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Experimental Evaluation of CNG Substitution Ratio on Exhaust Gas Emissions of Diesel/CNG Dual Fuel Combustion

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Abbreviations

CO – Carbon monoxide; CR – Compression Ratio; CNG – Compressed Natural Gas; EGR – Exhaust Gas Recirculation; BTE – Break Thermal Efficiency; BSFC – Break Specific Fuel Consumption; COPD – Chronic Obstructive Pulmonary Disease; CN – Cetane Number; MN – Methane Number; RON – Research Octane Number; DF – Dual Fuel; SI – Spark Ignition; CI – Compression Ignition; CO_2 – Carbon Dioxide; PM – Particulate Matter; HC – Hydrocarbon; IC – Internal Combustion; NO_X – Nitrogen Oxide; CRDI – Common Rail Direct Injection; VCR – Variable Compression Ratio.

1. Introduction

Diesel engines are extensively used in the transportation, agricultural, and industrial sectors worldwide due to their superior energy efficiency, reliability, adaptability, and cost-effectiveness than gasoline equivalents [1]. However, the emissions from diesel engines contribute to climate change and environmental deterioration. Ignition of diesel engines produced pollutants such as HC, CO, NOx, CO_2 and smoke, and acoustic sound [2, 3]. These pollutants increase the greenhouse effect and negatively impact the health of people and the environment in many ways [4]. Many studies have shown that diesel engine emissions may cause COPD, coughing, breathing, wheezing, asthma, respiratory illnesses and premature death in humans [5]. So, to achieve the lowest possible emissions of pollutants, emission control policies worldwide reduce PM and NOx emissions from diesel engines [6]. Further, the transportation energy demand is increasing rapidly, but the availability of fossil fuels is limited. So, despite the depletion of petroleum supplies, it is necessary to find a compromise between reducing emissions from IC engines by more strict emission standards and expanding energy consumption in all modes of transportation. Therefore, it is necessary to use alternative fuels in the existing CI engines, partially or completely replacing conventional fuels. Compressed natural gas is one of the best alternative fuels to reduce exhaust gas pollutants compared to diesel and gasoline combustion [7]. Compressed natural gas has additional benefits over fossil fuels. Since it is less expensive, has more reserves, has high octane number, and has a high calorific value and can be used in both SI and CI engines in dual fuel mode [8-10]. Regarding fossil fuel depletion and environmental pollution, the DF technique is becoming more interesting for researchers. Its combustion technology is efficient and environmentally friendly, and cost-efficient. Many experimental studies have been performed to describe the combustion characteristics and exhaust emission of dual fuel CI engines with CNG and diesel varying various operational parameters such as engine load, engine speed, compression ratio, injection strategy, diesel fuel quantity, EGR and others [11-18]. Increased in CNG substitution ratio, decreased brake thermal efficiency, CO_2 and NO_X while increasing CO and HC emissions at all tested loads [19]. Increasing the CNG substitution ratio from 0 to 45 per cent, combustion pressure and HRR increased, and HC and NOx emissions were reduced. Beyond 45 to 95 percent CNG substitution ratio increases the NOx emissions and decreases CO emissions [20]. While investigating the effect of a dual fuel (Diesel-CNG) operating model to analyse the performance and emissions at moderate and relatively high loads. It is found that a reduction in specific fuel consumption, NOx, and soot while increasing carbon CO and HC emissions [21]. The performance and emission characteristics of a diesel engine operating in dual-fuel mode with CNG and diesel, with diesel proportions varying from 10% to 100% and engine loads ranging from 1.1 KW to 2.8 KW. And the findings indicate that BTE decreases and increases BSFC in DF mode than pure diesel fuel mode. At 1.1 KW load, a maximum decrease in efficiency and increased growth of 68% of specific fuel consumption were noted in dual-fuel combustion mode. The exhaust emission of CO_2 and soot was lower and increased CO in DF combustion [22]. Under DF combustion at various load conditions. The performance of engine increases while emissions were decreases [23]. The performance and exhaust emissions are improved in diesel CNG dual fuel combustion. The energy shares of CNG 80% recorded a 2.7% increment in BTE and a 22.6% reduction in CO_2 emission than 100% diesel fuel combustion [24]. This work's interest is to exploit the dual fuel (diesel/CNG) engine combustion with minimal exhaust emission for power production. The exclusiveness of the present work lies in the fact that scant investigation is reported on diesel CNG dual-fuel engine combustion by the researcher's varying CNG substitution ratios and compression ratios. The study's objective was to investigate the impact of CNG substitution at different compression ratios to analyse the gaseous exhaust emissions of stationary single-cylinder, four strokes, water-cooled, CRDI VCR, DF (diesel/CNG) engines. The CR from 13:1 to 15:1 and CNG substitution of 40%, 60% and 80% were used to take the benefit of a higher octane number of CNG. The test set-up is regulated at an engine speed of 1500 rpm with a constant engine load of 10 Kg.

2. Experiment methodology

2.1. Experiment set up

Fig. 1 illustrates the schematic diagram of the experimental set-up consisting of a single-cylinder, four-stroke, CRDI VCR engine. The test engine configuration is shown in Table 1. The test engine was coupled to a SAJ make water-cooled eddy current dynamometer, Model AG10, to measure the engine load. A K-type thermocouple was used to measure the temperatures of exhaust gases and intake air**.** The CNG cylinder kit is coupled to the inlet manifold through a rubber hose. A Programmable electronic control unit (ECU), Model Nira i7r, measures and controls the CNG flow rate. AVL Di Gas 444N gas analyzer and AVL 437 smoke meter measured the exhaust gas emissions and smoke. The physicochemical properties of diesel and CNG fuels are listed in Table 2. The technical measurement of the exhaust gas analyser are given in Table 3.

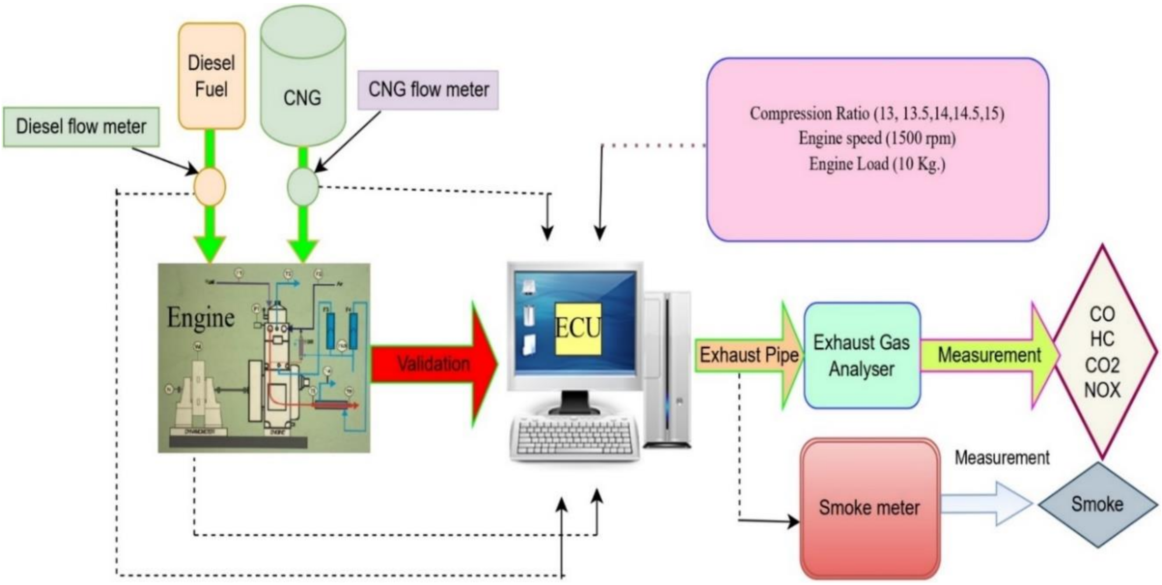

Fig. 1 Schematic diagram of experiment setup

Table 1

Technical data of the experimental engine setup

Parameters	Description
Engine	Make Kirloskar, Single cylinder,4-stroke,CRDI VCR engine
Bore, mm Stroke, mm	87.5 110
Type of cooling	Water-cooled
Displacement, cc	661
Rated power, kW Rated speed, rpm	3.5kW 1500
Compression ratio used	13, 13.5, 14, 14.5 and 15
Variable compression ratio range	12:1 - 18:1
Overall dimension, mm	W 2000 × D 2500 × H 1500
Fuel used	Diesel, Diesel/CNG dual fuel

Table 2

Fuel properties

Properties	Diesel	CNG
CN	52	0
MN	0	82
RON	20	130
Density, kg/m^3	830	0.72
Fuel calorific value, KJ/kg	42000	50000
Stoichiometric A/F ratio	14.5	17.05

Table 3

Technical data of exhaust gas analyser

Emission	Measurement	Resolution
CO	0-15% Vol.	0.001% Vol.
HC	0-20000 ppm Vol.	1 ppm/10 ppm
CO_2	0-20% Vol.	0.1% Vol.
NO_X	0-5000 ppm Vol.	1 ppm Vol.

2.2. Methodology

An experiment using D100% fuel and diesel/CNG DF combustion modes were conducted to examine the engine exhaust gas emissions. A single-cylinder, four-stroke, water-cooled, VCR diesel engine was used as the test setup. The experiment test was run with an engine speed of 1500 rpm and CR from 13:1 to 15:1 with a constant engine load of 10 Kg. was used to evaluate the investigation. The experimentation analysed the influence of CNG substitution ratios in the A/F mixture throughout combustion with diesel fuel. The CNG substitution ratio was calculated by Eq. (1).

$$CNG,\% = \frac{\dot{m}_{CNG}CV_{CNG}}{\dot{m}_{CNG}CV_{CNG} + \dot{m}_{Diesel}CV_{Diesel}} \times 100, \qquad (1)$$

where: $\dot{m}_{CNG}$ and $\dot{m}_{Diesel}$ are the fuel mass flow rate of CNG and diesel fuel in Kg/s, and CV_{CNG} and CV_{Diesel} are the net calorific value of CNG and diesel fuel.

Two steps were used to analyses the experiment. At CR of 18:1, the engine fired up using D100% fuel in the first step. The CR was adjusted from 13:1 to 15:1 in steps of 0.5:1 by tilting the head arrangements from the cylinder after achieving the thermal stabilization state and the engine speed and load varying from 1500 rpm and 10 kg. The combustion performance of single, double, and triple injections was also compared under these operating parameters. The engine exhaust gas emissions and smoke was recorded by the AVL Di Gas 444N gas analyzer and AVL 437 smoke meter. For DF combustion in the second step, diesel and CNG were used. CNG was mixed in the intake manifold's air stream, and diesel was injected after the compression of the CNG air mixture and adjusting the CNG substitution ratios of CNG40%, CNG60%, and CNG80% from the CNG supply valve. The same instruments used in the first step in DF combustion recorded the engine exhaust gas emissions and smoke.

3. Results and discussion

3.1. Carbon Monoxide emission

The primary influence of CO emission is low flame temperature and poor air/fuel mixture from the engine. Generally, CO emission increases as increasing in the CNG substitution ratio [21, 22]. With increasing CNG supply, the ignition fuel quantity and spray combustion region decrease at a lower CNG substitution ratio. The lower equivalence ratio in the CNG/air mixture indicates that the quenching region expands, and the CO emissions increase more than pure diesel. For a higher CNG substitution ratio, the equivalence ratio rises by increasing the CNG quantity and reducing pilot fuel quantity, decreasing the ignition temperature and leading to CO emissions.

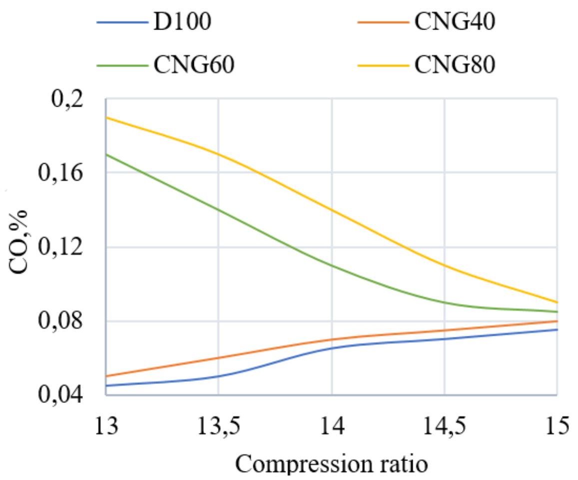

Fig. 2 Variation of CO emission versus compression ratio

Fig. 2 shows that CO emission increased as increased the CNG substitution ratio than D100% combustion. In comparison to D100, CO emissions increased by 11.1%, 20%, 7.6%, 7.1% and 7% at all CR for CNG40% DF combustion, as shown in Fig. 2. Similarly, The CO emissions raised by 277.7%, 180%, 69.2%, 28.5% and 13.3% at CNG60% substitution ratio than D100 fuel combustion. The same pattern was observed for CNG80% substitution ratio, and CO emission increased by 322.2%, 240%, 115.5%, 57.1% and 20% than D100% fuel at CR of 13:1 to 15:1.

3.2. Hydrocarbon emission

Hydrocarbon emission is imprimis from incomplete combustion as scarcity of oxygen and lower combustion rates in dual-fuel combustion. Fig. 3 shows that the HC emission increased with an increase in the CNG substitution ratio than D100 combustion. Usually, the HC emission is substantially higher compared to single diesel fuel combustion in DF mode [19, 25]. It is because ambient flame extinction zones in the CNG/air mixture are distant from the injection spray zones at a lower CNG substitution ratio; thus, the HC emissions are produced from the incomplete combustion of diesel/CNG DF combustion. In a higher CNG substitution ratio, the combustion throughout the spray zones is reformed because of the rich mixture; however, the quantity of CNG/air mixture compressed into the cylinder from the intake manifold during the compression stroke increases, increasing HC emissions. At higher CNG substitution, reduction in pilot fuel decreases the local temperature and ignition energy during expansion, which may lead to imperfect combustion and produce higher HC pollutants. The HC emissions are higher at CNG40% DF combustion compared to D100% fuel by 46%, 40.1%, 30.3%, 16.6% and 6.06% at all CR. At CNG60% substitution ratio, HC emissions increased by 98.6%, 66.6%, 70%, 105.5% and 142.4% compared to D100% combustion. The substitution ratio of CNG80% DF combustion increased HC emissions by 180%, 144.4%, 130%, 161.1% and 187.8%, respectively, compared to D100% fuel at CR of 13:1 to 15:1.

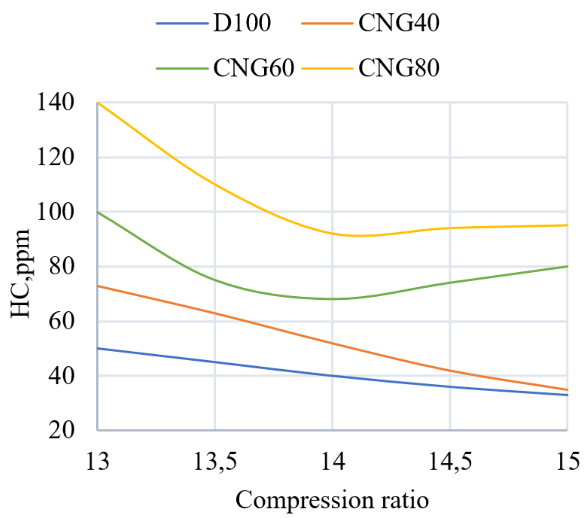

Fig. 3 Variation of HC emission versus compression ratio

3.3. Carbon Dioxide emission

Carbon dioxide is a leading element of greenhouse gases responsive to global warming. The scarcity of carbon atoms and oxygen content with CNG substitution influences CO_2 emission. Generally, the CO_2 emission is lower compared to single diesel fuel combustion in DF mode. CO_2 emission decrease with an increase in the CNG substitution ratios compared to D100% combustion [10, 26, 27].

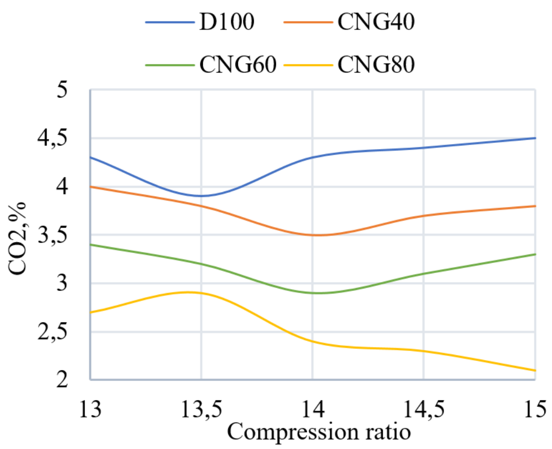

Fig. 4 Variation of CO_2 emission versus compression ratio

Fig. 4 shows CO_2 emission was lower in DF combustion at all CR. At the CNG40% substitution ratio, the CO_2 emissions are reduced by 7.5%, 2.6%, 22.4%, 18.9% and 18.4% at all CR from 13:1 to 15:1 compared to D100% fuel. The CO_2 emissions decreased by 26.4%, 21.8%, 48.2%, 41.9% and 36.3% for the CNG60% substitution ratio. The same pattern was observed for CNG80% substitution ratio, and CO_2 emissions were reduced by 59.2%, 34.4%, 79.1%, 91.3% and 114.3% than D100% fuel combustion.

3.4. Nitrogen oxides emission

The formation of NOx is facet by the rich oxygen level, high cylinder temperature and long reaction time resulting from combustion. Generally, NO_X emission decreases in DF mode [28, 29]. In diesel/CNG DF combustion, the combustion process occurs in the lean, premixed regime due to increased Stoichiometric air/fuel ratio, decreasing the cylinder temperature and decreasing NO_X emission. For single diesel combustion, maximum fuel is burned as a diffusion flame near the stoichiometric equivalence ratio resulting in stoichiometric combustion producing higher NO_X due to higher combustion temperatures. Fig. 5 shows that NO_X emission decreases with increases in CNG substitution ratios compared to D100% combustion. At CNG40% DF combustion substitution ratio, NO_X emissions are reduced by 3.02%, 10.5%, 25.9%, 19.1% and 16.9% at all CR. The NO_X emissions were reduced by 222.3%, 207%, 204%, 103.4% and 52.7% for CNG60% substitution ratio DF combustion. The same pattern was observed for the CNG80% substitution ratio, and NO_X emissions decreased by 396.8%, 746.7%, 990%, 904% and 840.5%, respectively, compared to D100% fuel combustion at CR of 13:1 to 15:1.

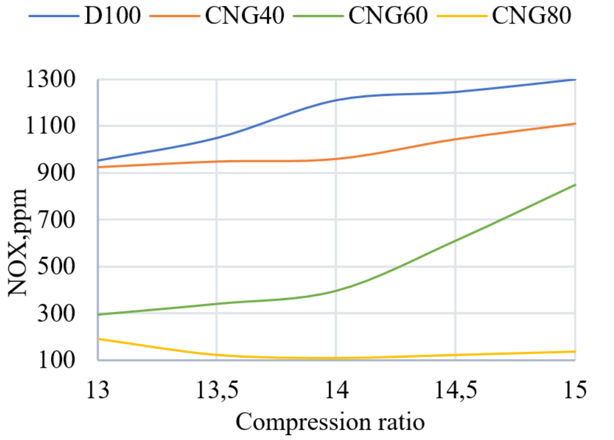

Fig. 5 Variation of NO_X emission versus compression ratio

3.5. Smoke emission

Fig. 6 shows that the smoke opacity changes for different CNG substitution ratios. The volume of liquid fuel injected is the most significant factor affecting the smoke opacity. A dual-fuel engine needs less diesel fuel since it replaces with a cleaner-burning CNG fuel and produces lower smoke. A higher CNG substitution ratio improves the fuel mixture combustion and lowers the C/H ratio, which leads to less smoke and more heat contribution from the CNG fuel. CNG's clean-burning gas quality helps reduce soot emissions and promotes soot oxidation at a higher CNG substitution ratio [30, 31]. Since CNG is mostly made of methane and belongs to the lower paraffin family, it does not tend to produce considerable soot. At a lower CNG substitution ratio, the heat input contribution of CNG fuel is reduced, and pilot liquid fuel raises the combustion carbon content and smoke levels compared to the high CNG substitution ratio. Fig. 6 demonstrates that as the CNG substitution increases, the smoke level decreases compared to D100% combustion. When the CNG40% substitution ratio is used in DF combustion, the smoke emissions are reduced by 35.2%, 64.7%, 14.2%, 38.6% and 50% at CR from 13:1 to 15:1 compared to D100% fuel combustion. The smoke emissions decreased by 17.1%, 16.6%, 23%, 16% and 125% for the CNG60% substitution ratio. Similarly, the same pattern was at the CNG80% substitution ratio, and the smoke emission was reduced by 68.4%, 194.6%, 33.5%, 55.3% and 350% than D100% fuel combustion for all CR.

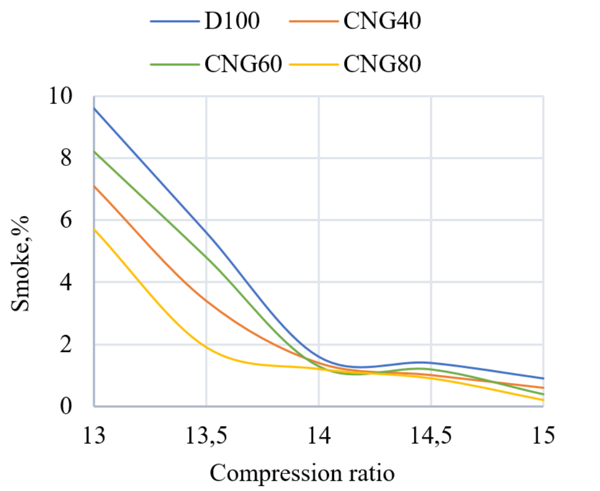

Fig. 6 Variation of smoke opacity versus compression ratio

4. Conclusion

The experiment investigates the effects of the CNG substitution ratio of CNG40%, CNG60%, and CNG80% in DF combustion and varying compression ratios from 13:1 to 15:1 of a CI engine to analyse the exhaust gas emissions characteristics. The investigation's main points are highlighted.

- Carbon Monoxide (CO) and hydrocarbon (HC) emissions were increased in DF combustion compared to single diesel fuel combustion. The substitution of CNG80% produced higher CO and HC emissions. When CNG is used more frequently, the equivalency ratios increase along with the CNG supply rate, which reduces the amount of liquid fuel and lowers the mixture's ignition temperature and spark energy. These facts increase CO and HC emissions in DF combustion compared to D100% combustion.
- The emission of CO_2 was lower in DF combustion than in pure diesel combustion at all CNG substitution ratios. CNG has a higher calorific value and lower carbon content making it a better alternative fuel to reduce CO_2 emissions than pure fuel diesel combustion. The maximum reduction of CO_2 emission was attained at the CNG80% substitution ratio at all CR.
- The amount of NOx and smoke emission in the exhaust gas is reduced when CNG is mixed with diesel fuel. At the CNG80% substitution ratio, the lowest NO_X and

smoke emissions were achieved. Higher CNG substitution ratio results in longer ignition delay times, slower flame propagation speeds, lower cylinder temperatures, and lower C/H ratios, which reduce NO_X emissions and smoke emissions during DF combustion.

Conflict of interest

The authors declare that they have no conflict of interest.

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EXPERIMENTAL EVALUATION OF CNG SUBSTITUTION RATIO ON EXHAUST GAS EMISSIONS OF DIESEL/CNG DUAL FUEL COMBUSTION

S u m m a r y

The addition of Compressed natural gas as a complement to diesel in compression ignition engines in dual-fuel combustion mode is a viable technology for increasing efficiency and lowering emissions. This work investigates the impact of a dual-fuel operating mode on the engine exhaust pollutant emissions of a diesel engine using compressed natural gas as the principal fuel and neat diesel as the pilot fuel. Compressed natural gas was injected into an intake manifold of a single-cylinder diesel test engine under different engine operating parameters, and up to 80% substitution was attained. And diesel fuel was injected after the compressed natural gas air mixture was compressed. The tests were carried out at five different compression ratios ranging from 13:1 to 15:1 in steps of 0.5:1. The experiment study revealed that injecting CNG into diesel engines via dual fuel combustion significantly impacted exhaust gas emissions compared to pure diesel combustion. The Carbon monoxide (CO) and hydrocarbon (HC) emissions were increased, while carbon dioxide (CO_2), nitrogen oxide (NO_X) and smoke opacity were decreased in dual fuel combustion compared to single diesel fuel.

Keywords: diesel, CNG, dual fuel, emissions, combustion.

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