dual fuel (Diesel/CNG) combustion and indicate that HC and CO emissions increased in dual fuel combustion than in single diesel combustion.

Jamrozik et al. (2019) performed the effects of the CNG substitution ratio using a single-cylinder CI engine. It concluded that increasing the CNG share from 0–45% decreased HC and NOx emissions, and CNG share beyond 45–95% increased the NOx emission and reduced CO emission.

Yousefi et al. (2019) experimentally investigated the performance and emission of diesel engines run with DF and varied load conditions. The results show that increasing BTE and NOx emission at all engine loads optimises the injection timings and decreases CO_2 emission.

Tripathi et al. (2020) investigated the impact of diesel methane dual fuel combustion on performance and emission--varying load conditions. The outcome reveals that the increased methane energy ratio decreased brake BTE, CO_2 and NO_X emissions while increasing CO and HC emissions at all the tested loads.

Lee et al. (2020) experimentally determined the combustion and emission characteristics of diesel CNG DF engine with CNG substitution rates of CNG0%, CNG70%, and CNG80% using a six-cylinder diesel engine, and results revealed that CNG80% presented 2.7% increased BTE and 22.6% reduction in CO_2 emission than 100% diesel fuel.

The objective of the present study is to evaluate the effect of different CNG energy share varying engine speeds on the performance and exhaust emissions of a single cylinder, four strokes, CRDI VCR engine in single diesel fuel and dual fuel (Diesel+CNG) combustion mode.

Experiment Methodology

Experiment set-up

The test engine was a Kirloskar make single-cylinder, four strokes, water-cooled, CRDI VCR diesel engine. The technical specifications of the engine are listed in Table 1. The test engine was equipped with all the basic units for calibrating the performance and emission characteristics. The test engine was coupled to a Saj make water-cooled eddy current dynamometer, Model AG10, to measure the engine load. The airflow was measured by Wika make airflow transmitter, Model SL1 and the pressure was sensed by the piezoelectric sensor, PCB Model AX-409. A radix makes, K-type thermocouple was used to measure the temperatures of exhaust gases and intake air. A Programmable electronic control unit (ECU), Model Nira i7r, is used to restrain the test. The exhaust emissions were measured by AVL Di Gas 444N gas analyzer. The smoke opacity was measured through AVL 437 smoke meter. The schematic diagram of the test engine is shown in Fig. 1. The Physicochemical properties of diesel and CNG fuels are listed in Table 2.

Methodology

An experiment was conducted using single diesel and diesel--CNG dual fuel operational modes to investigate the engine performance and exhaust emission. The test set-up was a single-cylinder, four strokes, water-cooled, VCR diesel engine. The experiment test was conducted at a compression ratio of 15, varying engine speeds from 1200 to 1500 rpm at a constant engine load of 10 kg.

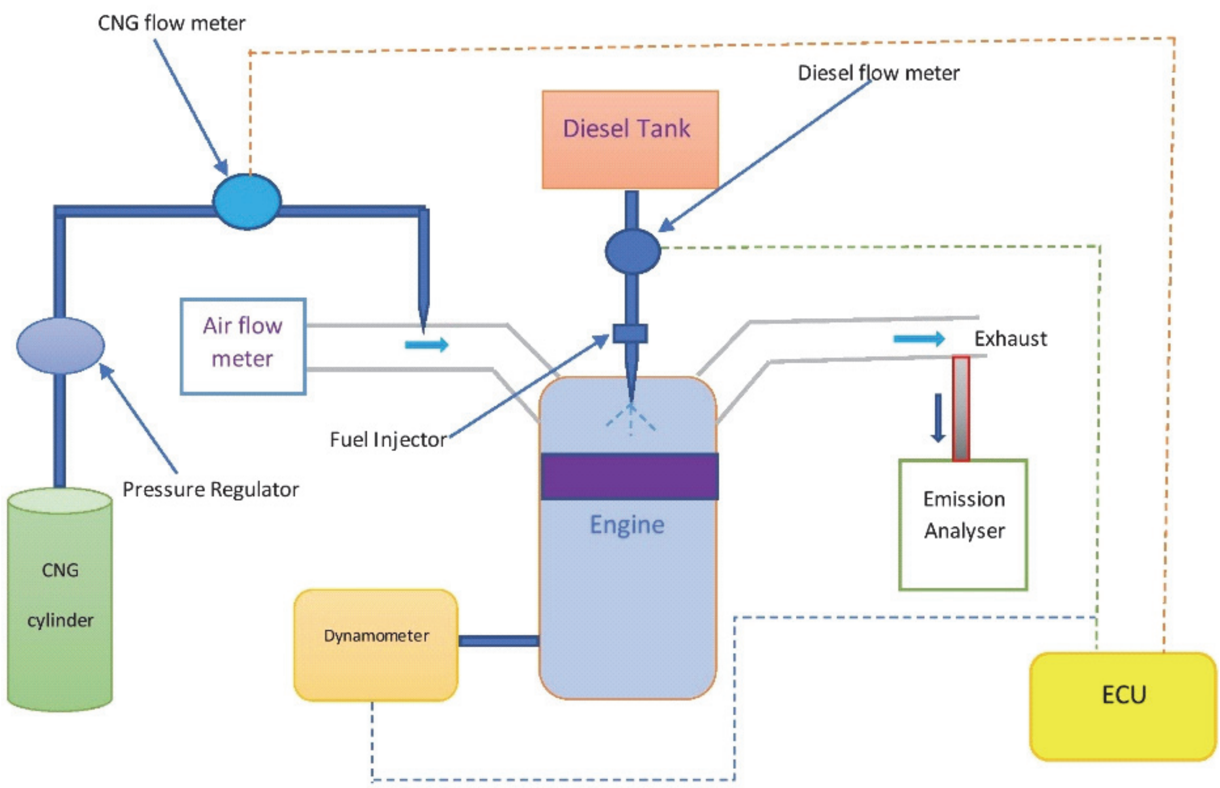

Fig. 1. Schematic diagram of engine set-up

The experiment analysis was divided into two stages.

– The engine started at CR of 18 using D100 fuel in the first stage. After reaching the thermal stabilization state, the compression ratio was adjusted to 15 by tilting the head arrangements from the cylinder. The engine speeds vary from 1200 rpm to 1500 rpm. The engine performance were recorded using enginesoft software, and exhaust emissions and smoke opacity was recorded by the AVL Di Gas 444N gas analyzer and AVL 437 smoke meter.
– Diesel and CNG were taken for dual fuel combustion in the second stage. CNG was mixed in the intake manifold's air stream, and diesel was injected after the compression of the CNG air mixture and adjust the CNG energy share at D60CNG40, D40CNG60, and D20CNG80 from the CNG supply valve. The performance and exhaust emissions were recorded by the same instruments used in the first stage for dual fuel combustion.

Results and Discussion

Performance Analysis

Brake thermal efficiency

The Brake Thermal Efficiency converts the chemical energy of fuel into practical work. Figure 2 depicts the impact of D100 and dual fuel combustion on BTE at various engine speeds. BTE increases as increasing the CNG energy share and engine speed, as seen in Fig.2.

Increased BTE was reported at a lower CNG energy share in dual fuel combustion than in D100 combustion. Because of a higher CNG substitution ratio, the flame propagation of the air-gas mixture was substantially slower. It was also observed that increasing the CNG energy share increased the igniting delay time. At a lower CNG energy share, diesel fuel is more readily available than CNG, resulting in better combustion efficiency due to a higher maximum flame temperature than a higher CNG energy share.

Figure 2 shows that when the engine speed increases, the BTE increases by 59.72%, 57.27%, 57.07%, 60.94%, 61.77%, 64.02%, and 65.59% for D60CNG40 dual fuel combustion compared to D100. For the D40CNG60 dual fuel combustion, BTE increased by 52.74%, 49.72%, 49.83%, 55.38%, 55.37%, 57.82%, and 59.93% to D100 fuel combustion. The same pattern is observed for the D20CNG80 combustion. As the engine speeds increased, BTE increased by 45.71%, 42.32%, 42.3%, 48.6%, 48.68%, 51.56%, and 58.57% at all engine speeds than D100 fuel combustion.

Brake Specific Fuel Consumption

The fuel consumed per unit of engine power output is known as brake specific fuel consumption. Figure 3 depicts the variation in BSFC for single D100 and dual fuel combustion at different engine speeds. BSFC increased in dual fuel combustion at all engine speeds than single diesel fuel combustion, as shown in Fig. 3.

The highest BSFC was achieved for all engine speeds with D60CNG40 energy share. Because the excess air ratio of the air-fuel mixture is substantially higher for a lower CNG energy share. When the air-fuel mixture is lean, the combustion chamber receives additional CNG, which replaces the diesel fuel.

Table 1. Engine Configuration

Parameters	Description
Manufacturer	Kirloskar
Number of cylinders	1
Number of strokes	4
Bore× stroke(mm)	87.5 × 110
Type of cooling	Water cooled
Displacement (cc)	661
Rated power	3.5kW at 1500 rpm
Compression ratio	15:1
Variable compression ratio range	12:1 to 18:1
Overall dimension(mm)	W 2000 × D 2500 × H 1500
Fuel used	Diesel, Diesel/CNG dual fuel mode

Table 2. Fuel Properties

Properties	Diesel	CNG
Cetane number	52	0
Methane number	–	82
Research Octane number	–	130
Density (kg/m^3)	826	0.72
Fuel calorific value (kJ/kg)	43000	50000
Stoichiometric air-fuel ratio	14.2	17.2

Because of the decrease in diesel fuel quantity, the spark energy of the air-fuel mixture is reduced at a higher CNG energy share, which is also responsible for incomplete combustion. Complete combustion happens when the air-fuel mixture is too rich, lowering BSFC at a higher CNG energy share.

Figure 3 shows that BSFC increased in dual fuel combustion for all CNG energy shares and engine speed compared to D100 fuel. When comparing D100 fuel combustion to D60CNG40 dual fuel combustion, the BSFC increased by 31.48%, 34%, 40.74%, 37.5%, 40%, 33.33%, and 37.03% at all engine speeds in dual fuel mode.

Compared to D100, the value of BSFC raised by 28.84%, 36.53%, 30.43%, 25.53%, 28.26%, 24.44%, and 20.93% for D40CNG60 dual fuel combustion. BSFC was increased by 28.84%, 34%, 33.33%, 28.57%, 28.26%, 27.65%, and 22.72% for D20CNG80 energy share, compared to D100 fuel.

Exhaust Emission Analysis

CO Emission

Figure 4 shows the CO emission deviations for D100 fuel and dual fuel combustion at different engine speeds. The engine's low flame temperature and a lack of air-fuel mixture are the primary causes of CO emissions.

When a lower CNG energy share is used, CO emissions are lower than a higher CNG energy share. Because at lower CNG energy share, the ignition fuel quantity and spray combustion region decrease with increasing CNG supply due to the lower equivalence ratio in the CNG/air mixture. It indicates that the quenching region expands, and the CO emissions increase compared to single diesel fuel. For a higher CNG energy share, the equivalence ratios increase with increasing the CNG supply and decreased pilot fuel quantity, resulting in decreased ignition temperature and increased CO emission.

In comparison to D100, CO emissions increased by 18.9%, 10%, 9.4%, 9.2%, 12.5%, 14.28%, and 16.66% at all engine speeds for D60CNG40 dual fuel combustion, as shown in Fig.4. The CO emissions increased by 13.33%, 15.38%, 9.09%, 5.8%, 12.5%, 25%, and 28.57% for D40CNG60 energy share than D100 fuel combustion. The same pattern was observed for D20CNG80 energy share, CO emission increased by 23.52%, 26.66%, 28.57%, 33.33%, 30%, 33.33%, and 37.5% than D100 fuel at engine speeds 1200 rpm to 1500 rpm.

HC Emission

The HC emission is imprimis originated by incomplete combustion. The Incomplete combustion was caused by a lack of oxygen which decreased the combustion rates in dual-fuel combustion and producing HC emissions. Figure 5 shows that the HC emissions are significantly higher in dual-fuel combustion than in single-diesel fuel combustion. In dual-fuel combustion, the gaseous fuels are incompletely burned due to the lower combustion temperature caused by the high specific heat content of the gases, poor burning rate, and poor injection characteristics of the pilot fuel. Increases in HC emission are also caused by the release of unburned gas in both the crevice and squish zones during the power stroke.

Compared to D100 combustion, HC emissions increased as the CNG energy share, and engine speeds increased. The HC emission at D60CNG40 dual fuel combustion is higher than D100 fuel by 40.9%, 42.37%, 39.21%, 36.95%, 22.5%, 5.71%, and 8.68%. At engine speeds of 1200–1500 rpm, HC emissions increased by 64.54%, 68.51%, 70.75%, 72.38%, 69%, 66%, and 63.15% for D40CNG60 energy share. The same pattern was observed for D20CNG80 dual-fuel combustion in Fig. 5. The HC emissions increased by 80.2%, 79.14%, 78.76%, 76.42%, 73.04%, 67%, and 61.11%, respectively, compared to D100 fuel.

NO_x Emission

The formation of NOx is influenced by a high oxygen content in the cylinder, a high cylinder temperature, and a long reaction time caused by combustion. Figure 6 shows NO_x emissions are lower in dual-fuel combustion than in single-fuel combustion. In dual-fuel combustion, the combustion process occurs in the lean, premixed regime due to an increase in Stoichiometric air/fuel ratio, which may decrease the cylinder temperature,

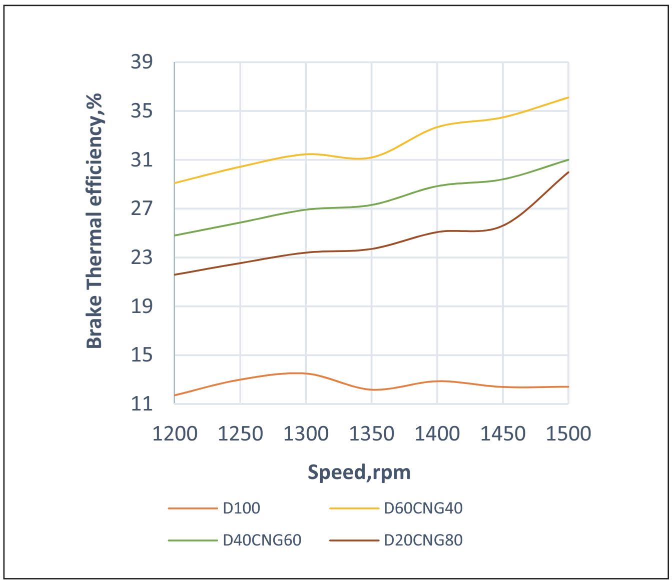

Fig. 2. Variation of brake thermal efficiency versus engine speed

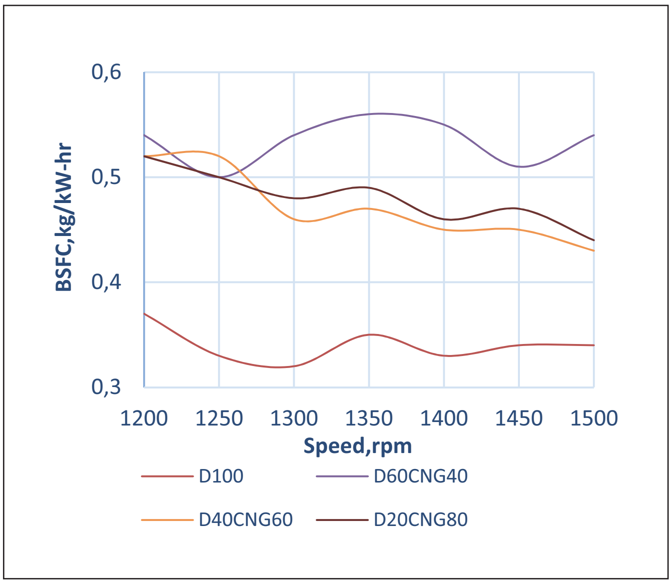

Fig. 3. Variation of brake specific fuel consumption versus engine speed

resulting decrease the NO_X emission. For single diesel combustion, maximum fuel is burned as a diffusion flame near stoichiometric equivalence ratio, producing higher combustion temperatures and increased NOx emission.

Figure 6 shows that when D60CNG40 is used as the primary fuel, NO_X emissions are reduced by 20.94%, 16.41%, 11.24%, 6.8%, 11.29%, 16.82%, and 20.08% at all engine speeds compared to D100 fuel. NO_X emissions were reduced by 160%, 133.3%, 108.6%, 80%, 105%, 93%, and 114% for D40CNG60 dual fuel compared to D100 fuel. The same pattern was observed for D20CNG80 energy share, NO_X emissions reduced by 705.4%, 416.9%, 282%, 248.2%, 213.5%, 192.8%, and 164.6%, respectively, compared to D100 fuel.

Smoke Emission

The fluctuation in smoke opacity for various CNG energy shares is depicted in Figure 7. The amount of liquid fuel injected has the greatest impact on the opacity of the smoke. In a dual-fuel engine, diesel fuel consumption is reduced since it is replaced by a CNG-air mixture that produces less smoke. Increased CNG energy share increases its quantity of heat contribution and decreases the C/H ratio in the fuel mixture, resulting in better combustion and reduced smoke opacity.

A higher ratio of CNG energy share enhances soot oxidation, and the clean burning gas quality helps reduce soot emissions. CNG is primarily composed of methane, and as a lower paraffin family member, it has a low tendency to generate soot. The heat input contribution of CNG fuel is reduced at lower CNG energy share, and pilot liquid fuel increases the carbon proportion in the combustion and the smoke levels in the exhaust.

Figure 7 shows a great reduction in smoke opacity in dual fuel compared to single D100 fuel. When D60CNG40 is used as the primary fuel, smoke opacity is reduced by 20%, 26.1%, 11.2%, 22.8%, 10.29%, 34.82%, and 45.08% at all engine speeds 1200 to 1500 rpm compared to D100 fuel. The smoke

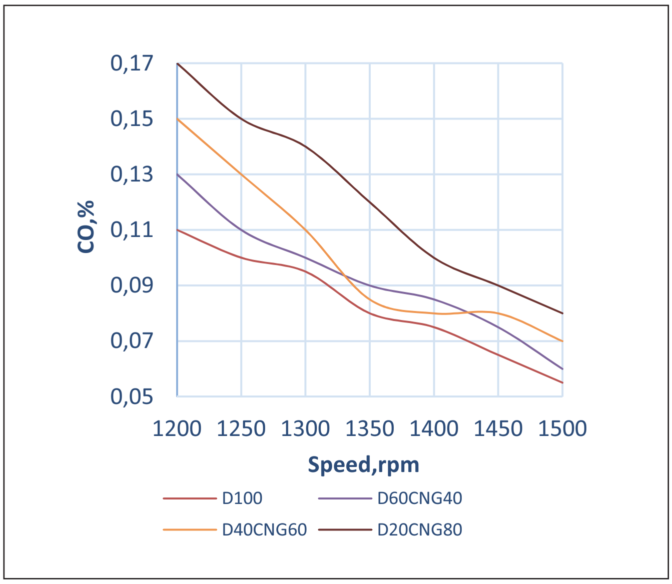

Fig. 4. Variation of CO emission versus engine speed

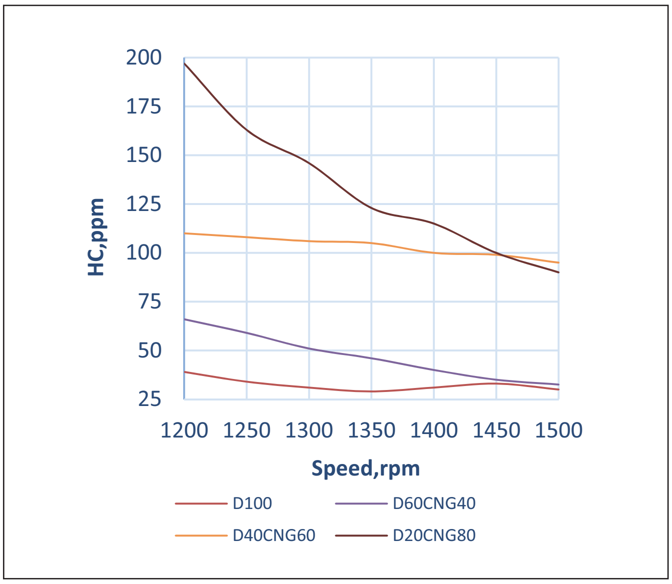

Fig. 5. Variation of HC emission versus engine speed

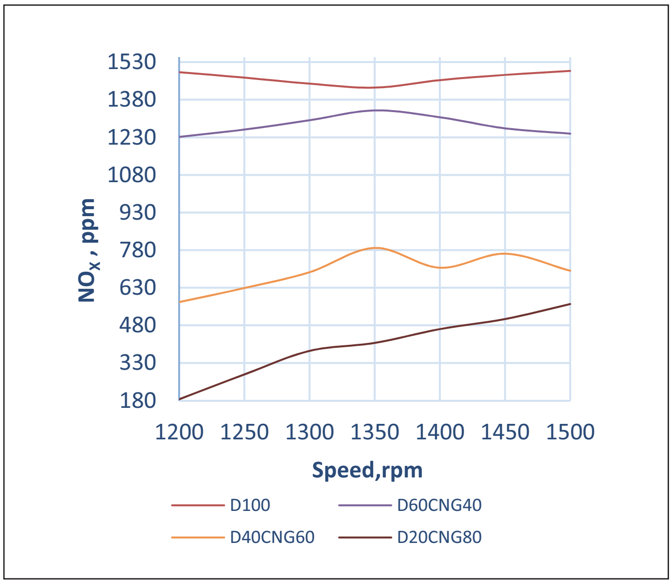

Fig. 6. Variation of NO_X emission versus engine speed

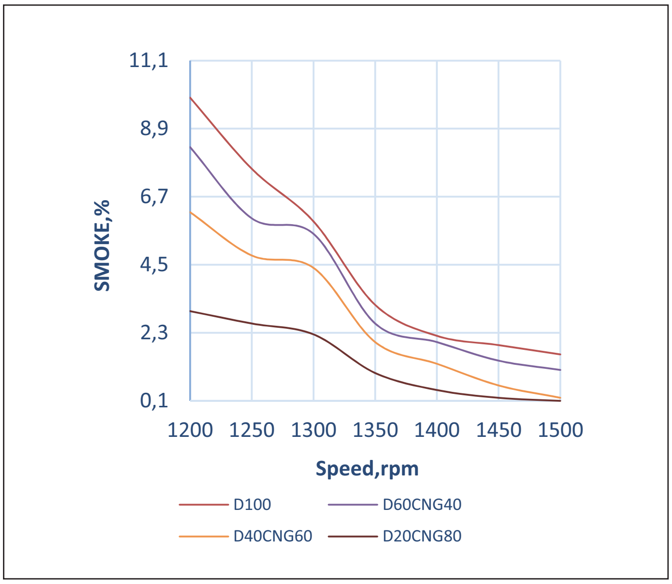

Fig. 7. Variation of Smoke opacity versus engine speed

opacity decreased by 69.54%, 58.32%, 27.75%, 60.3%, 69%, 216.1%, and 700.15% for D40CNG60 energy share. The same pattern was observed for D20CNG80 energy share, and smoke opacity decreased by 230.52%, 192.66%, 168.57%,220%, 388%, 850.43%, and 1500% than D100 fuel combustion.

Conclusion

The current experiment investigates the performance and emissions at an engine speed range of between 1200 rpm to 1500 rpm using the CNG energy share of D60CNG40, D40CNG60, and D20CNG80 in dual fuel combustion. The investigation's conclusions can be drawn from the following:

- Brake Thermal Efficiency and Brake Specific Fuel Consumption increased in dual fuel combustion at all engine speeds compared to pure diesel combustion. The maximum raised in BTE and BSFC detected at D60CNG40 energy share due to higher flame temperature excess air ratio mixture and pressure, resulting in a better air/fuel mixture and faster fuel evaporation at a lower CNG energy share.
- Carbon Monoxide (CO) and hydrocarbon (HC) emissions were increased in dual fuel combustion compared to single diesel fuel combustion. CNG energy share of D20CNG80 produced higher CO and HC emissions. Because at a higher CNG energy share, the equivalence ratios increase with increasing the CNG supply rate, which decreases the liquid fuel quantity resulting in lower ignition temperature and sparks energy of mixture. These facts increase CO and HC emissions in dual-fuel combustion.
- Adding the CNG to the diesel fuel reduces the NOx and smoke opacity in the Exhaust Gas. The Minimal NO_X emission and smoke opacity was attained at D20CNG80 energy share. At a higher CNG energy share, the ignition delay period prolongs, slows the flame propagation speed, and decreases the cylinder temperature and C/H ratio, reducing the NO_X emission and smoke opacity in dual fuel combustion.

Conflict of interest

The authors declare that they have no conflict of interest or particular relation that could have affected the work disclosed in this manuscript.

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