CONSEQUENCES OF SUPPLEMENTING THE HHO GAS AND CNG WITH EGR ON DIESEL ENGINE CHARACTERISTICS

by

***Suja THANGARAJ*[a*] *and Nagarajan GOVINDAN*[b]**

[a] Department of Mechanical Engineering,
ThanthaiPeriyar Government Institute of Technology, Vellore, Tamilnadu, India
[b] Department of Mechanical Engineering, Internal Combustion Engineering Division,
College of Engineering, Anna University Chennai, Guindy, Tamil Nadu, India

Original scientific paper
https://doi.org/10.2298/TSCI211119058T

Water electrolyzed hydroxyl gas (HHO or Brown gas) and compressed natural gas (CNG) are the important and promising alternatives to the pure fossil fuels. The global concern is about GHG emission in the environment and ambient air pollution steered by mass consumption of fossil fuels in automobile industries and power sectors. In this study, the combustion, performance and emission characteristics of HHO gas and CNG mixtures supplied to intake manifold of compression ignition engine using diesel as a pilot fuel are studied. The same investigations are repeated with various exhaust gas re-circulation (EGR) proportions to study the impact of EGR on multi fuel mode (diesel + HHO gas + CNG) in a Diesel engine. The multi fueled engine performance, combustion and emission parameters are presented and compared with graph and analytical discussion. The results indicated that at full load, the NO_x emission decreased by 4% (without EGR), 18% (with 10% EGR) and smoke density decreased by 78% with multi fuel mode comparing to the pure diesel operation at constant speed of 1500 rpm. Also more enhanced performance by improving the brake thermal efficiency by 17%, reducing the brake specific energy consumption by 19%, resulted better fuel economy, and power due to better combustion.

Key words: *HHO gas, CNG, EGR, combustion, emission, performance*

Introduction

The crude and petroleum oil produced by organization of the petroleum exporting countries (OPEC) would not be able to meet the energy demands beyond 2045. The massive dependence and consumption of conventional fossil fuels has made a great and deep impact on energy security, natural climate, environmental conditions of human beings and even on living life of animals and plants. To preserve the quality of the environment and energy conservation, the researches have been turned towards alternate fuels yielding less or zero emission all over the world. Among all the other alternate fuels in internal combustion engines (ICE), natural gas, hydrogen, oxy-hydrogen have great importance as well as impact on both engine performance and exhaust emissions.

Natural gas is highly attractive and eco-friendly alternative fuel since it has a clean nature of combustion, produces almost zero smoke and PM, reduces the NO_x emissions by 50-80%. The 12.5% of world natural gas vehicle (NGV) population were in India and was

* Corresponding author, e-mail: sujaravi001@gmail.com

ranked 3rd in the world, USA and China were in top two places. The government of India (GOI) believes that increasing the country's natural gas consumption will help to meet the GOI objective of reducing dependency on crude-oil by 10% by 2022. Indian companies and researches are experimenting with many techniques to integrate natural gas into the transport industry.

Hydrogen is an energy carrier and it is available in chemically combined form with other water, fossil fuels, biomass*, etc.* It will be liberated with the electricity or heat energy input. The various methods used to produce hydrogen are reforming of carbonaceous sources, fuel cell type (low pressure and temperature steam methane reformers), membrane reactors for steam reforming, partial oxidation reformer, electrolysis of water*, etc.* Carbonaceous raw materials are utilized for hydrogen production of about 95% out of all other methodologies. About 4% is produced through electrolysis of water. The water electrolysis can be carried out in different ways namely alkaline water electrolysis, acidic water electrolysis. In this present work alkaline water electrolysis method is used to generate the oxy-hydrogen gas.

The EGR is the most prevalent technique employed for controlling the emission of oxides of nitrogen in ICE. In the EGR system, the exhaust gas is recycled into the intake along with fresh air. This technique replaces some of the inlet air with EGR, dilutes the inlet charge, and increases the heat capacity of the mixture by which reduces the peak temperature prevailing inside the combustion chamber that reduces the NO_x emission extensively.

Natural gas has the major drawback of slow burning velocity and poor lean burn ability leads to incomplete combustion. To resolve this issue, mixing the fuel which has high burning velocity with natural gas is found to be the best effective way. Hydrogen is an excellent supplementary fuel to natural gas there by complete combustion and lower emissions can be achieved. So, adding a small amount of hydrogen into CNG could enhance the combustion, performance, and emission characteristics of a compresion ignition (CI) engine.

Several researches have examined the CI engine using HHO/H_2 and natural gas as an additive to diesel and the outcomes from the experiments were absolutely promising. An experimental investigation on combustion, performance and emission analysis of a single cylinder, four-stroke Diesel engine using hydrogen in dual fuel mode of operation was conducted by Deb *et al.* [1]. The test results demonstrated a consistent improvement in brake thermal efficiency (BTE) of the engine, along with the reduction in brake specific energy consumption (BSEC) with increasing hydrogen energy share as compared to baseline diesel operation. Further, the emission of CO, CO_2, and smoke diminished with increasing energy share, the emission of NO_x and UHC showed an increasing trend with an increase in energy share.

Yadav *et al.* [2] studied the emission and performance characteristics of a direct injection, Diesel engine coupled to an electric dynamometer. Reduced emission levels alongside enhanced performance were obtained with hydrogen inducted with EGR system. It was found that the efficiency was increased by 2% with the supply of 40 g per hour of hydrogen without EGR and the combustion became uncontrolled at high rates of hydrogen and hence there was a reduction in thermal efficiency.

Sakhrieh *et al.* [3] conducted the experiment with HHO gas produced through electrolysis process on 4-cylinder, four-stroke CI engine. The researcher observed better engine performances at low engine speed of 2000 rpm with 1.4 Lpm flow rate and at high engine speed of 3800 rpm with 3 Lpm of HHO gas. He declared that the reduction of BSFC by 10.6% and 9.7 % for 1.4 Lpm and 3 Lpm flow rate of HHO gas, respectively and the volumetric contribution of HHO gas is varying from 4.8-14.2%.

Dahake *et al.* [4] used 1 Lpm of HHO gas along with diesel on 3.5 kW single cylinder four-stroke CI engine and observed improvement in BTE from 32.4-35.8% and reduction in BSFC from 0.27-0.22 kg/kWh, and also observed the emission impact as decrease of UHC from 54-32 ppm, decrease of CO from 0.06-0.04 vpl.% and increase of NO_x from 500-565 ppm at full load comparing baseline diesel and with HHO gas enrichment. The improvement in performance parameters are due to increase in overall calorific value and better mixing of hydroxy gas with air and better combustion. The reason for reduction in UHC and CO is due to absence of carbon in HHO structure. Better combustion due to HHO gas presence resulting peak in-cylinder temperature which leads to escalation in NO_x emission.

Kusaka [5] studied the Diesel engine characteristics with natural gas addition. In lieu of lean natural gas premixed, the efficiency was higher at maximum load and at minimum load emission of HC is higher and efficiency also reduced. Sharif *et al.* [6], conducted an experiment in a conventional four cylinder CI engine and modified to operate on gaseous hydrogen and CNG. He indicated that NO_x emission dropped down about 10 times that of neat diesel operation and also reported that combustion properties of hydrogen favoring to fast burning condition as in high speed engines.

Kasidet *et al.* [7] used the pilot diesel and hydrogen-CNG blend with specially designed closed loop stepping motor diesel to CNG dual fuel system and hydrogen electrolyzer for the engine. He observed the emission characteristics and indicated that the CO emission, HC emission and NO_x emission decreased from 0.33-0.28 g/km, 0.19-0.15 g/km, and 0.015-0.014 g/km at 2000 rpm, respectively comparing baseline diesel operation with dual fuel operation of diesel and hydrogen-CNG.

Karagoz *et al.* [8] investigated the performance and emissions of dual fuel Diesel engine running with hydrogen and diesel which were introduced through LPG-CNG injector. From the outcomes, significant reductions in CO and smoke emissions were observed by hydrogen substitution with a marginal increase in UHC. Addition of hydrogen showed increased values of peak in-cylinder pressure as compared to conventional diesel. Arat *et al.* [9] reported that HHO and HHO-CNG fuels improved the engine performance and exhaust emission greater extend. He also expressed that HHO and CNG fuel mixtures results more efficient combustion with reduced duration and lowered emissions.

Novelty and objective

It is understood from the open literature survey that the addition of compressed natural gas in dual fuel mode has negative effect on engine efficiency, CO and HC emissions particularly at low and medium load conditions. During higher loads, gaseous fuel utilization lead to improvement in both engine performance and exhaust emissions. When HHO gas is inducted to dual fuel CNG mode, the performance is improved to good extend with adverse increment in NO_x emission. To overcome the aforementioned, EGR along with the intake mixture of HHO and CNG in this research work to reduce NO_x emission. The novelty of this research work is to establish a fulfilled result with respect to performance and emission by this combination of CNG and HHO gas along with EGR without any major modification in a conventional CI engine. The investigations were taken under different cases (first case is neat diesel, second case is HHO + pilot diesel and third case are 40%CNG + HHO + pilot diesel and fourth case is 40%CNG + HHO + diesel + 5%EGR and fifth case is 40%CNG + HHO + diesel + 10%EGR and sixth case is 40%CNG + HHO + diesel + 15%EGR), compared and illustrated.

Materials and methods

The HHO generation methods and processes

Riis *et al.* [10] reported about various fossil, renewable and sustainable energy sources to generate HHO gas by utilizing processes like organic, electrolytic, photolytic, chemical and thermo-synthetic. It is explained about the various hydrogen generation processes in the previous article [11] and the HHO production in electrolysis process has been considered due to zero outflow of ozone harming substances and lesser operating expenses.

Table 1. Rate of hydrogen generation

	Silver	Hydrogen
Atomic weight	107.94	1
Valency	1	1
Chemical equivalent weight	107.94	1
Liberation/coulomb	0.001118 g	0.001118/107.94 = 0.000010357 g (Faraday's law)

Table 2. Details of brown gas generator

Parameters	Values
Physical dimensions [mm]	185 height × 51 Dia
Power source – battery	12V 10A DC
Chemical catalyst used	Sodium hydrogen carbonate ($NaHCO_3$)
Electrode material used and size	Surgical grade steel (SG-135). 95.3 mm × 25.4 mm × 1.2 mm
Electrodes configuration	–NNNNNN+
Number of electrodes and water cell	8 electrode and 7 water cell
Volts per water cell	1.7143 V
Electrolyte concentration	2 g of $NaHCO_3$ per liter of distilled water
Amount of electrolyte	340 ml

During the electrolysis process, water is getting spilt as oxygen and hydrogen as per faraday's law by inputting electricity. The 1.7 V electricity is minimum required per unit cell for $NaHCO_3$ electrolyte [12] and the same was used in our experiment. From the book *The chemistry and manufacture of hydrogen* [13], hydrogen generation can be derived by comparing with silver deposition in electrolysis process. From the tab. 1, hydrogen generation mass can be expressed as *0.000010357 A* (A – ampere and t – seconds). The details of Brown gas generator and the rate of hydrogen generation are given in the tabs. 2 and 3, respectively. The dimensions are adopted such that to get optimum results based on both power consumption as well as HHO generation.

Experimental set-up

This experimental study was carried out in internal combustion engine laboratory at Anna University, Chennai India. In this tests, CNG was injected and HHO gas was inducted into diesel engine with substitution of diesel fuel to initiate the ignition. Specification of engine is given in tab. 4.

Table 3. Rate of HHO gas generation

Particulars	Expression
Expression for hydrogen generation by electrolysis process	0.000010357 At [g]
Hydrogen generation by one ampere minute	0.000010357*x*1*x*60 = 0.00062 g per minute
Rate of hydrogen generation (density of H_2 = 0.0898 g/l)	0.00062142/0.0898 = 0.0069 Lpm
In this experiment, 10 amps and 7 water cells are used. Hence the rate of hydrogen generation	0.0069*x*10*x*7 = 0.4844 Lpm
Rate of oxygen generation (half of the hydrogen generation)	0.2422/2 = 0.2422 Lpm
Rate of HHO generation	0.4844 + 0.2422 = 0.73 Lpm

Table 4. Engine specification

Parameter	Specifications
Make and model	Kirloskar, AV1
Bore and stroke	80 mm × 110 mm
Swept volume	553 cc
Compression ratio	16.5: 1
Clearance volume	36.87 cc
Rated output	3.7 kW at 1500 rpm
Injection timing	24° bTDC
Combustion chamber	Hemispherical open type
Weight of flywheel	33 kg
Connecting r od length	235 mm
Valve dia and max lift	33.7 mm and 10.2 mm
Injection nozzle	BOSCH, 3 hole nozzle, 116º spray angle

An electrical model hydraulic dynamometer was used for loading the test engine and Horiba-Mexa 584 gas analyzer was used to measure exhaust gas emission. Data output of crank angle encoder and pressure transducer were collected via data logger and were transferred to computer for further processing. Diesel fuel was injected at 24 °bTDC and diesel fuel amount is controlled by fuel pump plunger. All the engine set-up, test apparatus and measurement device are illustrated schematically with detailed lay-out in the figs. 1-4.

Intake air phenomenon is an important task in ICE since the combustion purely depends on the supply of right amount of adequate air into the combustion chamber. Gaseous fuels require lean combustion operation. Air fuel ratio (AFR) and equivalent ratios are influenced by intake air properties and mixtures of fuel supplied to the engine. The HHO and natural gas mixtures have a great impact on both performance and emissions when working on lean conditions. The experimental set-up was equipped with fire and flame arrester for safety. Pressure gauge and rotameter were installed to control CNG pressure to three bar and to measure flow rate, respectively, [14-18].

Karim *et al.* [19], reported clearly that if constant AFR is not maintained by adjusting the amount of hydrogen supply, cylinder temperature increases for both SI engine and CIE due to high reactivity of hydrogen fuel. Thus HHO addition extends the lean limit of the engine by replacing the air under various testing conditions.

Thus, the replacement of intake air by HHO and CNG gases tend not only to lean burn operation, but also lowering the engine emissions. All the tests were conducted when the engine was loaded between 0 kW and 3.75 kW with the constant speed of 1500 rpm. Three trials of experiments were performed, and an average test data had been selected to achieve an optimized results with lesser errors. Engine performance, combustion and emission parameters were calculated, measured and compared each other for previously represented six cases.

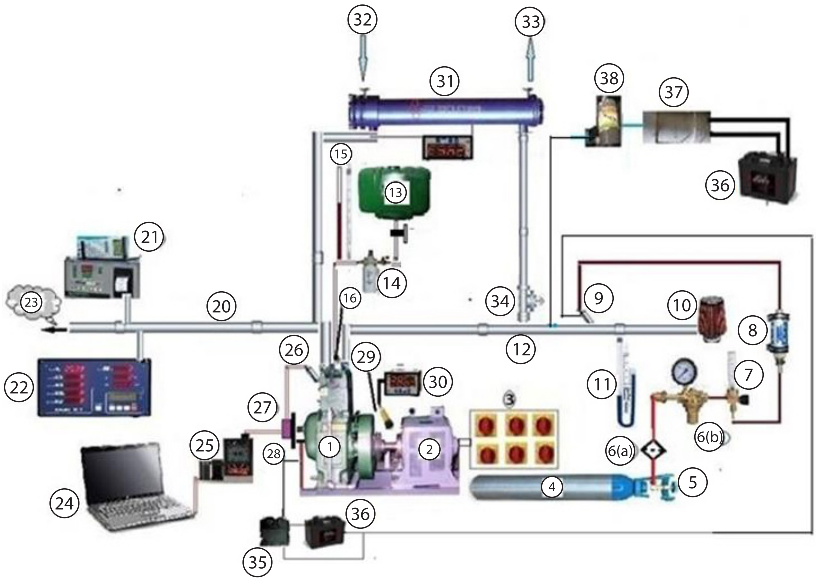


Figure 1. Schematic diagram of experimental set ups: *1 – Diesel engine, 2 – generator, 3 – electrical loading device, 4 – CNG cylinder, 5 – CNG valve, 6(a) – filter and 6(b) – pressure regulator, 7 – rotameter, 8 – flame and fire arrester, 9 – CNG injector, 10 – intake air filter, 11 – U-tube manometer, 12 – intake manifold, 13 – diesel fuel tank, 14 – fuel filter, 15 – burette, 16 – fuel injector, 20 – exhaust gas manifold, 21 – smoke meter, 22 – exhaust gas analyzer, 23 – exhaust gas, 24 – computer, 25 – data acquisition system, 26 – pressure sensor, 27 – crank encoder, 28 – cam position sensor, 29 – rpm sensor, 30 – rpm digital meter, 31 – EGR, 32 – cooling water in, 33 – cooling water out, 34 – exhaust gas control valve, 35 – ECU, 36 – vattery, 37– HHO gas generator, and 38 – safety filter and fire arrestor*

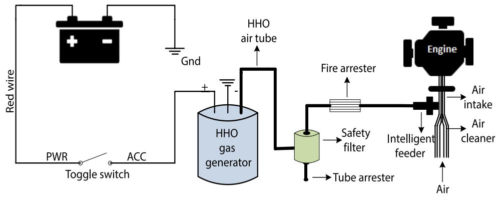


Figure 2. Browns gas (HHO) generation lay-out

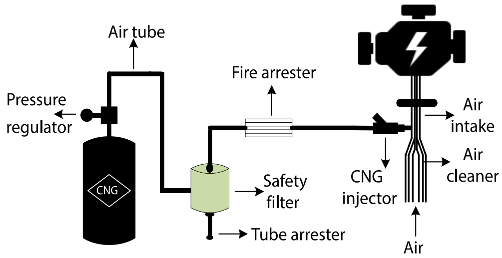


Figure 3. The CNG injection circuit

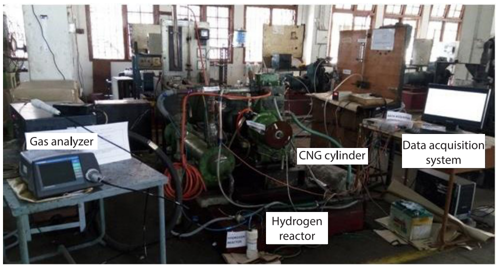


Figure 4. Photographic view of experimental lay-out

Result and discussions

Experimental investigation was carried out using diesel fuel along with constant 40% energy share of CNG and constant 0.73 Lpm flow rate of HHO gas with various EGR rates in a Diesel engine. Firstly, the engine was run with only diesel and heat input, Q_s, required for minimum load (25% = 1.1 kW) to maximum load (100% = 3.7 kW) were calculated based on the consumption of diesel. In this case Q_s for 25% load is 24366 kJ/h and 100% load are 65790 kJ/h. After understanding the heat input required for all the load, CNG flow rate was adjusted for minimum load to maximum load in order to ensure 40% energy share. In this case 5 Lpm CNG is used for 25% load to get 9750 kJ/h heat input and 13 Lpm is used for 100% Load to get 26316 kJ/h. The HHO gas energy share varies from 4-10% from minimum to maximum load. The CNG dual fuel operation exhibited reduction in emissions and the performance was poor particularly at lower and medium BMEP. Hence, in this investigation enhance the performance and reduce the emissions of the CNG dual fuel engine, generated HHO gas was added along with CNG in the intake manifold to study the influence of combined effect of both the gaseous fuels where diesel was used as a pilot fuel. In the experimentation, EGR of 5%, 10%, and 15% was employed. The 10% EGR gave better results compared to 5% and 15% of EGR and the results are presented for 10% EGR and compared with neat diesel and diesel enriched with HHO and CNG operation.

Performance characteristics

Brake thermal efficiency

Figure 5 depicts the variation of BTE with brake mean effective pressure (BMEP) in diesel + CNG + HHO operation with 10 % EGR. When the Diesel engine is fuelled with CNG + HHO gas, the efficiency is improved by 21% at 1.5 bar BMEP and 17% at 5.4 bar BMEP compared to diesel fuel. The BTE is observed as 23%, 25%, 27%, and 26% for diesel, diesel + CNG, diesel + CNG + HHO and diesel + CNG + HHO + 10%EGR operations, respectively at 5.4 bar BMEP. The hydrogen present in the HHO gas (octane number of hydrogen: 130) has the effect of increasing the octane index of the fuel added to it. The CNG also has high octane number of 120. When CNG was added with 0.73 Lpm of HHO gas along with high ce-

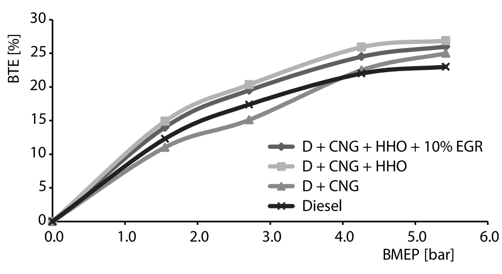


Figure 5. The BTE with BMEP

tane rated diesel (cetane number: 49), the mixture gives improved and better performance and reduce the cyclic variations [20]. Higher octane number fuel gives out more power due to better combustion.

The BTE is an indication of converting the chemical energy of the fuel into brake power. The fuel mixture diesel + CNG + HHO gas has a good capability to convert the chemical energy possessed by the fuel into brake power output. The results show that D + CNG + HHO combination improves the efficiency by 17% and 8% compared to diesel operation and D + CNG operation, respectively at 5.4 bar BMEP.

Although, CNG fuel offered lesser efficiency during lower BMEP, due to the superior flame speed and reactivity of the HHO gas, higher calorific value of hydrogen molecules present in the HHO gas causes an improvement in the efficiency in the case of D + CNG + HHO. The gaseous fuels were inducted during the suction stroke, hence, better mixing was achieved which makes the fuels to get burnt clean that would result in enhanced efficiency. Effective participation of CNG gaseous fuels during higher mean effective pressure is an added advantage that led to improve the efficiency.

With 10% EGR, it is observed that the efficiency is decreased up to 6% compared to D + CNG + HHO operation at all mean effective pressures due to the deficiency in oxygen and higher specific heat of inert gases CO_2 and H_2O.

Brake specific energy consumption

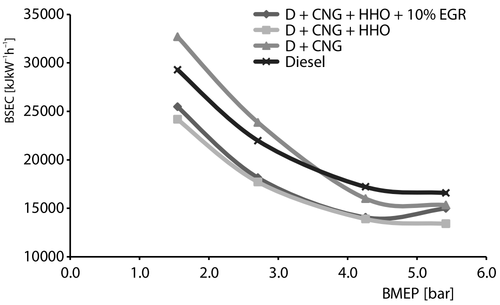


Figure 6. The BSEC with BMEP

Figure 6 delineates the variation of BSEC with BMEP in CNG and HHO enriched diesel fuel with EGR. At the maximum BMEP of 5.4 bar, the BSEC is highest in Diesel operation (16571 kJ/kWh), while it is lowest in the case of D + CNG + HHO (13397 kJ/kWh). Compressed natural gas has the characteristics of slow burning velocity and poor ability to burn during lean mixture condition which leads to incomplete combustion. Hence, it is an effective way to mix the CNG fuel with high burning velocity HHO gas that would result in improved combustion. Adding a small amount of hydrogen into natural gas can improve the combustion characteristics and reduce brake specific energy consumption [9, 21].

When HHO gas is added in dual fuel operation, significant reduction is observed in specific energy consumption due to active participation of HHO gas that would enhanced the combustion by its rapid flame speed and high reactivity with clean burn characteristics. From fig. 6, it can be observed that the BSEC of D + CNG + HHO operation is decreased by 19% and 13% compared to diesel operation and D + CNG operation, respectively at 5.4 bar BMEP. In D + CNG + HHO operation, combustion becomes more efficient by absorbing lesser energy from the fuel air mixture. The trend is same at all BMEP which shows the contribution of HHO gas during the combustion process. It is observed that the supplementation of 10% EGR, results in increased BSEC in the case of D + CNG + HHO with EGR compared to CNG and HHO enriched diesel fuel. The increase in BSEC is attributed to reduced oxygen availability which deteriorates the combustion process and this effect becomes more substantial because of the presence of hydrogen molecules in HHO gas which produces water on oxidation and thus reducing the temperature of the cylinder by dilution effect.

Combustion characteristics

Figures 7-10 elucidates the variation of cylinder pressure with crank angle, variation of heat release rate (HRR) with crank angle, adiabatic temperature and exhaust gas temperature, respectively, for various fuel mixture experimented at full load.

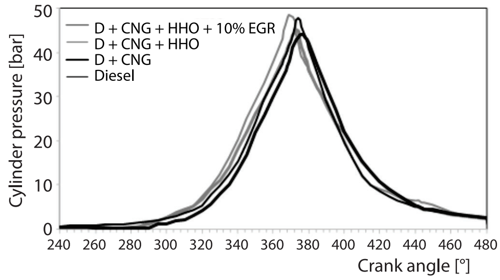


Figure 7. In-cylinder pressure *vs.* crank angle for variuos fuels combinations at full load

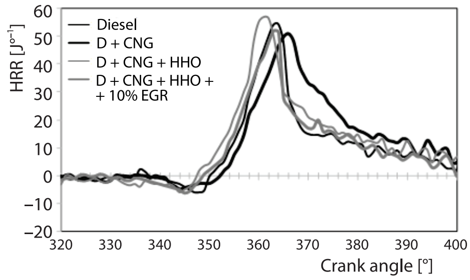


Figure 8. Heat release rate *vs.* crank angle for various fuels combinations at full load

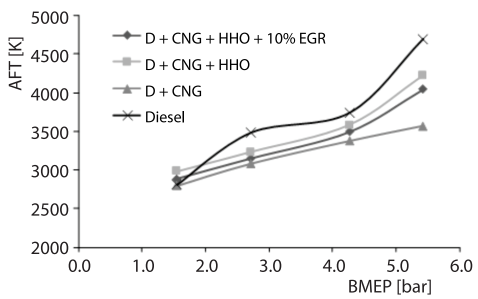


Figure 9. Adiabatic temperature of the fuel maixture combination with BMEP

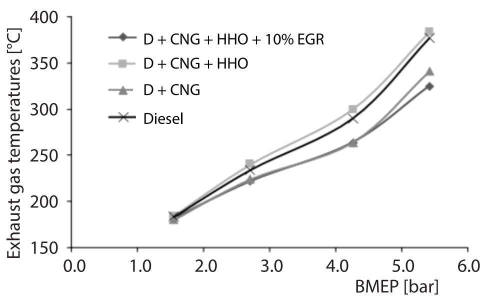


Figure 10. Exhaust gas temperature of the fuel maixture combination with BMEP

The CNG dual fuel operation shows de-escalated peak pressure and HRR occurrence compared to diesel due to slow burning velocity, lower *C*/*H* ratio and thus increased specific heat of the mixture. The HHO gas is an excellent additive to CNG for improving the burning characteristics. The elevated laminar flame speed in D + CNG + HHO mode enables increased cylinder pressure, HRR and temperature. It is observed that the peak pressure and HRR are declined when CNG is added with diesel, however the peak pressure and HRR rises in HHO enriched CNG operation because of the higher flame speed of hydrogen present in the HHO gas. Both the gaseous fuels are inducted into the intake manifold during the suction stroke and have adequate time to mix with air. In the premixed phase, both the gaseous fuels help in igniting the air-fuel mixture followed by the rapid flame propagation stimulated by hydrogen. The flame establishment and development are influenced by HHO gas than CNG. Thus there is an increase in HRR and hence BTE. The HHO gas not only reduces the GHG and atmospheric pollutants, but also enhances the combustion characteristics of the engine by higher HRR. Hydrogen available in the HHO gas reduces the equivalence ratio to lean limit of combustion of natural gas without increasing the combustion duration, resulting in higher thermal efficiency and lowering the emission levels.

Because of the presence of hydrogen, the thermal effect and dilution effect is dominating than the chemical effect with 10% EGR. The mixture is diluted with molecules of CO_2, N_2, and water vapour produced by the oxidation of hydrogen in HHO gas. Thus, the air-fuel mixture is diluted, and the specific heat capacity of the mixture is increased which marginally reduces the peak pressure and HRR.

Adiabatic flame temperature (AFT) was determined as detailed in the [22]. The AFT is the maximum temperature will be obtained during combustion process and the value is based on combustion process, fuel chemistry and pressure. The AFT was observed as 4694 K, 3568 K, 4225 K, and 4044 K for diesel (D), D + CNG, D + CNG + HHO and D + CNG +HHO + 10%EGR, respectively, at full load. It was understood CNG addition reduces the AFT and addition of HHO gas escalate the AFT due to better combustion of fuel oxygen mixture. The implication of AFT communicates the fuel quality aspects. Exhaust gas temperature increase with respect to increase in BMEP. The EGR addition marginally contributes decrease in exhaust gas temperature.

Figures 11-13 details the in-cylinder pressure profile, HRR profile and temperature profile, respectively, during compression and combustion phase for Diesel + CNG + HHO operation for various load conditions. Peak pressure was noticed as 48.4 bar, 47.5 bar, 45.4 bar, and 37 bar, peak HRR was 56.8, 44.2, 40.1 and 36 J per crank angle and peak temperature was 919 K, 914 K, 902 K, and 851 K for 100%, 75%, 50%, and 25% load, respectively. The HHO gas addition improves the peak pressure and HRR. The engine characteristic is assessed based on peak value of pressure and HRR and how closer to TDC. Air-fuel ratio diminishes based on load increase, thus fuel supply increases resulting in shorter delay period and temperature rise.

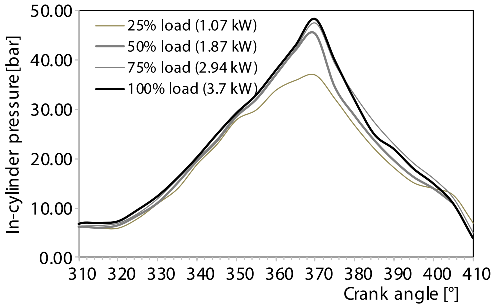


Figure 11. In-cylinder pressure profile during compression and combustion phase for D + CNG + HHO operation

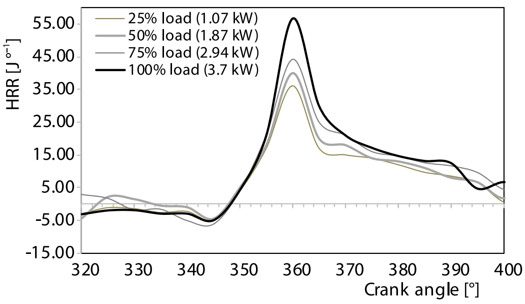
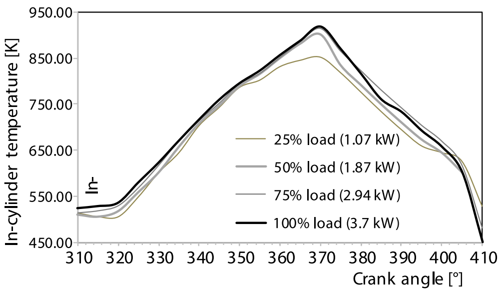


Figure 12. The HRR profile during compression and combustion phase for D+CNG+HHO operation



Figire 13. Temperature profile during compression and combustion phase for D + CNG + HHO operation

Emission characteristics

Oxides of nitrogen

Figure 14 displays the variation of emission of NO_x with respect to BMEP in CNG +HHO gas enriched diesel fuel with EGR. Generally, NO emission is influenced by specific heat capacity of the air, availability of oxygen in the intake mixture and the combustion temperature [23] . The emission of NO_x can be reduced either by reducing the hydrogen or by increasing the CNG measure or by increasing the EGR rate. In D + CNG + HHO operation, at highest BMEP of 5.4 bar, the NO_x discharge level is observed as 460 ppm which is 5.7% lower than diesel operation (488 ppm) and an increase of 4.1% is observed compared to D + CNG (442 ppm) dual fuel mode as shown in fig. 14.

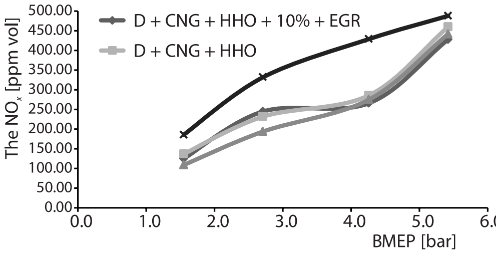


Figure 14. The NO_x with BMEP

By enabling the rapid burning rate by widening the flammability limit, HHO increases the NO_x emission, while the presence of methane in CNG counteracts this effect by its slow burning characteristics and thus reducing the temperature. In CNG dual fuel operation, CNG replaces the diesel fuel consumed by the engine to attain the rated speed. Thus, the quantity of diesel and the carbon hydrogen ratio (*C*/*H* ratio) are decreased because of lower carbon content of CNG. Combustion of carbon is one of the main factors which increase the cylinder temperature. These effects reduce the cylinder temperature and reflected positively on the emission of NO_x. Whereas, HHO increases the NO_x emission [11]. The increase in NO_x emission compared to D + CNG operation could be mainly due to effective participation of HHO gas and lower density (0.768 kg/m^3) of hydrogen present in HHO gas and this effect becomes significant at higher BMEP. This is the combined effect of diesel and HHO which increases the total energy released, and the faster combustion rates produced by hydrogen that is present in the HHO gas.

With EGR at the rate of 10%, it exchanges the oxygen with CO_2 and H_2O, the temperature is reduced thereby decrements the emission level. Further increase in the percentage give added advantage in the light of discharge level. The NO_x emission observed in D + CNG + + HHO + 10%EGR is 428 ppm which is lower by 12.3% compared to neat diesel operation and 7% compared to D + CNG + HHO operation at 5.4 bar BMEP.

Unburned hydrocarbon and CO

Figures 15 and 16 shows the emission pattern of UHC and CO with respect to BMEP in CNG + HHO gas enriched diesel operation with EGR. The addition of CNG at a constant energy share of 40% to diesel fuel shows a considerable increase in the CO and UHC emission due to poor utilization and oxidation with natural gas. However, a significant decreasing trend at higher BMEP is observed in CNG dual fuel operation as more amount of fuel experiences a complete combustion at high temperature and pressure. The rate of formation of CO is the function of availability of unburned fuel particles in the exhaust and mixture temperature, both of which control the rate of fuel decomposition and oxidation. These factors have to be optimized in dual fuel operation that helps in the reduction of CO emission [24]. From figs. 15 and 16, it is evident that CO and hydrocarbon emissions decrease with the introduction of HHO gas along with CNG injection in Diesel engine. This is due to the flame speed and diffusivity of hydrogen are higher and facilitates towards the complete combustion [25].

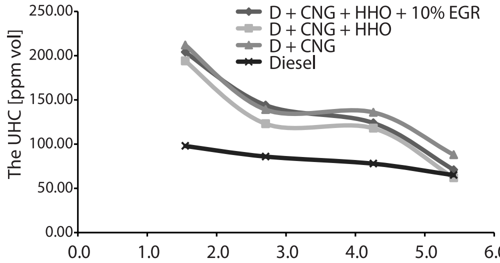


Figure 15. The UHC emission with BMEP

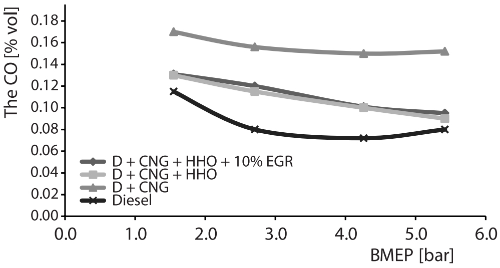


Figure 16. The CO emission with BMEP

The emissions of CO and UHC are considered to be the by-product of incomplete combustion of fuels. The CO and UHC emissions increase when CNG is added and decreases with hydrogen content. The slow burning velocity of methane in CNG and utilization of gaseous fuel is not effective, flame quenching of methane leads to incomplete combustion which produces higher amount of CO and UHC emissions in D + CNG operation. But addition of hydrogen in HHO gas broadened the flammability limit of methane and increase the flame velocity which helps in improved combustion that reduces CO and UHC emission. Hydrogen available in HHO leads to enhanced combustion attributed by faster reaction rates, high heat flux, higher flame velocity and diffusion rate converts the UHC to burn and oxidized [26].

The CNG and HHO enriched Diesel engine with EGR further increases CO and UHC emissions due to deficiency of oxygen in the engine and thus the combustion is deteriorated.

Smoke opacity

Figure 17 shows the variation of smoke opacity with respect to BMEP in CNG + HHO gas enriched diesel fuel with EGR. Smoke opacity means the degree to which the smoke blocks the passage of light. It means more smoke in exhaust emission would have greater smoke opacity and *vice versa* in the context of diesel emissions. The smoke emission in a diesel is higher than D + CNG operation. Since CNG contains higher proportion of methane, it does not produce particulate like combustion of the liquid fuel. With D + CNG + HHO, smoke emission drops as 6.4-16 % compared to diesel value of 16-74% from minimum to maximum mean effective pressures. This is likely as a result of non-productivity of smoke particles by homogeneous operation of both the gaseous fuels. Examining the fig. 17, it is observed that association of CNG and HHO gaseous fuel is a potential way for reducing smoke emission. With 10% EGR, smoke emissions decrease marginally. The reduction in smoke emission with 10% EGR is attributed to clean burning characteristics of gaseous fuels which makes homogeneous combustion and thus smoke opacity decreases.

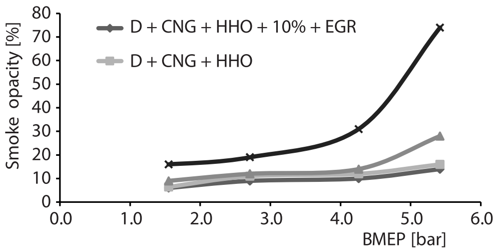


Figure 17. Smoke opacity with BMEP

Trade off study

Figure 18 and 19 show the trade-off study between BSEC with NO_x and smoke opacity with NO_x for diesel fuel enriched with both constant mass-flow rate of HHO and constant energy share of CNG at full load.

The characteristics chosen for trade-off study had proved that a close relation exists between the energy consumption and NO_x emission because when the EGR acts as a suppressing agent, it reduces the NO_x emission simultaneously origins an increase in fuel consumption. From the figs. 18 and 19, it is clear that HHO gas lessens BSEC and smoke by increasing the chemical reaction amid the fuels over its high diffusivity and increment in NO_x. When EGR is introduced, NO_x are decreased. From the trade-off study, it is understood that CNG and HHO enriched diesel operation with 10% EGR would agreements with no compromise in performance of BSEC and emission of NO_x and smoke.

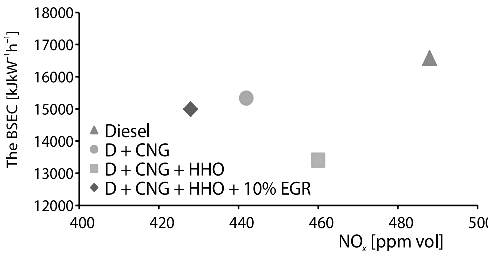


Figure 18. The BSEC and NO_x

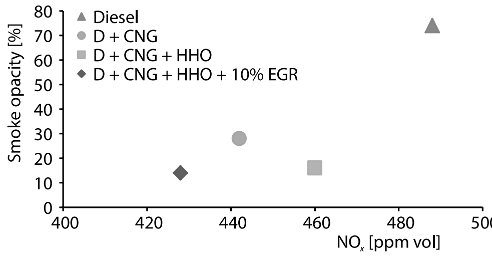


Figure 19. Smoke opacity and NO_x

Conclusion

The addition of constant share of CNG into the Diesel engine diminishes the temperature and pressure inside the cylinder resulting in lower NO_x emission and performance. However, this effect is overweighed by the introduction of constant flow rate of HHO gas resulting an increase in NO_x and improved performance. With EGR supplementation, the negative impact of HHO gas on NO_x is improved. The overall performance and emission characteristics are better in diesel with CNG and HHO gas when compared with neat diesel operation. The commercial vehicles industry can adopt the HHO gas generator experimented in this research work easily to improve the operating cost.

References

[1] Deb, M., *et al*., An Experimental Study on Combustion, Performance and Emission Analysis of a Single Cylinder, 4-Stroke DI-Diesel Engine Using Hydrogen in Dual Fuel Mode of Operation, *International Journal of Hydrogen Energy*, *40* (2015), 27 pp. 8586-8598

[2] Vinod, S. Y., *et al*., Performance and Emission Studies of Direct Injection CI Engine in Duel Fuel Mode (Hydrogen-Diesel) with EGR, *International Journal of Hydrogen Energy*, *37* (2012), 4, pp. 3807-3817

[3] Sakhrieh, A. H., *et al*., Optimization of Oxyhydrogen Gas-Flow Rate as a Supplementary Fuel in Compression Ignition Combustion Engines, *Internation J. Heat Technol.*, *35* (2017), 1, pp. 116-122

[4] Dahake, M. R., *et al*., Effect of Hydroxy Gas Addition on Performance and Emissions of Diesel Engine, *Int. Res. J. Eng. Technol*., 03 (2016), 01, pp. 756-760

[5] Kusaka, J., Combustion and Exhaust Gas Emission Characteristics of a Diesel Engine Dual-Fueled with Natural Gas, *JSAE Review*, *21* (2000), 4, pp.489-496

[6] Sharif, M., *et al*., Performance and Combustion Characteristics of a Diesel Engine Operated on Dual Fuel Mode CNG and Hydrogen, *International Journal on Mechanical Engineering and Robotics*, *3* (2015), 4, pp. 2321-5747

[7] Kasidet, P., *et al*., Emission Characteristics of Using HCNG in the Internal Combustion Engine with Minimum Pilot Diesel Injection for Greater Fuel Economy, *International Journal of Hydrogen Energy*, *39* (2014), 23, pp. 12182-12186

[8] Karagoz, Y., *et al*., Effect of Hydrogen Enrichment on Combustion Characteristics, Emissions and Performance of a Diesel Engine, *International Journal of Hydrogen Energy*, *41* (2016), 1, pp. 656-665

[9] Arat, H. T., *et al*., Effect of Using Hydroxy-CNG Fuel Mixtures in a Non-Modified Diesel Engine by Substitution of Diesel Fuel, *International Journal of Hydrogen Energy*, *41* (2016), 19, pp. 1-10

[10] Riis T., *et al*., *Hydrogen production R&D Priorities and Gaps*, International Energy Agency (IEA), Head of Publications Service, OECD/IEA, Paris, France, 2015

[11] Suja, T., Nagarajan, G., Investigating the Pros and Cons of Browns Gas and Varying EGR on Combustion, Performance, and Emission Characteristics of Diesel Engine, *Environmental Science and Pollution Research*, *25* (2018), Nov., pp. 422-435

[12] Yadav Milind, S., *et al*., Investigations on Generation Methods for Oxy-Hydrogen Gas, It's Blending with Conventional Fuels and Effect on the Performance of Internal Combustion Engine, *Journal Mech. Eng. Res*., *3* (2014), 9, pp. 325-332

[13] Teed, P. L., *The Chemistry and Manufacture of Hydrogen*, Longmans, Green and Company, London, UK, 2019
[14] Firmansyah, A. A., Heikal, M., The Combustion Behavior of Diesel/CNG Mitures in a Constant Volume Combustion Chamber, *Proceedings*, IOP Conference Series: Materials Science and Engineering, Pahang, Malaysia, 2015, Vol. 100, pp. 012-032
[15] Ryu, K., Effects of Pilot Injection Timing on the Combustion and Emissions Characteristics in a Diesel Engine Using Biodiesel-CNG Dual Fuel, *Applied Energy*, *111* (2013), Nov., pp. 721-730
[16] Namasivayam, A. M., *et al*., Biodiesel, Emulsified Biodiesel and Dimethyl Ether as Pilot Fuels for Natural Gas Fuelled Engines, *Applied Energy*, *87* (2010), 3, pp. 769-778
[17] Basavarajappa, Y. H., Banapurmath, N. R., Effect of CNG Manifold Injection on the Performance, Combustion and Emission Characteristics of a CNG-Biodiesel Dual Fuel Operation, *International Journal of Automotive Engineering and Technologies*, *4* (2015), 4, pp. 223-244
[18] Patil, M., Arakerimath, D., Analysis of Exhaust Emission, and Performance Characteristics of Single Cylinder CIEngine Fuelled With Palm Oil and CNG', International Journal of Innovative Research in Science, *Engineering and Technology*, *04* (2015), 01, pp.18556-18562
[19] Karim, G. A, *et al*., Methene-Hydrogen Mixtures as Fuels, *International Journal of Hydrogen Energy*, *21* (1996), 7, pp. 625- 631
[20] Orhan, M. F, *et al*., Integrated Hydrogen Production Options Based on Renewable and Nuclear Energy Sources, *Renew Sustain Energy Rev*., *16* (2012), 8, pp. 6059-6082
[21] Mallikarjun, B., *et al*., Effect of Hydrogen and Hydrogen Enriched Compressed Natural Gas Induction on the Performance of Rubber Seed Oil Methy Ester Fuelled Common Rail Direct Injection (CRDi) Dual Fuel Engines, *European Journal of Sustainable Development Research*, *1* (2017), 2, pp. 1-12
[22] Ganesan, V., Air Standard Cycles and Their Analysis, in: *Internal Combustion Engine*, 12^{th} Reprint 2006, Published by Tata McGraw-Hill, New Delhi, India, Chapter 3, 2006
[23] Ying, W., Longbao, Z., Experimental Study on Exhaust Emissions from a Multi-Cylinder DME Engine Operating with EGR and Oxidation Catalyst, *Applied Thermal Engineering*, *28* (2008), 13, pp. 1589-1595
[24] Papagiannakis, R. G., Hountalas, D. T., Experimental Investigation Concerning the Effect of Natural Gas Percentage on Performance and Emissions of a DI Dual Fuel Diesel Engine, *Applied Thermal Engineering*, *23* (2014), 3, pp. 353-365
[25] Talibi, M., *et al*., Effect of Hydrogen-Diesel fuel co-Combustion on Exhaust Emissions with Verification Using an in-Cylinder Gas Sampling Technique, *Int. J. Hydrog Energy*, *39* (2014), 27, pp. 15088-15102
[26] Saravanan, N., Nagarajan, G., Performance and Emission Study in Manifold Hydrogen Injection with Diesel as an Ignition Source for Different Start of Injection, *Renewable Energy*, *34* (2009), 1, pp. 328-334

Paper submitted: November 19, 2021
Paper revised: January 15, 2022
Paper accepted: March 9, 2022