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Citation

ANUPONG, Wongchai, Ruangwong ON-UMA, Kumchai JUTAMAS, Beáta GAVUROVÁ, Arunachalam CHINNATHAMBI, Tahani Awad ALAHMADI, Manigandan SEKAR, Kathirvel BRINDHADEVI, and Arivalagan PUGAZHENDHI. Utilization of enriched hydrogen blends in the diesel engine with MgO nanoparticles for effective engine performance and emission control. *Fuel* [online]. vol. 334, Elsevier, 2023, [cit. 2024-02-01]. ISSN 0016-2361. Available at https://www.sciencedirect.com/science/article/pii/S0016236122033762

DOI

https://doi.org/10.1016/j.fuel.2022.126552

Permanent link

https://publikace.k.utb.cz/handle/10563/1011259

Utilization of enriched hydrogen blends in the diesel engine with MgO nanoparticles for effective engine performance and emission control

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ABSTRACT

The influence of hydrogen on the diesel engine has been examined in this study. In addition, the impact of MgO nanoparticles was also analysed by conducting a series of tests on samples such as Diesel (100 % diesel), DN (Diesel-50 ppm MgO), H1N (10 % Hydrogen-50 ppm MgO) and H2N (20 % Hydrogen-50 ppm MgO). Hydrogen was injected through intake manifold at the volume of 10 % and 20 %. Nanoparticles were dispersed using the ultrasonication techniques to accrue stable suspension. The experiments were conducted between 6 N-m to 24 Nm loads on a four-stroke single cylinder engine. The parameters such as brake thermal efficiency (BTE), brake specific fuel consumption ($BSFC$), and heat release rate (HRR) were assessed. In addition to the performance and combustion, the environmental impact of the test blends was also analysed by examining the exhaust with a gas analyser. From the series of tests, it was evident that hydrogen enrichment in the test blends reported lower levels of emissions compared to neat diesel. The formation of the hydrocarbons (HC), nitrogen of oxides (NOx), carbon monoxide (CO), and carbon dioxide (CO2) was reduced due to the drop in the carbon atoms and enriched oxygen content in the combustion chamber. With regard to the performance, the hydrogen enriched nanoparticle blends reported peak BTE (37 %) and HRR (75 J/deg) than the other test blends. By assessing all the results, the addition of hydrogen is a potential option to reduce the environmental impact created by the fossil fuel without forfeiting the engine efficiency.

Keywords: Hydrogen, combustion, nanoparticles, emission of pollutants, fossil fuel

1. Introduction

Conventional fossil fuels and internal combustion engines play a major role in today's transportation and power systems. The inherent advantages of diesel engines, such as their high power-to-weight ratios and efficiency values, mean that they remain a dominant energy resource. The catastrophic effects of pollution and fossil fuel scarcity have prompted the demand for clean energy sources [**1**,**2**]. The automotive and power industries are responsible for the majority of pollution in the atmosphere across the world. Researchers have been exploring for better forms of energy to power the automotive sector for the last several decades. The period has passed when a nation's developmental needs were solely determined by the quantity of energy available [**3-5**]. Now, the time has come to consider more sustainable, environmentally friendly, and efficient energy sources. There is a thriving market for clean energy because fossil fuels are running out quickly and vehicles are generating more pollution. In this scenario, H_2 seems to be a good source of renewable energy for the world today. H_2 is a better source of fuel than diesel or any other fuel that isn't green. H_2 has a lot of advantages, like a vast scope of flammability limits and quick flame spread, which make it possible for the engine to run even at optimized stoichiometric ratio [**6-8**]. Numerous researchers have worked with H_2, and a substantial amount of literature exists on its uses. However, the main problem with H_2 based on previous studies is increase in the emission of nitrogen of oxide. Leaner operation reduces the amount of fuel used, which makes the engine more efficient and cleaner, however, these conditions affect the engine performance when they are operated with conventional blends. A hydrogen vapour cloud created under equivalent conditions may have a greater combustible volume than a liquid fuel cloud. Additionally, an engine can start on a lean mixture of hydrogen due to its lower ignition energy than other fuels. There is a possibility that this will result in pre-ignition, and the flame will return to the hydrogen cylinder. A flashback arrester can be used to prevent the occurrence of a flashback [**9-11**].

Nanoparticles were used widely to enhance the characteristics of diesel. The high surface area and strong reactivity of nanoparticles are two of the most significant advantages of this technology. Adding nanoparticles to biodiesel blends has been proven to greatly increase the combustion efficiency and reduce emissions [**12**,**13**]. Yousof et al. investigated the effects of nanoparticles such as copper oxide (CuO), zinc oxide (ZnO), carbon nanotubes (CNT) and cerium oxide (Ce_2O_3) on the properties of fuel for conventional and biodiesel fuels as well as the performance and emissions of CI engines when these additives were used [**14**]. They found that the physiochemical properties and catalytic activity were enhanced due to the addition of nanoparticles in biofuel. A variety of additives have been shown to cause varying effects on vehicle emission, performance and combustion. The reduction of pollutant formation in the exhaust was advocated by employing nanoadditives to improve combustion and performance. Karthikeyan et al. assessed the engine performance of ZnO-based biodiesel blends. Although there was no substantial reduction in NOx emissions, the calorific value of the fuel increased significantly and the emissions of carbon monoxide (CO), hydrocarbon (HC), etc. were greatly reduced. As a result of these investigations, it was concluded that the inclusion of nanoparticles to biodiesel blends can boost the engine's performance [**15**]. The CI engine' s performance is also influenced by the amount and size of nanoparticles added to the biodiesel blend. Nanoparticles are increasingly being used in a wide range of industries, from metallurgy to energy, despite their distinctiveness.

Hydrogen gas can be injected into the engine by a variety of methods. Chemicals with hydrogen bases can be used conventionally in conjunction with diesel blends to implement hydrogen in the engine. Hydrogen can be extracted from water via electrolysis and breaking water molecules. Ideally, hydrogen was injected from the cylinders to combustion chamber through intake manifolds [**16-18**]. Hydrogen and biodiesel mixes have been the investigated by several researchers. Hydrocarbon and oxygen emissions from the engine were significantly reduced by utilizing H_2 in engine. Carburetion was employed by Sar-avanan et al. to incorporate hydrogen into the mixture for use as a fuel. Despite the high levels of NOx emissions, other pollutants such as hydrocarbons, carbon dioxide, and carbon monoxide were also found to be present. Moreover, the engine's brake thermal efficiency improved as a result [**19**]. As a result, it can be determined that using hydrogen in conjunction with the desired technique can improve engine performance while also reducing emissions of several harmful gases such as CO, CO_2, and HC. Nanoparticles are another type of particles that have the potential to boost the engine' s overall performance. The huge surface area and extremely strong reactivity of nanoparticles make them particularly useful. Adding nanoparticles to biodiesel blends has been proven to greatly increase combustion efficiency and reduce emissions. The current study focuses on establishing the relationship between the nanoparticles and hydrogen as the promising source of energy in greener routes.

2. Materials and method

2.1. Experimental setup

The present work has been carried out in the single cylinder four stoke compression ignition engine fuelled with diesel and hydrogen. The maximum torque at the full load condition was 26 N-m at the engine speed of 3000 rpm. Further, the maximum power was 5 hP. **Fig. 1** shows the typical layout of the experimental test rig. MgO nanoparticles were dispersed with diesel at the concentration of 50 ppm using ultra-sonication technique. The test blends such as Diesel (100 % diesel), DN (Diesel $+$ 50 ppm MgO), H1N (Diesel 90 %$+$10 % Hydrogen $+$ 50 ppm MgO) and H2N (Deisel 80 %+ 20 % Hydrogen + 50 ppm MgO) were analysed for performance, combustion and emission characteristics. The engine was allowed to run between the initial load conditions of 6 N-m to the full load condition of 24 N-m. Two types of fuel were used. Both the fuel rates were closely followed in order to measure the consumption rates via a flow meter and a differential pressure transmitter. Simple burette type flow meter was used to measure the mass flow rate of diesel. On the other hand, the engine loading was varied using the dynamometer and the load cell. The emissions such as CO, CO_2, HC and NOx were measured using $AVL\ Gas$ analyser [**20**]. All the measured parameters were analysed using the electronic control unit and data acquisition system. ECU controls the pressure sensor and fuel ignition timing values. **Table 1** shows the specifications of the engine and **Table 2** lists the properties of gaseous hydrogen. The uncertainty of all the instrumentation was below 3 %, which is acceptable.

3. Results and discussion

The engine performance, combustion and emission characteristics were determined across various engine loading conditions for the blends, Diesel (100 % diesel), DN (Diesel + 50 ppm MgO), H1N (Diesel 90 % + 10 % Hydrogen + 50 ppm MgO) and H2N (Diesel 80 % + 20 % Hydrogen + 50 ppm MgO). All the procured data were pictorially represented and compared to find the role of hydrogen and nanoparticles in the diesel engine.

3.1. Engine performance

3.1.1. Brake thermal efficiency

BTE emphasizes the effectiveness of the engine, which converts chemical energy into mechanical energy. That usefulness was measured and listed as the brake thermal efficiency. Typically, the heating value of the test samples is responsible for a higher production of power. On the other hand, viscosity of the working fluids also enhances the spray atomization and vaporization of the fuel. Higher the atomization, better is the efficiency. **Fig. 2** shows the change in the BTE for different test blends. In this study, a series of tests were conducted at different engine loads such as 6 N-m, 12 N-m, 18 N-m and 24 N-m on Diesel, DN, H1, H1N, H2 and H2N. Among the various blends, maximum efficiency has been reported for H2N and H2 as 35.7 % and 37 %. Compared to diesel, adding hydrogen increases the efficiency of the system. Furthermore, addition of nanoparticles increases the presence of oxygen atoms resulting in improved thermal efficiency. As the hydrogen concentration increases, the production of BTE also increases owing to the flame speed and combustion intensity. On the other hand, increasing the concentration of hydrogen in the test blends improves the flammability limits and calorific value of the fuel [**20**,**21**]. As the loading progressed, there is an increase in the thermal efficiency. For all the samples, peak efficiency has been reported at 24 N-m load. Among the different blends, H1N and H2N have reported superior results than diesel. For instance, Diesel, DN, H1, H1N, H2 and H2N at 24 N-m recorded 32 %, 32.5 %, 35.1 %, 36.05 %, 35.7 % and 37 % BTE. The identical pattern has been tailed by all the samples irrespective of the engine loading condition. Compared to diesel, H1 and H2 reported 9 % and 11 % higher BTE. With regard to the nanoparticles, 2 %, 2.8 % and 3.5 % improvement has been observed compared to non-nanoparticle treated samples. Henceforth, it is evident that adding nanoparticles increased the thermal efficiency [**22**,**23**].

Upon addition of hydrogen as the secondary fuel to diesel, the combustion quality has been enhanced and hence, there is a significant change in the BTE for all the samples, which have the hydrogen content.

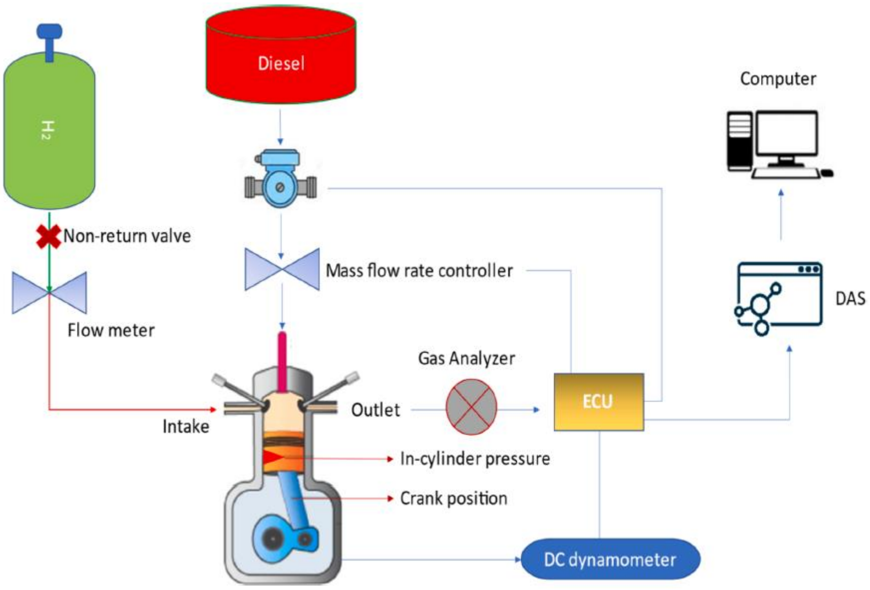

Fig. 1. Experimental test rig layout.

Table 1 Engine specification.

Cylinder	1
Ignition	Compression
Bore (mm)	82
Stoke length (mm)	66
Compression Ratio	19:1
Torque at Full Load	24 *N*-m @ 3000 rpm
Maximum power	5 HP @ 3000 rpm
Dynamometer	Eddy current
Power Take-off	Flywheel End
Type of Fuel Injection	Direct Injection
Physical dimensions of bare engine (Length X Width X Height)	462 X 494 X 560 mm
Starting	Rope Start
Fuel	Dual

Table 2 Properties of Hydrogen gas [**20**].

Property	Value
Purity	99.99 %
Heating value (MJ)	120
Density (kg/m^3)	0.062
Stoichiometric air to fuel ratio (mass)	1.6
Flame velocity (m/s)	1.85
Adiabatic flame temperature (K)	2480
Self-ignition temperature (K)	858

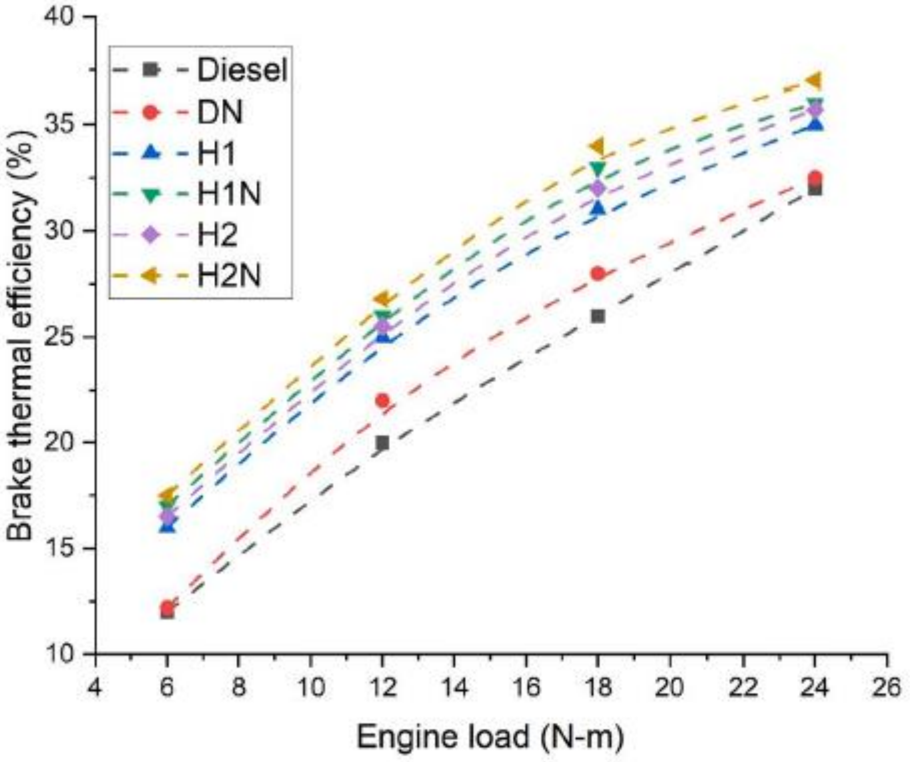

Fig. 2. Effect of hydrogen and MgO on BTE at different engine loading conditions.

3.1.2. Brake specific fuel consumption

$BSFC$ measures how much energy is consumed to create work through combustion. Adding hydrogen to the combustion chamber reduces the fuel consumption rates owing to the flame propagation speed and quenching. Using hydrogen blends has lowered the gap of quenching than diesel. Improved combustion is viable, when the hydrogen included as the secondary fuel due to the high heating value. **Fig. 3** shows the change in fuel consumption related to engine load. Compared to diesel fuel, all the hydrogen blends reported have reduced fuel consumption [**24**]. Higher the fractions, lower is the fuel consumption. Further adding the nanoparticles affects the viscosity of the blends, which indeed reduced the diesel consumption. At lower engine condition, the fuel consumption rates of Diesel, DN, H1, H1N, H2 and H2N were 390 g/kWh, 375 g/kWh, 350 g/kWh, 332 g/kWh, 345 g/ kWh, and 348 g/kWh, respectively. As the engine load increased, the fuel consumption subjected to decreases. In general, at lower engine load, the amount of fuel usage will be higher due to an increased demand of power. When there is an increase in the engine load, the engine attains the complete combustion mode, which trends to drop the fuel consumption to the required power demand. The lowest range of BSFC was found at the 24 N-m of engine load as, 190 g/kWh, 180 g/kWh, 175 g/kWh, 170 g/kWh, 165 g/kWh, and 162 g/kWh. A drastic reduction in fuel consumption was witnessed when the blends were dispersed with the nanoparticles. For instance, the sample without nanoparticles such as Diesel, H1 and H2 reduced 4.5 %, 6 % and 0.8 % higher fuel consumption than the blends with nanoparticles. Adding the nanoparticles to the blends enhanced the system to attain higher combustion rates without affecting the fuel consumption patterns. Besides, when the hydrogen concentration increased, the influence of the nanoparticles was negligible [**25**,**26**]. From this, it was clear that at a higher concentration, the role of the nanoparticles was not substantial. By adding hydrogen to the diesel, the fuel consumption was reduced by 12 % and 8 % for H1N and H2N, respectively. From this, it could be presumed that hydrogen helped in complete combustion, which indeed reduced the fuel consumption.

3.2. Combustion characteristics

Fig. 4 shows the change in the heat release rate (HRR) during combustion of each blend. All the best blends reported the similar expected behaviour like neat diesel. The peak HRR has been recorded at the crank angle between — 5 to — 1 °CA. Among the various blends, the test blend with a higher hydrogen concentration reported the maximum HRR of 74 J/deg. Adding hydrogen to the diesel increased the diffusion properties of the blends and the flame speed. When hydrogen was added to diesel, the stochiometric ratio was notably affected, so, the fuel burnt more quickly than diesel; hence, the hydrogen blends have reported higher HRR than diesel irrespective of the crank angles [**27**]. On the other hand, adding nanoparticles to the blends also increased the HRR to 75 J/deg.

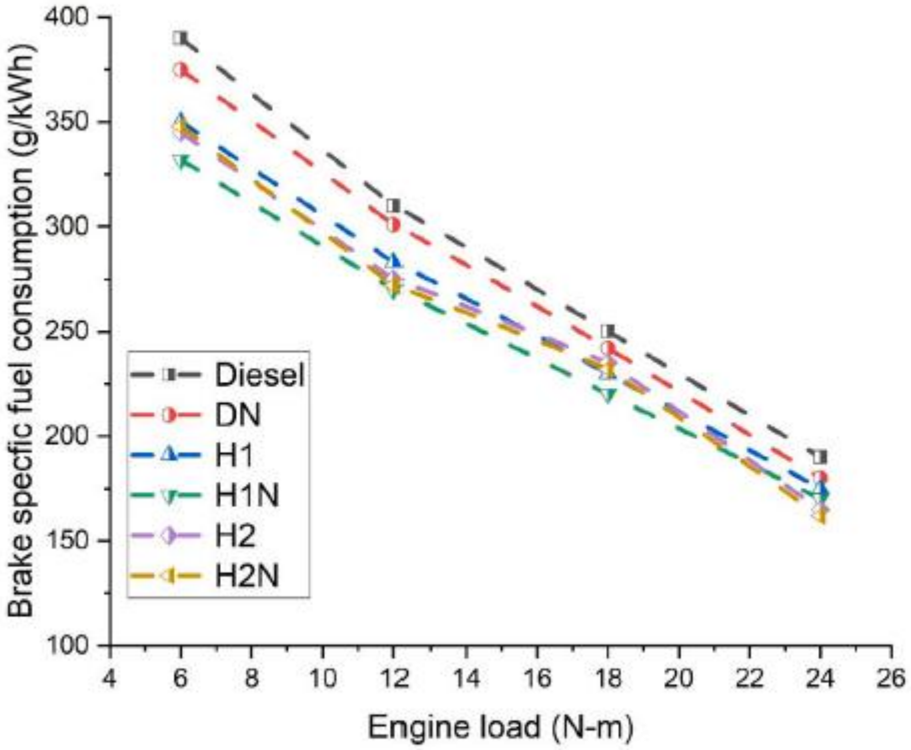

Fig. 3. Effect of hydrogen and MgO on $BSFC$ at different engine loading conditions.

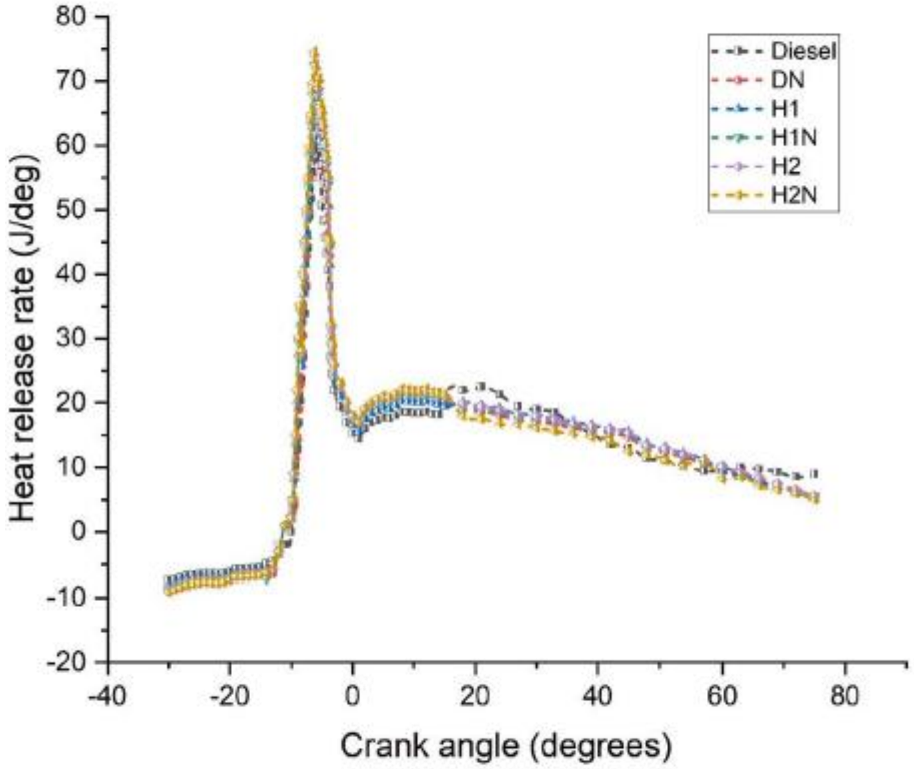

Fig. 4. Effect of hydrogen and MgO on HRR at different engine loading conditions.

3.3. Emission characteristics

3.3.1. Hydrocarbon emission

Typically, the hydrocarbon concentrate was released from the diesel engine due to the incomplete combustion of the fuel products. **Fig. 5** shows the observation of HC variations for different blends. The changes between the diesel and hydrogen blends were not significant between the engine loading conditions of 12 N-m and 9 N-m owing to the OH radicals in the alcohol. As the engine load increased, the HC emissions were dropped massively [28]. For example, at 6 N-m, the HC emissions were 53 ppm, 50 ppm, 40 ppm, 38 ppm, 35 ppm and 32 ppm for Diesel, DN, H1, H1N, H2 and H2N. At the maximum engine load, the HC emissions were 32 ppm, 30 ppm, 23 ppm, 20 ppm, 18 ppm and 16 ppm, respectively. By adding the nanoparticles to the Diesel, H1 and H2, the HC emissions were dropped by 6 %, 14 % and 10 %. When the hydrogen and nanoparticles were added to the neat diesel, the combustion rates were increased due to the combustion duration and ignition delays. On the other hand, higher flame speed of gaseous mixture and short quenching distance were also other typical reasons for the reduced amount of HC emissions.

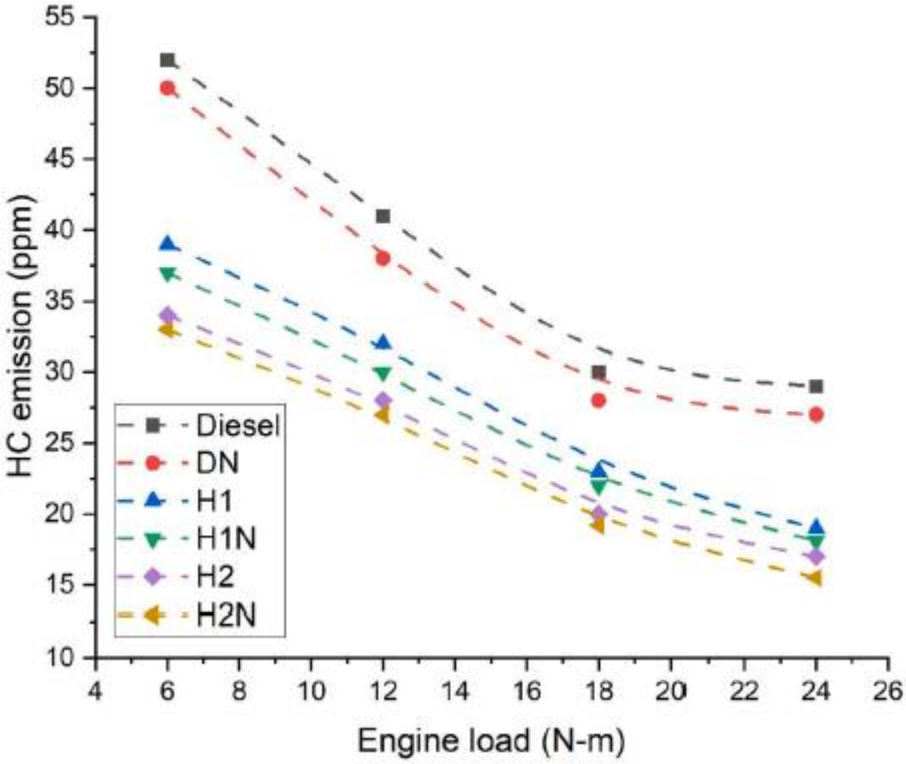

Fig. 5. Effect of hydrogen and MgO on HC at different engine loading conditions.

3.3.2. NOx emission

Oxides of nitrogen were the by-products of the reaction between the two compounds of nitrogen such as nitric oxide and nitrogen di-oxide. NOx is formed due to the reaction between N_2 and O_2. Compared to nitrogen di-oxide, the role of the nitric acid is vital. Nitric oxide is responsible for the production of higher NOx emissions. **Fig. 6** represents the changes in the NOx for various engine loads [**29**]. When the engine load is increased, there is a larger formation of NOx. Elevated cylinder temperatures are the other key reasons for the high formation of NOx. Adding the hydrogen blends to diesel reduced the formation of NOx due to the residence time and in-cylinder temperature variation. In general inclusion of the hydrogen increases NOx, however in this study the results obtained were contrary to the some of the previous work due to the higher-pressure injection strategy. Injection of hydrogen at higher pressure reduces the cylinder temperature and hence NOx. Further, the combustion of hydrogen is faster than neat diesel. Hence, adding the hydrogen molecules to diesel increased the possibility of complete combustion and eventually, higher HRR. At lower engine loads, the NOx emissions for all the test blends were between the range of 330 ppm to 380 ppm. There was no evidence of massive change in the NOx compared to diesel. However, due to the influence of nanoparticles, there was a slight decrease in the production of NOx. As the engine loads increased, the emission of NOx was high due to the elevated cylinder temperature. The maximum NOx concentration was witnessed at 24 Nm as 1570 ppm, 1430 ppm, 1320 ppm, 1310 ppm, 1012 ppm and 990 ppm for Diesel, DN, H1, H1N, H2 and H2N, respectively. Adding the nanoparticles to the test fuels reduced the NOx by 9 %, 0.8 % and 2 % for DN, H1N and H2N. Compiling all the above, it was acceptable that adding hydrogen and nanoparticles to neat diesel reduced the formation of NOx.

3.3.3. CO emission

Formation of CO was due to the combination of oxygen content in the fuel, cylinder temperatures and reaction time. From the previous findings, it was clear that adding hydrogen to diesel would diminish the formation of CO. When H_2 was dispersed with diesel, the possibility of complete combustion was high.

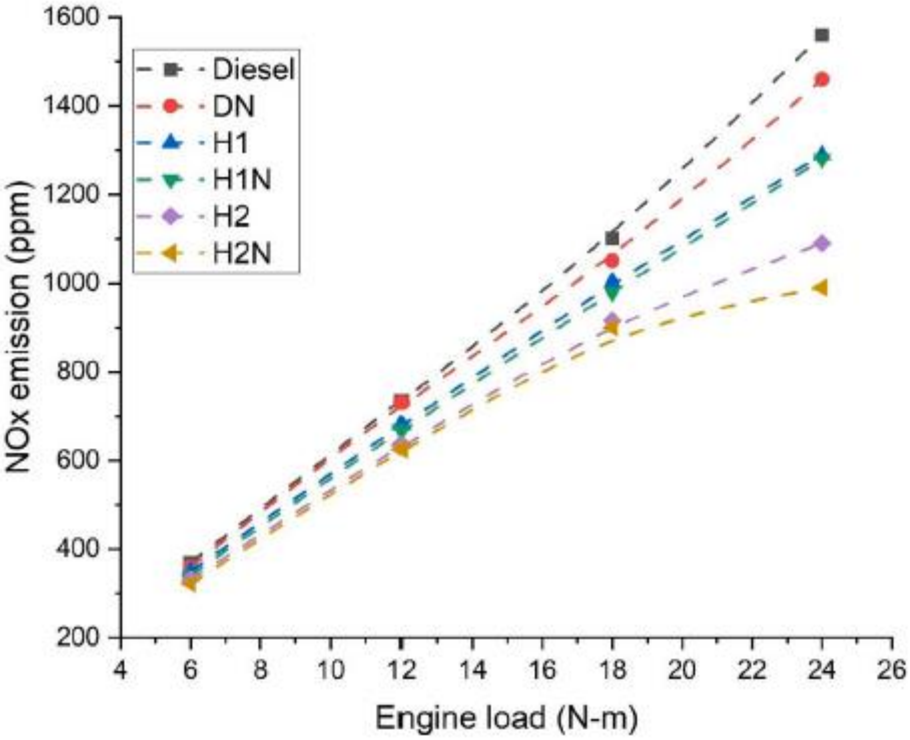

Fig. 6. Effect of hydrogen and MgO on NOx at different engine loading conditions.

The typical reasons for the role of hydrogen on complete combustion was flame speed propagation, spray velocities, and in-cylinder pressure [**30**,**31**]. By attaining complete combustion, the formation of OH radicals can be avoided, which is a distinctive reason for CO emission and followed by CO_2 emission. **Fig. 7** shows the CO formation for various engine loading states. All the hydrogen blends reported the least CO formation. Adding hydrogen and nanoparticles to neat diesel reduced the carbon atoms; hence, the formation of both CO_2 and CO were avoided. For instance, the samples H1N, H2N reported 45 % and 56 % less formation of CO compared to neat diesel. According to the findings, it was clear that all the test blends were observed to have least CO emissions across different engine loads. The maximum CO was observed at 6 N-m and the minimum was recorded at 24 N-m engine load. As the engine load increased, the formation of CO reduced. For instance, the maximum CO emitted at 6 N-m load was 0.92 %vol, 0.86 %vol, 0.64 %vol, 0.61 %vol, 0.59 %vol, and 0.56 %vol for Diesel, DN, H1, H1N, H2 and H2N, respectively. When the engine was running at high load, the emission was dropped to 0.45 % vol, 0.43 %vol, 0.38 %vol, 0.35 %vol, 0.32 %vol, and 0.28 %vol, respectively. Compared to the regular blends, the blend with nanoparticles reduced the CO formation by 4.8 % and 5.2 %. The main reason for this radical reduction was better dilution effects of the nanoparticles and fuel blends. Moreover, the presence of the H_2 molecules reduced the carbon content, which would have certainly reduced the overall CO formation during combustion.

3.3.4. Carbon dioxide emission

Carbon dioxide emission is a vital parameter to emphasize the rate of complete combustion. When hydrogen was added to diesel, the presence of the carbon content in the fuel has been reduced, which was the key reason for the drop in both CO_2 and CO [**32**,**33**]. **Fig. 8** shows the variations in CO_2. emission. When the engine load was increased, there were higher combustion rates, which obviously increased the CO_2 formation. All the best blends reported the rise in CO_2 formation related to the engine loading. In addition to above, the cylinder temperature and combustion duration were also responsible for the reduced CO_2. Maximum CO_2 was observed at 24 N-m and the minimum was recorded at 6 N-m engine load. At 6 N-m, the test blends, Diesel, DN, H1, H1N, H2 and H2N reported 3.5 %vol, 3.3 %vol, 2.45 %vol, 2.25 %vol, 2.1 %vol and 1.85 %vol, respectively. When the load increased to 24 N-m, the formations of CO were reduced by 48 %, 45 %, 46 %, 43 %, 44 % and 40 % compared to the early conditions. Among the various blends, H2N was reported to have the least emissions of 1.8 %vol, 2.5 %vol, 3 %vol, and 3.4 %vol at 6 N-m, 12 N-m, 18 N-m and 24 N-m, respectively.

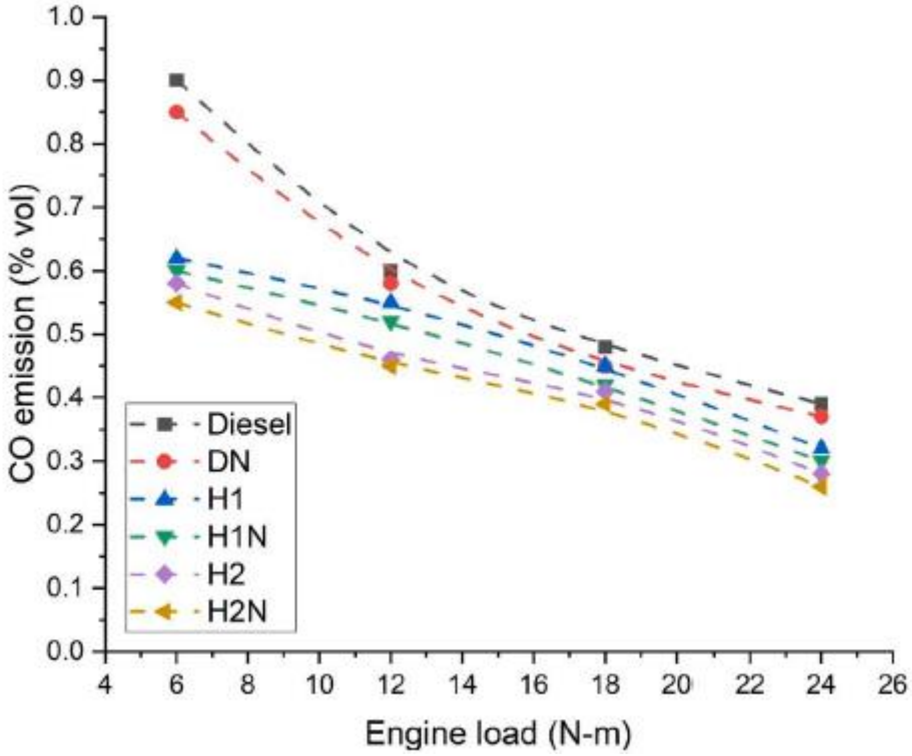

Fig. 7. Effect of hydrogen and MgO on CO at different engine loading conditions.

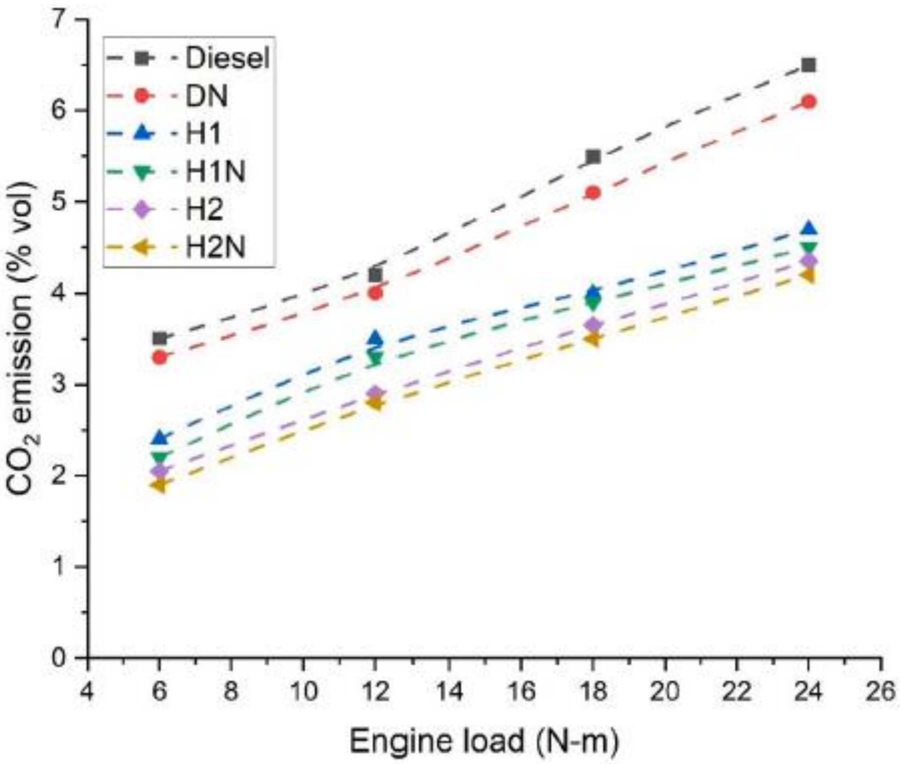

Fig. 8. Effect of hydrogen and MgO on CO_2 at different engine loading conditions.

Fig. 9 shows the trade-off comparison between the engine performance values to the emission parameters. The present study was carried out to examine how the engine performance values such as BTE and $BSFC$ would influence the formation of CO, HC and NOx. When the concentration of hydrogen increased, both the engine performance and emissions were better. The main reason for the drastic change in the performance and emissions was the replacement of carbon content in the diesel fuel. Further, adding hydrogen reduced the time of combustion by lowering the carbon to hydrogen ratio. Added to the above, dilution effects and cylinder temperatures were also other key reasons for the change in performance by adding the nanoparticles to the test blends. Both diesel and hydrogen blends showed positive effects on the nanoparticles. Compared to all, the best condition for the better performance and reduced CO and HC emissions was 24 N-m. With regard to the NOx emissions, 6 N-m was expected to be better due to the low cylinder temperature.

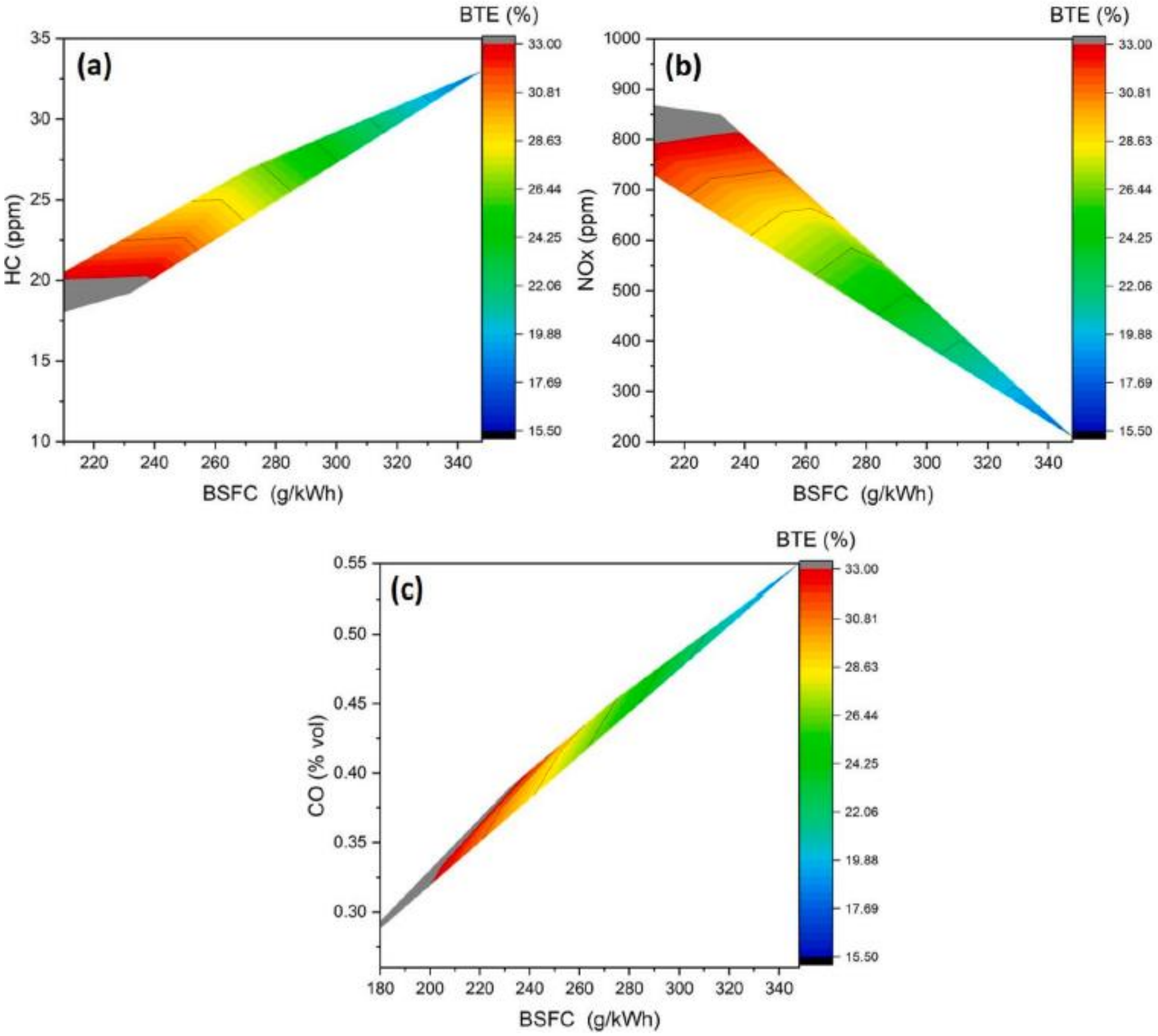

Fig. 9. Trade-off characteristics of H2N blend. (a) HC, (b) NOx, (c) CO.

4. Conclusion

In the current study, a series of tests was conducted on diesel, DN, H1, H1N, H2 and H2N across wide loading conditions of 6 N-m, 12 N-m, 18 N-m and 24 N-m to witness the effects of hydrogen and concentration of nanoparticles. The dispersion of the nanoparticles in the diesel blends was stable. Both diesel and the hydrogen blends were treated with nanoparticles to enhance the performance of the engine by supplying extra oxygen content to the combustion chamber. The highest BTE values of Diesel, DN, H1, H1N, H2 and H2N at 24 N-m were 32 %, 32.5 %, 35.1 %, 36.05 %, 35.7 % and 37 %. The maximum efficiency reported by H2N and H2 was 11 % and 14 % higher than neat diesel. Compared to diesel, H1 and H2 reported 9 % and 11 % higher BTE. With regard to the nanoparticles, 2 %, 2.8 % and 3.5 % improvement in efficiency was reported compared to non-nanoparticle treated samples. The fuel consumption rates of Diesel, DN, H1, H1N, H2 and H2N were 390 g/kWh, 375 g/kWh, 350 g/kWh, 332 g/kWh, 345 g/kWh, and 348 g/kWh, respectively, implying that adding nanoparticles had reduced the fuel consumption rates. Compared to regular samples, the nanoparticle present blends reduced the fuel consumption by 4.5 %, 6 % and 0.8 % for DN, H1N and H2N. The maximum HRR has been witnessed for H2 and H2N as 74 J/deg and 75 J/deg. With regard to emissions, all the hydrogen blends reported reduced emission rates. In particular, H2N reported reduced HC, NOx, CO and CO_2 emissions. The samples with nanoparticles reported 6 %, 14 % and 10 % reduced hydrocarbon formations compared to Diesel, H1 and H2. Further, adding nanoparticles to the test fuels reduced the NOx formation by 9 %, 0.8 % and 2 % for DN, H1N and H2N, respectively. When the hydrogen and nanoparticles being included to the regular diesel, the carbon content was reduced that indeed abridged the formation of both CO_2 and CO. From the above findings, it was concluded that the addition of hydrogen to diesel was effective. However, adding nanoparticles to hydrogen was not very effective alike diesel.

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