

Experimental investigation of hydrogen enrichment and nano-catalyst additives for advanced combustion in compression ignition engines

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ABSTRACT

Advanced combustion processes in compression ignition CI engines have been developed as a result of the increasing demand for more efficient and clean energy conversion devices. The present research deals with the effect of hydrogen enrichment along with the introduction of nanoparticles in the performance of a single cylinder direct injection diesel engine based on experimental results. The metal oxides' nanoparticles were introduced into the fuel in two concentrations, which were 50 ppm and 100 ppm. Moreover, the hydrogen flow rate through the intake manifold was constant (H_2 , 2 L/min). Under different load conditions, the experiment was carried out at a constant speed of 1500 rpm. It was found that using H_2 (2 L/min) + 100 ppm nanoparticles raised the brake thermal efficiency from 30% for diesel to 33%. Consequently, there was a 10% rise. Similarly, from 11.8 MJ/kWh to 10.6 MJ/kWh, the brake specific energy consumption dropped. According to emission study, smoke opacity dropped from 28% to 18%, CO emissions dropped from 0.23% to 0.16%, and HC emissions dropped from 42 ppm to 32 ppm. However, because of the high combustion temperature, NO_x emissions also rose from 680 parts per million for diesel fuel to 820 parts per million for hydrogen-enriched nano-fuel blends. According to the results of the combustion analysis, the maximum heat release rate increases from 45 J/°CA to 82 J/°CA for hydrogen-enriched nano-fuel blends, while the peak cylinder pressure climbs from 68 bar, which corresponds to diesel fuel, to 90 bar. The findings demonstrate that adding nanoparticles along with hydrogen enrichment improves engine performance, combustion efficiency, and emission characteristics, making it a viable strategy for running cleaner CI engines.

Keywords: biodiesel blends, energy efficiency, dual-fuel combustion, metal oxide nanoparticles, combustion enhancement, CI engine emissions, alternative fuels.

INTRODUCTION

Compression ignition (CI) engines are widely used in industrial, agricultural, and transportation applications due to their high efficiency, robust construction, and reliable operation. Nevertheless, because of the wide-scale application

of traditional diesel fuel, several environmental problems have arisen, such as those caused by the emission of greenhouse gases, as well as the emission of other harmful substances like particulate matter, carbon monoxide, hydrocarbons, and nitrogen oxide [28–29]. In an effort to extract optimum performance from the CI engine without

creating adverse effects on the environment, it has become imperative to investigate alternative fuels because of the increasing fuel demand and limited fossil fuel sources [1]. Biofuels like biodiesel are one of these promising renewable energy sources. Biodiesel fuel is an eco-friendly source of energy and can be made from vegetable oil, animal fat, and used cooking oils. Due to the presence of oxygen in the chemical structure of biodiesel, it is effective in reducing harmful emissions, including hydrocarbons and carbon monoxide. However, biodiesel has high viscosity and low calorific values and poor atomization properties compared to petroleum-based diesel fuel. These limitations could affect the engine's performance in a CI engine operating under heavy loads [2]. One of the methods that can be utilized to enhance the combustion process in CI engines is hydrogen enrichment in diesel engines. Some unique properties of hydrogen when undergoing combustion include increased flame velocity, minimal ignition energy requirements, wide flammability limits, and high diffusivity. Hydrogen injection into the air being introduced to the diesel engine in its intake phase will lead to an enhanced combustion process due to increased flame velocity. Furthermore, there will be lower quantities of incomplete combustion products alongside enhanced brake thermal efficiency. Nevertheless, combustion processes will result in elevated temperatures and the formation of NO_x gases [3]. The last few years have seen extensive research on the use of nanoparticle additives in fuels as an approach that could help in enhancing the combustion process as well as reduce the engine exhaust emissions. The catalytic properties of metal oxide nanoparticles such as zinc oxide (ZnO), cerium dioxide (CeO₂), titanium dioxide (TiO₂), and alumina (AlO₃) promote efficient oxidation of the fuel during the combustion process. This is because the small particle sizes promote efficient air-fuel mixture and oxidation, improved heat transfer in the combustion chamber, and better fuel atomization. Moreover, hydrogen enrichment coupled with nano-catalyst addition can enhance the efficiency of fuel combustion in CI engines. Due to its higher diffusivity and wide flammability range, hydrogen improves the characteristics of ignition and combustion. Nano-catalysts act as catalysts that accelerate chemical reactions and improve atomization. Although there are numerous investigations into the effects of hydrogen and nanoparticles separately, limited studies exist on the effects of both

hydrogen and nano-catalyst simultaneously, especially when applied to biodiesel fuel. It is imperative to conduct experimental studies to determine the effects of hydrogen and nano-catalyst on CI engine performance, combustion process, and emissions when biodiesel is used [6]. Studies on the use of alternative fuels and enhancement in the combustion process in CI engines have been conducted owing to the rising level of concern about environmental pollution and the reduction in fossil fuels. Some of the methods that have proved promising in enhancing the combustion efficiency of the fuels in CI engines and minimizing pollutants in the atmosphere include the use of biodiesel fuels, hydrogen augmentation, and fuel additives such as nanoparticles [7]. The use of biodiesel fuels in CI engines has been studied. Biodiesel fuels are more efficient than conventional diesel fuels in being sustainable, decomposable, and having oxygen content which improves their efficiency during the combustion process. It is established that biodiesel fuels have relatively less particulate matter, hydrocarbon, and CO. But because of the relatively lower calorific value of biodiesel fuel, as well as the higher viscosity of fuel, there would be greater consumption of fuel and less power generation. Besides, higher oxygen content and combustion temperature can lead to slightly high NO_x emissions [8]. The hydrogen enrichment technique is an effective means of enhancing the combustion properties of diesel engine fuel. Among the many special features associated with hydrogen combustion are the fast flame propagation rate, extensive flammability limits, low ignition energy, and high diffusivity. These characteristics allow hydrogen injection in the intake air of the diesel engine to enhance combustion. The results of experiments conducted revealed that hydrogen injection decreases the emissions of CO, HC, and smoke but raises brake thermal efficiency. In addition, it was found that hydrogen addition to fuel leads to an increase in the combustion process temperature and thus leads to NO_x emission growth. This problem still poses serious concerns in hydrogen-fueled engines [9]. Recent investigations have revealed that the addition of nanoparticles to fuels can have beneficial impacts on the fuel characteristics and combustion processes. Examples of metal oxide nanoparticles used in fuel additives include zinc oxide (ZnO), titanium dioxide (TiO₂), cerium oxide (CeO₂), and aluminum oxide (AlO₃). The particles have catalytic characteristics due to their

small size and can be helpful in oxidation reactions occurring during burning. It has been established that the nanoparticles improve fuel atomization, enhance heat transfer in the combustion chamber, and ensure that the fuel-air mixtures burn completely [10]. The application of hydrogen enrichment, together with nanoparticle addition, in CI engines has been researched by some authors. Hydrogen and nanoparticle addition together improve the efficiency of combustion. The nanoparticles act as combustion catalysts to hasten oxidation reactions and fuel/air mixing, while hydrogen enhances flame propagation and ignition. According to some experimental research, the dual method could result in higher efficiency and reduced exhaust emissions from incomplete combustion. However, not enough research has been done to assess the dual method of adding hydrogen and nano-catalysts as biodiesel fuel CI engines' additives. Furthermore, there has been little research done to assess the impact of the dual strategy on efficiency and combustion characteristics of the engines in varied operating conditions [13]. The current research focuses on evaluating the impact of both hydrogen fueling and Al_2O_3 particles on performance and exhaust emissions of CI engines.

MATERIALS AND METHODS

This part includes the description of materials, process of fuel production, nanocatalyst synthesis, and method adopted for fuel production in this experiment. Also included is the process of nanoparticle dispersion and engine operational processes used for experimental purposes.

Fuels used and production methods

In this study, biodiesel-diesel fuel blends are adopted as the main type of fuels used in the experiments on the CI engine. This selection is made based on the biodegradable characteristics of these fuels, oxygen-rich molecular structure, and emission-reducing ability during combustion.

For improving the burning qualities even further, the use of metal oxide nanoparticles was suggested as catalysts. Different types of nanoparticles were considered, but it was decided to use aluminum oxide (Al_2O_3) because of their thermal conductivity, catalytic ability, and stability. In the

course of experiments, nanoparticles at 50 ppm and 100 ppm were used.

The nano-fuel mixture was made as follows:

1. An accurate amount of the nano-particles was weighed.
2. The nano-particles were dispersed in the diesel-biodiesel fuel mixture.
3. Surfactant was added to make their suspension stable.
4. The (mixture) was then exposed to ultrasonic mixing for 30–40 minutes using ultrasonic homogenizer to attain uniform dispersion.

The above procedure made it possible for the suspension of nano-particles to be stable without settling during engine use. The nano-particles (Al_2O_3) were obtained by sol-gel precipitation technique. Initially, aluminum nitrate was dissolved in distilled water to form a homogeneous solution. Ammonia solution was then added to adjust the pH to 9–10, resulting in the formation of aluminum hydroxide gel. The gel was dried at 110 °C and subsequently calcined at 600 °C for three hours to obtain aluminum oxide nanoparticles. The synthesized nanoparticles were then incorporated into the fuel blends as catalytic additives (Figure 1).

SEM analysis

The scanning electron microscopy (SEM) image in Figure 2 demonstrates the morphology of the synthesized aluminum oxide (Al_2O_3) nanoparticles. From the SEM micrograph in Figure 2, it is evident that the synthesized aluminum oxide nanoparticles are in a clustered/agglomerated form due to their high surface energy. It is also evident from Figure 2 that the synthesized aluminum oxide nanoparticles are nearly spherical in shape and uniformly distributed in a porous agglomerated form. This confirms that the nano-sized aluminum oxide particles have been successfully synthesized. From the scale bar in Figure 2, which is 200 nm in size, it is evident that the synthesized aluminum oxide particles are in the nanometer range (Table 1).

Reaction mechanism

In this section, the reactions are discussed, which lead to the formation of aluminum oxide (Al_2O_3) nanoparticles by using the precipitation method through sol-gel technique. There are two

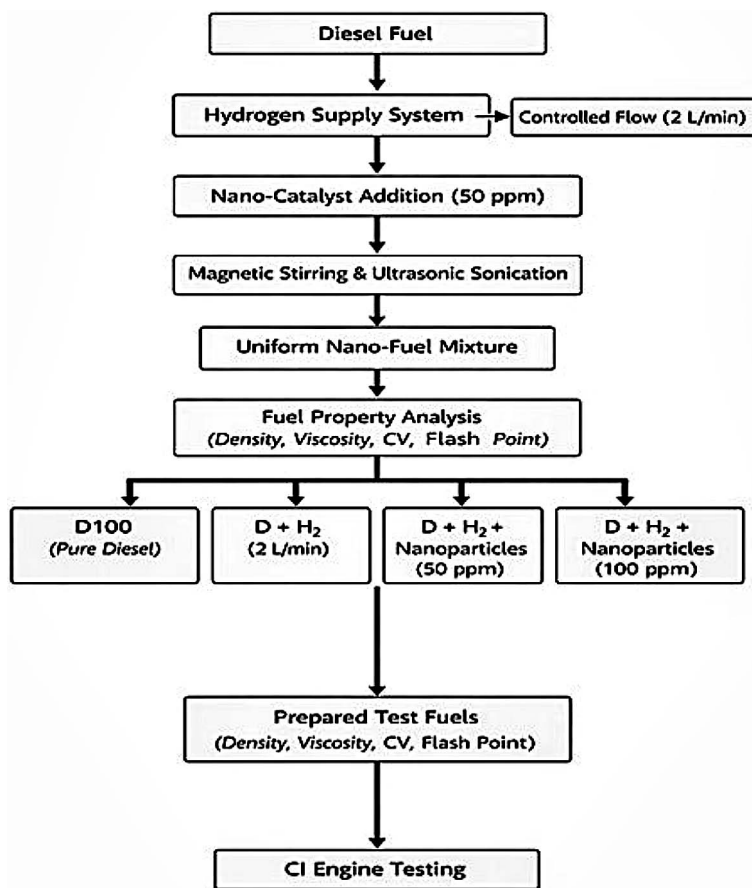


Figure 1. Fuel preparation flow chart

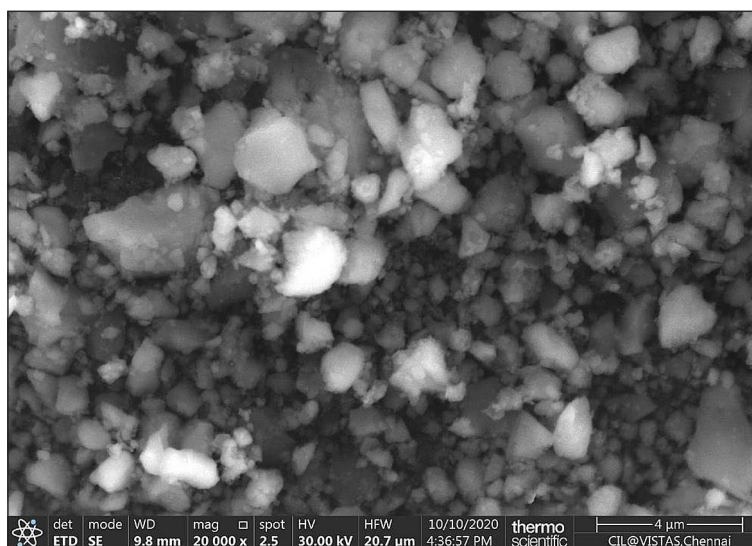


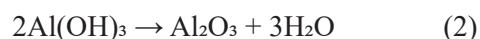
Figure 2. SEM of Al₂O₃ nanoparticles

main steps involved in the reaction process; these include precipitation and calcination.

During the process of precipitation, aluminum nitrate reacts with ammonium hydroxide to form aluminum hydroxide precipitate as follows:



Afterward, the aluminum hydroxide is calcined to obtain aluminum oxide nanoparticles through the following reaction:



It is very important to know the above-mentioned reactions in order to understand the

Table 1. Properties of Al₂O₃ nanoparticles

Property	Value
Material	Aluminum oxide (Al ₂ O ₃)
Particle size	20–50 nm
Shape	Spherical (approx.)
Purity	≥ 99%
Density	~3.9 g/cm ³
Crystal structure	Gamma (γ-Al ₂ O ₃)
Surface area	High (nano-scale)
Thermal conductivity	High
Appearance	White powder

mechanisms involved in the formation of aluminum oxide nanoparticles.

Fuel properties

Properties of the test fuels used in this work were assessed in order to achieve proper comparability and reproducibility of the results. The physicochemical properties of diesel fuel, biodiesel blends, and nanoparticle-based fuel blends are listed in Table 2. Test procedures for measuring various physicochemical properties of fuels have been followed in a standardized manner. Properties considered for measurement are density at 15 °C, kinematic viscosity at 40 °C, lower heating value, cetane number, flash point, and elemental analysis. The presence of higher oxygen and viscosity in biodiesel blends

than diesel affects their combustion behavior. Regarding nanoparticle-blended fuel samples, their stability was obtained using surfactant-stabilized ultrasonication process. The suspension stability of nanoparticle fuel blends was confirmed by observing the suspension for 48 hours, no sedimentation was detected. Average size of Al₂O₃ nanoparticles is in nanometer scale with large surface area.

EXPERIMENTAL SETUP

In this study, a single cylinder, water cooled, 4-stroke diesel internal combustion engine was used. For determination of brake power and various loads, the engine was coupled to an eddy current dynamometer. The engine was run at a fixed speed of 1500 rpm while various loads were applied on the engine to observe its performance and combustion emissions. Hydrogen gas was provided to the engine through a flow control valve and pressure regulator. Hydrogen gas was measured with the help of a calibrated flow meter before the fuel supply to the engine. In order to guarantee the stability of the fuel mixture, biodiesel and diesel fuels were combined with nano-catalyst additives, such as aluminum oxide nanoparticles. Fuel consumption was determined using the burette method and stop-watch method, even though the in-cylinder pressure during combustion was tracked using a piezo-electric

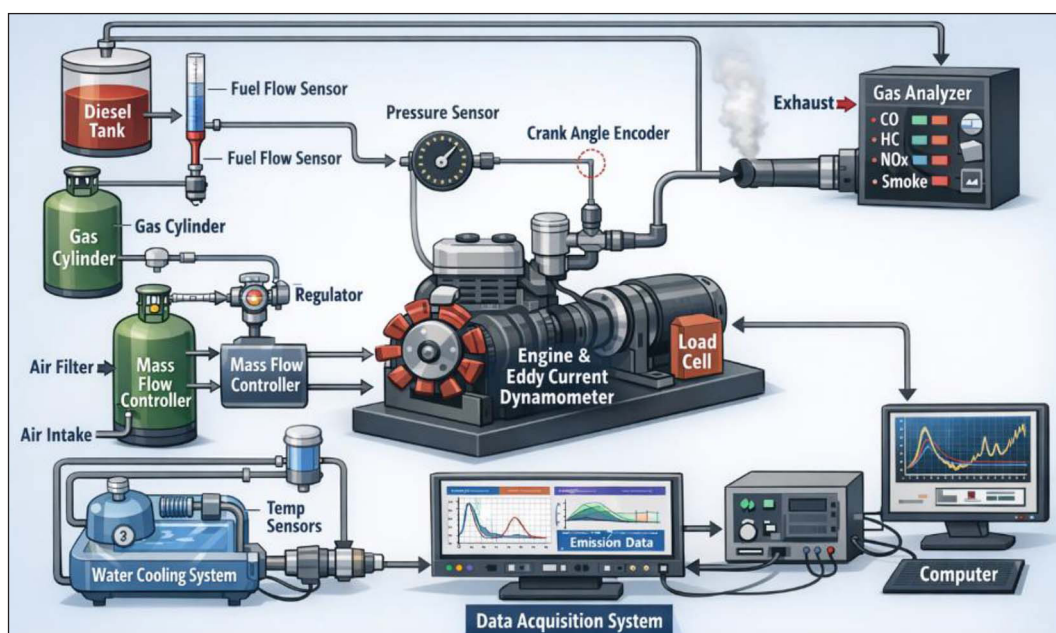


Figure 3. Experimental setup

Table 2. Properties of fuel

Property	Diesel	Biodiesel blend	Nano-fuel
Density (kg/m ³)	830	860	865
Viscosity (cSt)	2.5	4.2	4.4
LHV (MJ/kg)	43	39	39
Cetane number	48	52	52
Flash point (°C)	60	130	135

sensor in conjunction with a combustion analyzer to detect parameters including cylinder pressure and heat release rates. Additionally, a smoke meter was installed at the engine’s exhaust outlet to measure smoke, and a multi-gas exhaust analyzer was utilized to monitor exhaust gas emissions such as carbon monoxide, hydrocarbons, and nitrogen oxides. A computerized data collection system was utilized to track all engine parameters for additional analysis of combustion, exhaust gas emissions, and engine parameters (Figure 3, Table 3).

RESULTS AND DISCUSSION

Brake thermal efficiency

Brake thermal efficiency (BTE) for diesel fuel, hydrogen enrichment H₂ (2 L/min), hydrogen enrichment with 50 ppm nanoparticles, and hydrogen enrichment with 100 ppm nanoparticles is shown in Figure 4 as a function of engine load. It has been discovered that the brake thermal efficiency increases with engine load for all fuel types. This is because the fuel-air mixture burns more effectively when engine load increases, raising combustion temperature and reducing relative heat losses. For all engine operating

situations, diesel fuel is determined to have the lowest brake thermal efficiency values. This is a result of diesel fuel’s partial oxidation and slow rate of combustion. This is because of the fast flame speed, wide range of flammability, and high diffusivity of hydrogen, which all contribute to improving the combustion process in the premixed combustion phase. The improvement in BTE is further achieved by using nanoparticles as additives and enriching with hydrogen, as mentioned in reference [14]. The performance of the fuel blend H₂ (2 L/min) + 50 ppm nanoparticles is better than that of hydrogen enrichment. This is due to the discovery that nanoparticles function as catalysts and enhance heat transport, atomization, and oxidation reactions within the combustion chamber. When the nanoparticles are put to the H₂ (2 L/min) + 100 ppm nanoparticles combination, the maximum BTE is discovered. This is because adding more nanoparticles to the hydrogen-enriched fuel blend increases the surface area of the nanoparticles available for the combustion reaction. Consequently, the chemical energy of the fuel is transformed as much as feasible into mechanical energy. The findings demonstrate that combining hydrogen enrichment with nanoparticles improves engine efficiency. Engine efficiency increases more when engine loads are higher. BTE has improved since the

Table 3. Measurement uncertainty

Parameter	Instrument	Uncertainty
Load	Dynamometer	±1%
Speed	Tachometer	±10 rpm
Fuel consumption	Burette & stopwatch	±1%
Temperature	Thermocouple	±1 °C
Cylinder pressure	Piezo sensor	±1 bar
CO emission	Gas analyzer	±0.01%
HC emission	Gas analyzer	±1 ppm
NOx emission	Gas analyzer	±10 ppm
Smoke opacity	Smoke meter	±1%

combustion technique improves engine performance more effectively.

Brake specific energy consumption

Figure 5 shows the brake specific energy consumption (BSEC) for diesel, hydrogen enrichment, and hydrogen with nanoparticle additions varies with engine load. This graph shows that, for all fuel circumstances, BSEC steadily declines as engine load increases. This is due to the engine’s increased efficiency at higher loads, which raises the conversion efficiency of fuel energy into

mechanical output. Conventional diesel fuel produces higher BSEC under all load circumstances. This is because low combustion efficiency and slow combustion rates demand more energy to produce a unit quantity of brake power [16]. In comparison to the diesel mode, the BSEC drops when the hydrogen enrichment is added at a rate of H₂ (2 L/min). This is because the fuel has a high flame velocity, diffusion rate, and flammability limits. With hydrogen enrichment, all the three aspects contribute positively towards the process of combustion. BSEC is discovered to be reduced when the nanoparticles are added to the

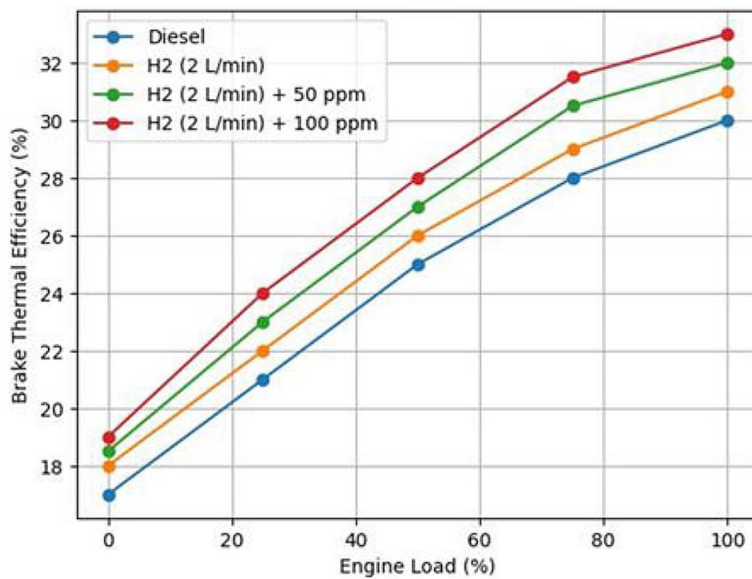


Figure 4. The variation of brake thermal efficiency (BTE) with engine load

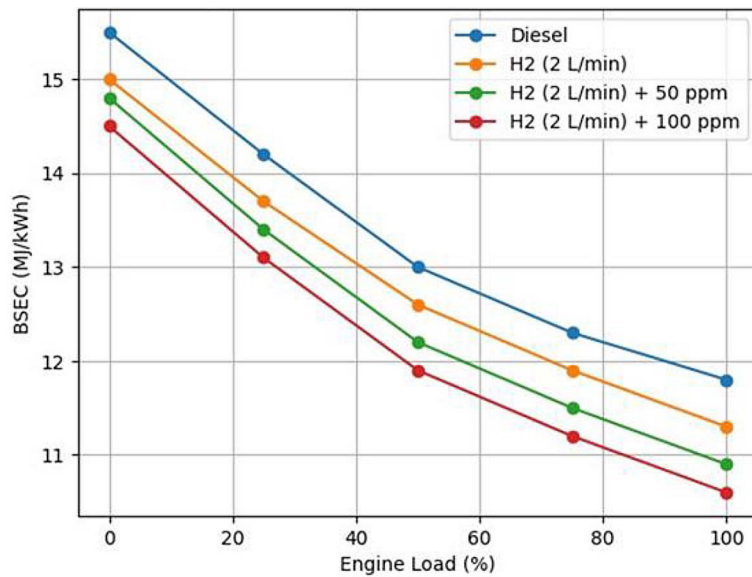


Figure 5. The variations of brake specific energy consumption (BSEC) with engine load

fuel. The BSEC was found to be low when the fuel used contained 50 ppm nanoparticles and H₂ enrichment at H₂ (2 L/min). This is due to the fact that adding nanoparticles to fuel improves the oxidation and fuel atomization processes. The fuel with 100 ppm nanoparticles and H₂ enrichment at 2 L/min was found to produce the lowest BSEC. This is because when the nanoparticles are added to the fuel, the amount of the nanoparticles in the fuel increases. This improves the combustion process. Therefore, the combustion process in the combustion chamber was efficient. From the results of the experiment, it was clear that the efficiency of the engine was improved by adding nanoparticles and H₂ enrichment to the fuel, thus reducing the BSEC, especially at high loads [17].

CO emission

Figure 6 shows the variation of carbon monoxide (CO) emission with engine load for diesel, hydrogen enrichment (H₂ L/min), and hydrogen with nanoparticle additions (50 ppm and 100 ppm). This figure shows that, for all test fuels, carbon monoxide emission levels are decreasing steadily with increasing engine loads. This is because inadequate oxygen availability for oxidation reactions causes incomplete combustion reactions in the combustion chamber, which results in carbon monoxide emissions [18]. CO emissions are lower under hydrogen enrichment (2 L/min) than under diesel engine running conditions.

This is due to hydrogen’s rapid flame speed and superior diffusivity, which enhance combustion and speed up fuel oxidation. When nanoparticles are introduced as additives, CO emissions are further reduced. CO emissions are shown to be lower when gasoline is combined with H₂ (2 L/min) + 50 ppm nanoparticles as opposed to diesel engine operating conditions. When H₂ (2 L/min) + 100 ppm nanoparticles are added as additives, the lowest amount of CO emissions will be produced. This is because the nanoparticles added as combustion catalysts will improve the combustion process, thus increasing the rate of fuel oxidation. The performance of the compression ignition engine will improve when hydrogen enrichment and nanoparticles are added as additives, as shown in the results [19].

HC emission

As shown in Figure 7, hydrocarbon (HC) emission characteristics vary with engine load for diesel fuel, hydrogen enrichment (H₂ 2 L/min), and hydrogen with nanoparticle additions (50 ppm and 100 ppm). As can be seen, for each test fuel, the HC emission gradually decreases with increasing engine load. This is because, with increasing engine load, the combustion temperature increases, and thus the oxidation of unburned hydrocarbons in the engine combustion chamber is enhanced. For all engine loads, diesel fuel has the maximum HC emission compared to other test

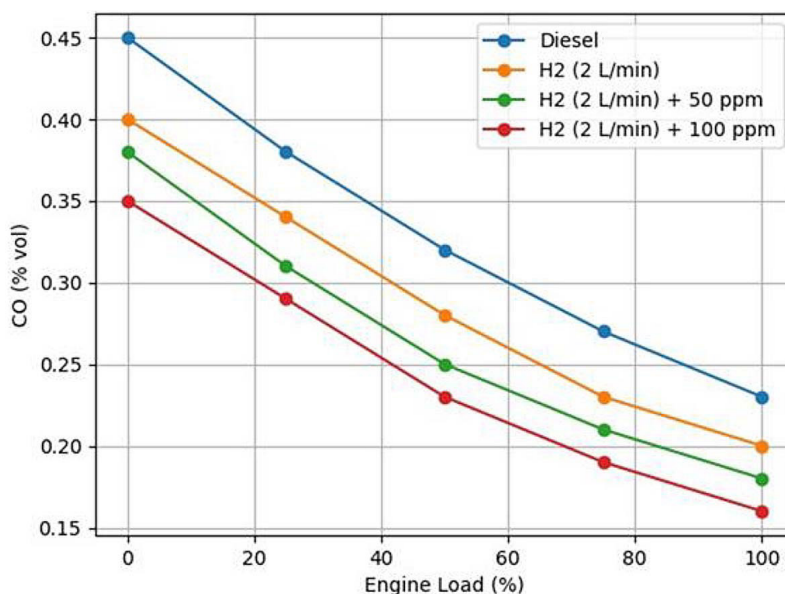


Figure 6. The variation of carbon monoxide (CO) emissions with engine load

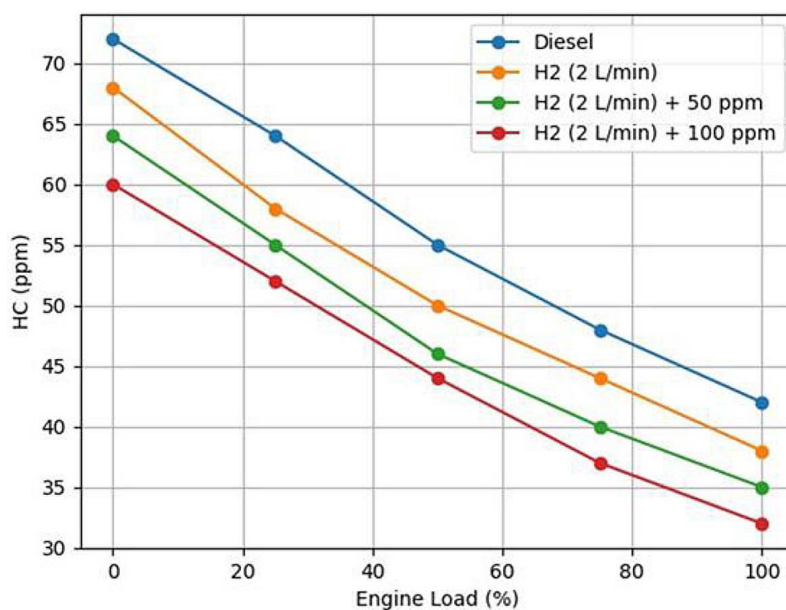


Figure 7. The variation of hydrocarbon (HC) emissions with engine load

fuels [20]. This is primarily caused by incomplete combustion, which is caused by a sluggish flame in the combustion chamber and an insufficient fuel-air combination. HC emissions are reduced when hydrogen enrichment (2 L/min) is introduced as opposed to using diesel. Hydrogen has a fast flame speed and a wide range of flammability restrictions. The fuel is fully oxidized as a result of the increased rate of burning. The emission of HC is decreased when nanoparticles are added. The fuel mixture including H₂ (2 L/min) + 50 ppm nanoparticles had lower HC emissions because the presence of nanoparticles speeds up the oxidation of the fuel mixture. The combination of H₂ (2 L/min) + 100 ppm nanoparticles produces the least amount of HC emissions. This is because the high rate of oxidation results from the high amount of nanoparticles, which raises the rate of catalytic reactions and consequently raises the combustion rate. The results have revealed that hydrogen and nanoparticle additions decrease HC emissions, raise the combustion rate, and minimize pollution in compression ignition engines [21].

NO_x emissions

Effect of engine load on nitrogen oxide emission from diesel fuel, hydrogen enriched at 2 L/min, and nanoparticle added hydrogen (50 ppm and 100 ppm) is shown in Figure 8. The NO_x emission levels are observed to increase slowly with an increase in the engine load for all kinds

of fuels. This is due to the fact that both the combustion temperature and oxygen concentration increase with the increase in the engine load. Diesel fuel emits more NO_x when the engine load increases because the peak temperature of combustion rises as well. This will cause the concentration of nitrogen and oxygen to rise at higher temperatures, resulting in the emission of NO_x [22]. In comparison with the diesel engine, it is noted that the amount of NO_x emissions slightly increases with the addition of hydrogen enrichment (2 L/min) as fuel. When nanoparticles are added as additives, the amount of NO_x emissions increases. From the figure, it is also noted that the amount of NO_x emissions is higher in the H₂ (2 L/min) + 50 ppm nanoparticles blend compared to the H₂ enrichment blend. This is because both the combustion efficiency and the rate of heat release improve when nanoparticles are added as additives. The mix with the highest NO_x emissions is the H₂ (2 L/min) + 100 ppm nanoparticles combination. This is because the nanoparticles enhance the fuel-air mixture and catalytic activity, raising the combustion temperature. It was found that by using nanoparticles and hydrogen enrichment as additives, efficiency in combustion is increased, thus reducing emissions. It was found that using nanoparticles and hydrogen enrichment as additives increased NO_x emissions. Therefore, in order to improve performance characteristics in an engine, NO_x emissions have to be optimized [23].

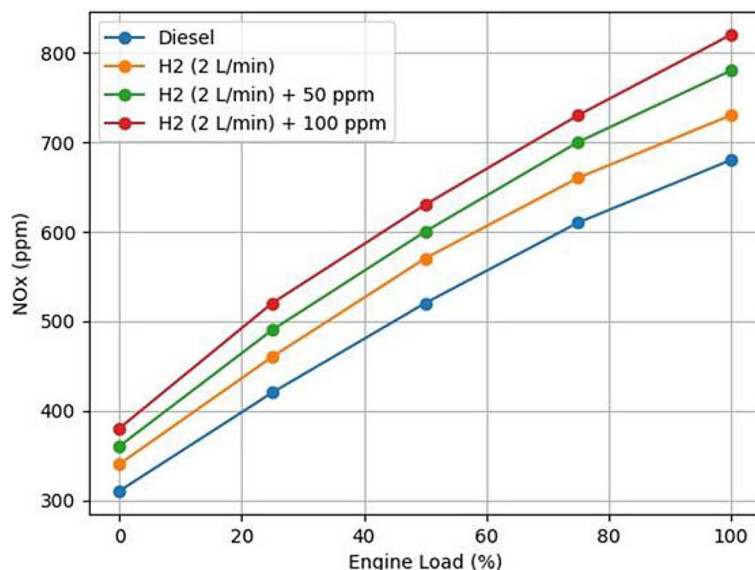


Figure 8. The variation of nitrogen oxides (NOx) emissions with engine load

Smoke emissions

Figure 9 demonstrates the variation in the value of smoke opacity as the load is varied using diesel fuel, hydrogen enriched fuel using H2 L/min, and hydrogen fuel with 50 ppm and 100 ppm nanoparticle addition. The figure shows that when the load increases, the value of smoke opacity decreases for all fuels. This is due to the combustion process's efficiency and the increase in the temperature inside the cylinder, hence fast oxidation of the soot particles. Among all fuels, diesel fuel is the one that produces the most smoke density under any load of engines. This

happens mostly because of inadequate oxygen for fuel combustion, hence inefficiency of combustion and formation of soot particles [24]. During injection of hydrogen enrichment at a flow rate of two liters per minute, the smoke produced is lower than that from normal running of the diesel engine. This happens since hydrogen has many flammability limitations and high flame speed, thus fast combustion with minimal soot particle emissions, other than carbon. It is also clear that the emissions of smoke are reduced by adding nanoparticles in the fuel blend. Smoke emissions are reduced in the fuel combination of H2 (2 L/min) + 50 ppm nanoparticles because the

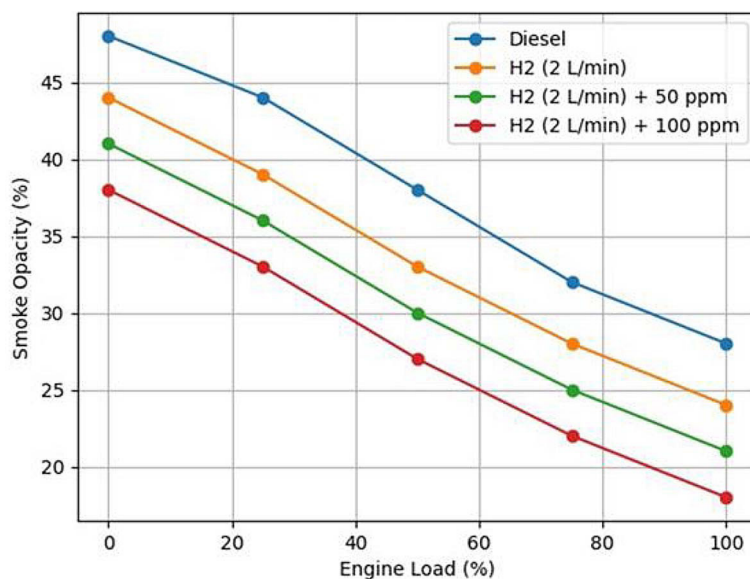


Figure 9. The variation of smoke opacity with engine load

presence of nanoparticles improves the rate of combustion and speeds up heat transfer in the combustion chamber. The combination of 100 ppm nanoparticles with H₂ (2 L/min) resulted in the lowest smoke opacity. This demonstrates how the nanoparticles' catalytic qualities improve the burning of soot. The study's conclusion is that adding hydrogen enrichment and nanoparticles improves compression ignition engines' combustion quality by lowering soot particles [25].

Cylinder pressure

Figure 10 shows how cylinder pressure changes with crank angle for diesel fuel, hydrogen enrichment (H₂ + 2 L/min), and hydrogen enrichment with nanoparticle additions (50 ppm and 100 ppm). The cylinder pressure progressively rises throughout the compression stroke, peaks just before the top dead center (TDC), and then begins to fall during the expansion stroke. When using diesel fuel, the typical combustion process in the diesel engine causes the maximum cylinder pressure to be seen just after the TDC. The slow rate of combustion and comparatively longer ignition delay period in comparison to the hydrogen-enriched fuel mixtures are the causes of the relatively low peak pressure. The peak cylinder pressure is found to be larger when hydrogen enrichment (2 L/min) is used as opposed to diesel operation. Because of its superior diffusivity and fast flame speed, hydrogen enhances the premixed combustion phase and

speeds up the rate of heat release in the combustion chamber. By adding nanoparticle additions, the cylinder's pressure is further improved. Because of the enhanced catalytic oxidation processes and fuel-air mixing, it is found that the fuel blend including H₂ (2 L/min) + 50 ppm nanoparticles has a higher peak pressure. The fuel blend containing H₂ (2 L/min) + 100 ppm nanoparticles achieves the highest peak pressure. The peak pressure in the cylinder will also rise due to the increased concentration of nanoparticles, which will improve the combustion rate. From the results, it can be concluded that adding nanoparticles to hydrogen will improve the peak pressure in the cylinder, thus improving the efficiency of the engine [26].

Heat release rate

Figure 11 demonstrates the change in the rate of heat release as it relates to the crank angle for diesel fuel, hydrogen enrichment (H₂ 2 L/min), and hydrogen enrichment with nanoparticle addition (50 ppm, 100 ppm). The initial rate of heat release is negative due to the absorption of heat as compression occurs. However, it increases sharply as the crank angle approaches top dead center due to premixed combustion and the start of combustion. It increases progressively after the top dead center and reaches a moderate peak for standard diesel fuel. The primary cause of this anomaly is the typical diffusion-controlled combustion in diesel engines, where a longer ignition delay and less premixed

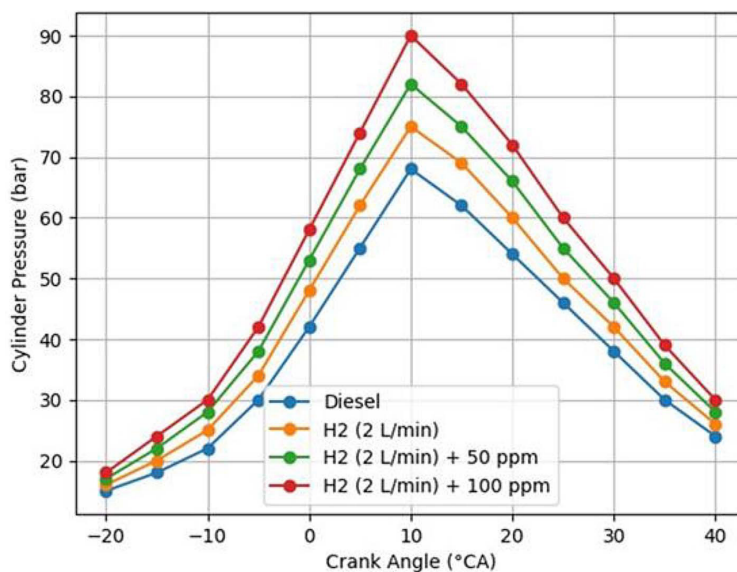


Figure 10. The variation of cylinder pressure with crank angle

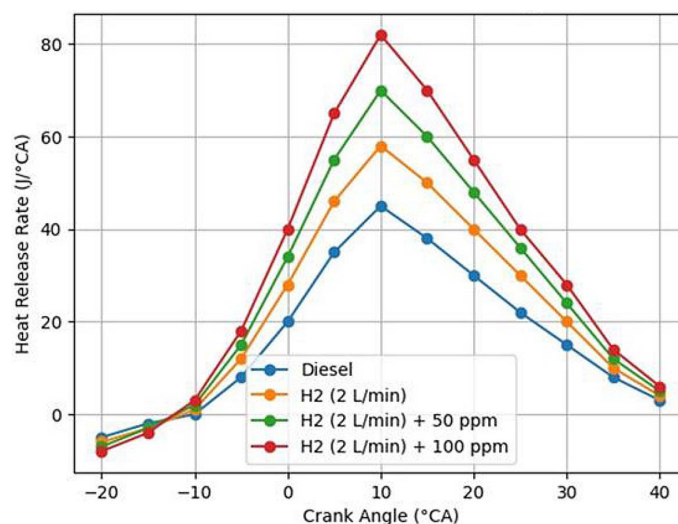


Figure 11. The variation of heat release rate with crank angle

combustion result in a comparatively slower rate of heat release. In comparison to diesel fuel, the heat release rate is shown to increase considerably with the addition of hydrogen enrichment (2 L/min). This is because of the high rate of flame speed and high diffusivity of hydrogen. These properties improve the combustion reaction as well as the pre-mixed combustion. The results show that the rate at which the heat is released is greater and happens a bit sooner. The addition of nanoparticles into the fuel increases the rate of heat release. Since the rate of catalytic oxidation reaction and fuel atomization is very high, it is found out that the heat release rate of H₂ (2 L/min) + 50 ppm nanoparticles is greater. It is also observed that the heat release rate of H₂ (2 L/min) + 100 ppm nanoparticles is the greatest. This is because nanoparticles possess a higher oxidation reaction rate and efficiency in combustion reactions. In all these processes, heat is released at a faster rate. It is therefore concluded that the use of hydrogen enrichment and nanoparticles improves the efficiency of the engine in compression ignition engines due to a higher heat release rate [27].

CONCLUSIONS

The present experimental work analyzed the impacts of hydrogen addition (2 L/min) and incorporation of Al₂O₃ nano-catalysts (50 and 100 ppm) on the efficiency, combustion, and emissions of a single-cylinder diesel engine working at various loading conditions. The findings indicated that the brake thermal efficiency was found to improve with an increase in engine loading for

all the fuels used, where the highest brake thermal efficiency was found in the case of hydrogen addition and nano-fuel blend of 100 ppm. This is due to the improved combustion rate because of the increased flame speed and diffusion of hydrogen. Brake specific energy consumption decreases with increased loading; the least value of energy consumption was seen in the case of nano-fuels of hydrogen additions. Emission analysis showed that there have been noticeable improvements in CO, HC, and smoke opacity emissions because of better burning and oxidization procedures. There has been an increase in NO_x emission, but it is understandable considering that hydrogen addition and the use of nanoparticles have raised the cylinder temperature and heat release rate. The same thing can be seen from the results obtained during the combustion analysis where peak cylinder pressure and heat release rate both rose, meaning the combustion process had improved. Nevertheless, there are still some drawbacks to this experiment. Firstly, the tests were done with a single-cylinder engine and cannot be directly applied to multi-cylinder engines. Secondly, the engine was run at a constant speed of 1500 rpm, and the amount of hydrogen flow rate and nanoparticle concentration were very narrow. Moreover, the effects of engine life, wear behavior, and possible consequences of nanoparticle deposits were not considered. The stability of the nanofuels was not analyzed during longer storage periods, and an uncertainty analysis was not performed in depth. Also, the tests were carried out at a very narrow load spectrum of the engine. Therefore, the recommendations for future research include optimal adjustment of hydrogen

flows and nanoparticle amounts, analysis of engine durability, and assessment of fuel stability in practical use. Besides, additional measures to reduce NO_x emissions might be considered, including EGR or after-treatment of the exhaust gases, which would allow balancing between increased efficiency and lowered emissions.

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