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# EXPERIMENTAL STUDY ON DUAL-FUEL OPERATION OF HYDROGEN AND DIESEL IN CI ENGINES

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**Abstract**

*This current study examines the effects of the use of hydrogen gas as well as nanoparticle additives on the performance, combustion, and emission characteristics of a compression ignition (CI) engine. A fixed flow rate of 2 L/min of hydrogen gas was supplied to the system, and concentrations of 25, 50, and 75 ppm of nanoparticle additives were employed. Engine performance was determined by measuring the Brake Specific Energy Consumption (BSEC) and Brake Thermal Efficiency (BTE), while the combustion efficiency was analyzed through the cylinder pressure and heat release rate (HRR). The emissions parameters of CO, HC, NOx, and Smoke opacity were also tested at varying loads of engine operations. The findings of this experimental study demonstrate significant improvement in combustion efficiency and engine performance from hydrogen gas enrichment as well as nanoparticle additives. The fuel blend with the highest BTE and lowest BSEC was $H_2$ at 2 L/min + 75 ppm. The combustion analysis showed that the maximum heat release rate increased from 45 J/°CA to 82 J/°CA and the maximum cylinder pressure for diesel increased from 68 bar to 90 bar. The system was supplied with hydrogen gas at a set flow rate of 2 L/min, and concentrations of 25, 50, and 75 ppm of nanoparticle additives were utilized. Significant reductions in CO, HC, and smoke opacity were achieved due to the increased combustion and oxidation processes within the fuel blends. Under full load, there was about a 30%, 24%, and 36% reduction in CO, HC, and smoke* *opacity, respectively. However, NOx emissions increased as a result of the increased temperatures in the cylinder due to effective combustion. Generally, the results indicated significant improvements in combustion efficiency as well as reductions in incomplete combustion pollutants due to the combination of hydrogen and nanoparticles. Based on the results, $H_2$ at 2 L/min + 75 ppm gave the best blend in terms of emission reductions and increased efficiency.*

**Keywords:** Hydrogen enrichment, Nanoparticle additives, Compression ignition engine, Brake thermal efficiency, Heat release rate, Energy Efficiency, Combustion analysis.

## I. Introduction

The compression ignition (CI) engine is very common in industries, agriculture, and even transportation since it provides a good level of efficiency, is durable, and works effectively. Nevertheless, because of its extensive utilization in relation to conventional diesel fuel, major ecological problems arise, including greenhouse gas emissions together with other dangerous emissions such as particulates, CO, hydrocarbons, and nitrogen oxides. To achieve the highest possible efficiency of CI engines while causing minimal ecological damage, it becomes increasingly important to consider various fuels and ways of combustion because of the rising fuel consumption and decreasing fossil fuel resources [I]. One of the renewable types of fuels, created as a substitute for traditional diesel fuel, is biodiesel fuel. Vegetable oils, animal fat, and waste oil could serve as a basis for biodiesel fuel production, which is a renewable and biodegradable type of fuel. The existence of oxygen within the chemical makeup of biodiesel fuel allows it to serve as a great source for the reduction of harmful emissions like carbon monoxide and hydrocarbons [II]. Hydrogen enrichment in diesel engines is one method of improving combustion in CI engines. Some special characteristics of hydrogen during combustion include stronger diffusivity, a wide range of flammability, reduced ignition energy, and higher flame velocity. When hydrogen is added to the air used by the diesel engine in the process of intake, the speed of flame propagation will increase and enhance the combustion process. Moreover, the combustion process will minimize incomplete combustion products and enhance the brake thermal efficiency. However, since the temperature will be increased, NOx fumes will be produced [III]. Recently, much attention has been given to the addition of nanoparticles to fuel in order to achieve better performance in terms of combustion characteristics as well as lowering emission levels from the engine. Metal oxide nanoparticles such as ZnO, $CeO_2$, $TiO_2$, and $AlO_3$ possess catalytic effects on fuel oxidation processes during combustion. Because of their extremely small size and high surface area/volume ratios, these nanoparticles help achieve more mixing and combustion of air and fuel, greater heat transmission within the combustion chamber, and better fuel atomization [IV]. It means that the use of such nanoparticles helps increase engine efficiency and lowers emissions in terms of smoke and CO and HC emissions[V]. In addition, the combustion efficiency of CI engines can be increased by adding hydrogen and nanoparticle catalysts. Owing to enhanced diffusivity and wider flammability ranges, hydrogen assists in improving the ignition qualities and flame propagation. Whereas many researchers have looked at the individual effects of hydrogen addition and nanoparticle introduction, very few have analyzed the effects of these processes taken together, especially in relation to biodiesel fuels. As for the evaluation of hydrogen addition and nanocatalyst application effects in CI engine operation on biodiesel blends in terms of engine performance, combustion characteristics, and emission reduction, experimentation is essential [VI]. A concerning trend toward environmental contamination and the depletion of fossil fuels has prompted research on alternate fuels and enhanced combustion in CI engines. Biodiesel fuels, hydrogen enrichment, and nanofuel additives have proven to be the most promising methods for increasing the efficiency of combustion in CI engines and reducing the emissions of hazardous compounds to the environment [VII]. Biodiesel-based fuels for CI engines have been researched. It has been demonstrated that biodiesel fuels are renewable, biodegradable, and include oxygen to improve the fuel's combustion efficiency. They are also known to emit less particulate matter, hydrocarbons, and carbon monoxide compared to conventional diesel fuels. However, biodiesel fuels are known to require more fuel consumption because of their lower calorific value and higher viscosity than conventional diesel fuels. Higher oxygen content and higher combustion temperatures have been found to produce higher NOx emissions [VIII]. Biodiesel-based fuels for CI engines have been researched. It has been demonstrated that biodiesel fuels are renewable, biodegradable, and include oxygen to improve the fuel's combustion efficiency. They are also known to emit less particulate matter, hydrocarbons, and carbon monoxide compared to conventional diesel fuels. However, biodiesel fuels are known to require more fuel consumption because of their lower calorific value and higher viscosity than conventional diesel fuels. Higher oxygen content and higher combustion temperatures have been found to produce higher NOx emissions [IX]. It is important to note that hydrogen enrichment has been proven to be an effective process for the improvement of diesel engine fuels' combustion characteristics. Strong flame speed, a broad flammability limit, low ignition energy, and strong diffusivity are some of the unique combustion characteristics of hydrogen. These are a few of the justifications for adding hydrogen to the diesel engine's intake air to improve combustion. Some authors have looked into the inclusion of hydrogen in addition to nanoparticles in CI engines. The inclusion of nanoparticles and hydrogen together can improve combustion efficiency.[X] This is because the nanoparticles help to speed up the oxidation process and fuel/air mixing through acting as combustion catalysts, while hydrogen helps to accelerate flame propagation and ignition. From some experimental studies, the combined addition may lead to increased efficiency and lowered exhaust emissions due to partial combustion. [XI] However, the use of hydrogen and nano-catalysts together as biodiesel fuel in CI engines has not received much attention. The purpose of this experimental investigation is to ascertain how the hydrogen and nanocatalyst additions affect the performance, combustion, and exhaust emissions of a single-cylinder direct injection diesel engine that runs on biodiesel fuels. [XII] Future generations of internal combustion engines may profit from the advanced combustion systems that have been developed according to the findings of this study.

## II. Materials and Methods

### II.i. Fuel Selection and Preparation

In the present study, blends of biodiesel and diesel fuel were used as the main source of fuel for the experiments in compression ignition engines. Blends of biodiesel and diesel fuel were used as the main source of fuel due to their renewable nature, rich-oxygen molecule structure, and capability of reducing hazardous emissions of exhaust gases during the combustion process. [XIII] Furthermore, the blends of biodiesel and diesel fuel were used in specific ratios in order to ensure stability in the operation process. For the enhancement of the combustion process, metal oxide nanoparticles are utilized as the catalytic fuel blend in biodiesel and diesel fuel. [XIV] In the current research, metal oxide nanoparticles like aluminum oxide are selected as the catalytic fuel blend in view of their good catalyst characteristics. Metal oxide nanoparticles were mixed in very low amounts ranging from 25-75 ppm.

For the preparation of the nano fuel blend, the following procedures were conducted:

1. The amount of nanoparticles was measured precisely.

2. The required amount of nanoparticles was added to the biodiesel-diesel fuel blend.

3. A surfactant was added to the fuel blend to make the suspension of nanoparticles more stable.

4. Ultrasonic agitation of the fuel blend was conducted for about 30-40 minutes through an ultrasonic homogenizer so as to allow proper mixing of the nanoparticles with the fuel blend.

The use of the above procedure allowed proper mixing of the nanoparticles in the fuel blend, thereby preventing their sedimentation while operating the engine. The sol-gel technique was used in preparing $Al_2O_3$ nanoparticles. The preparation of nanoparticles through the sol-gel technique involved the following procedure:

a) Mixing aluminum nitrate with distilled water.

b) Adding ammonia solution to form aluminum hydroxide gel at pH 9-10.
c) Drying the mixture for some time at 110°C and then calcination of the dried mixture at 600°C for three hours.
d) Addition of the obtained nanoparticles into the fuel blend.

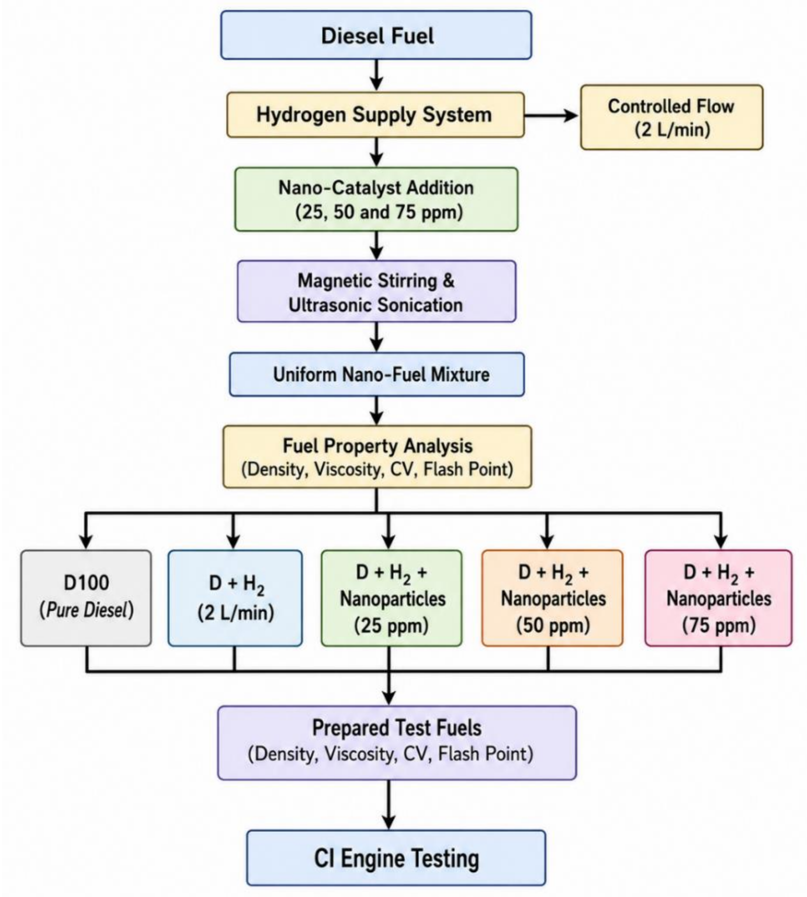


**Fig. 1.** Fuel preparation flow chart

**II.ii. SEM Analysis**

The shape of the produced aluminum oxide ($Al_2O_3$) nanoparticles is depicted in Figure 1 below. Because of their high surface energy, the produced aluminum oxide nanoparticles have a clustered/agglomerated shape, as seen in Figure 1 above. (XV) The produced aluminum oxide nanoparticles appear to have a near-spherical geometry with a uniform distribution in a porous agglomerated form, as seen in Figure 1 above. This demonstrates unequivocally that the fabrication of nanoscale aluminum oxide particles was effective.

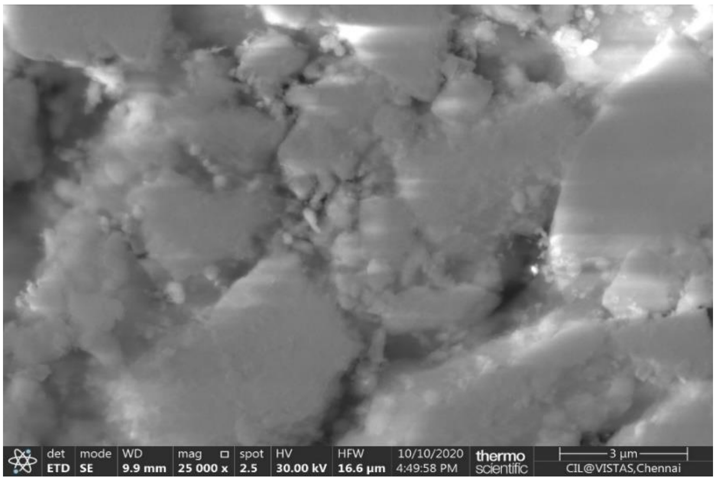


**Fig. 2.** SEM of $Al_2O_3$ nanoparticles

### II.iii. Chemical Reaction

Precipitation reaction

**Al(NO_3 )_3+3NH_4 OH→Al(OH)_3↓+3NH_4 NO_3**

Calcination reaction

**2Al(OH)_3→Al_2 O_3+3H_2 O**

### II.iii. Hydrogen Enrichment System

The inclusion of hydrogen gas into the CI engine increases the combustion qualities because of its fast flame velocity, wide flammability limits, and low ignition energy. The hydrogen gas was taken from a high-pressure cylinder, and the flow of this gas was controlled by control valves and a pressure regulator. The required flow rate of hydrogen was calculated by a gas flow meter, after which the hydrogen was introduced into the engine through its intake manifold. [XVI] To achieve efficient mixing of the gas, it was added to the air that enters the engine combustion chamber. Different flow rates of hydrogen were used in the experimental work.

## III. Experimental Setup

A single-cylinder, water-cooled, four-stroke direct injection engine was used in this experiment. To evaluate the engine's performance, load, and power, an eddy current dynamometer was attached to the engine. The engine was driven under different loads at a steady-state speed of 1500 RPM in order to examine engine performance and emissions. The engine was supplied with hydrogen gas via the flow control valve and pressure regulator.

The hydrogen gas flow rate was measured using a calibrated gas flow meter before the fuel was added to the engine [XVII]. To ensure fuel blend stability, nanocatalyst materials, such as aluminum oxide nanoparticles, were added to both diesel and biodiesel blends. [XVIII] Fuel consumption was measured using both the burette and stopwatch methods, despite the fact that the combustion in-cylinder pressure was recorded using piezoelectric pressure sensors connected to the combustion analyzer for the detection of parameters like cylinder pressure and heat release rate. A multi-gas exhaust gas analyzer was used to monitor exhaust gas emissions, including carbon monoxide, hydrocarbons, and nitrogen oxides, and a smoke meter was installed in the exhaust opening to record smoke emissions. [XIX]. Each of these engine properties was measured using a computerized measurement instrument (Fig. 3).

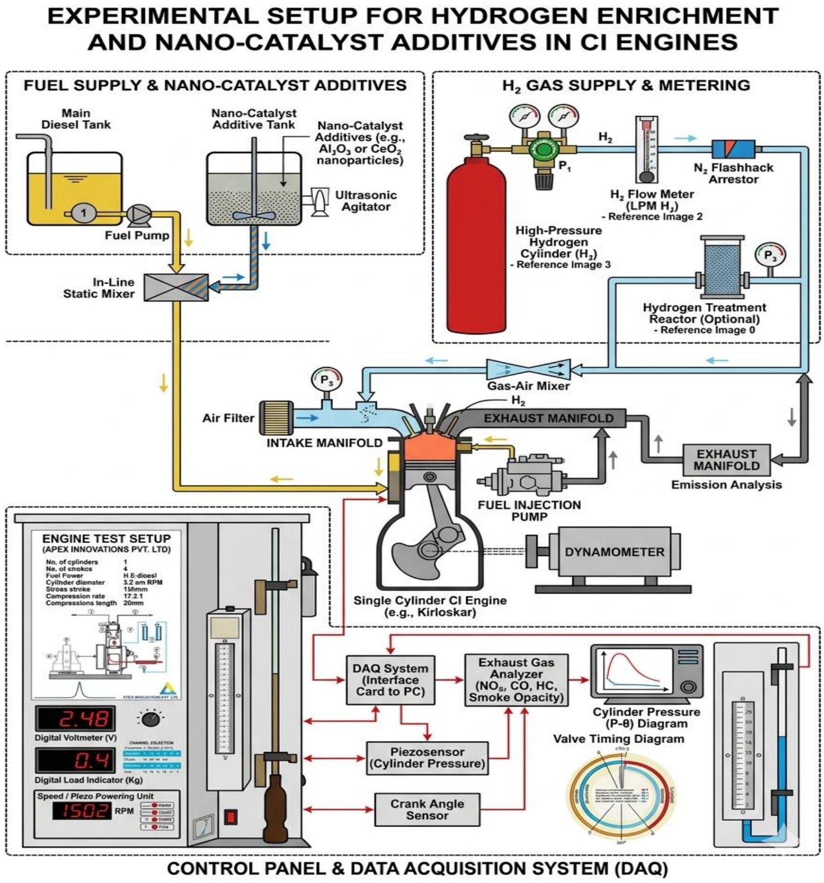


**Fig. 3.** Experimental setup

## IV. Results and Discussions

### IV.i. Brake Thermal Efficiency (BTE)

The effect of engine loading on BTE for diesel, $H_2$ at 2 L/min, $H_2$ at 2 L/min + 25 ppm, $H_2$ at 2 L/min + 50 ppm, and $H_2$ at 2 L/min + 75 ppm fuel operation modes is shown in the figure. In every instance, the BTE increases as the engine load increases, suggesting that engine loading has improved the efficiency of combustion processes and energy conversion. The thermal efficiency is significantly higher than that of a diesel engine when hydrogen and nanoparticles are added. The entire spectrum of engine loads exhibits the same characteristic. Diesel's BTE is 30% when the engine is operating at 100% load; H2 at 2 L/min is 31%; H2 at 2 L/min + 25 ppm is 32%; and H2 at 2 L/min + 50 ppm and H2 at 2 L/min + 75 ppm is 33%. This rise in BTE is caused by hydrogen's superior burning properties, such as increased flame speed and flammability constraints. Furthermore, the catalytic properties of nanoparticles increase oxidation, heat transfer rate, and atomization. It produces more heat and consumes less energy during combustion due to its increased efficiency. $H_2$ at 2 L/min + 75 ppm has the highest thermal efficiency of all the fuels used in the trials, indicating the most energy utilization from the fuel used. $H_2$ at 2 L/min + 75 ppm is the engine load with the best brake thermal efficiency. It performs 10% better than full-load diesel. [XX]

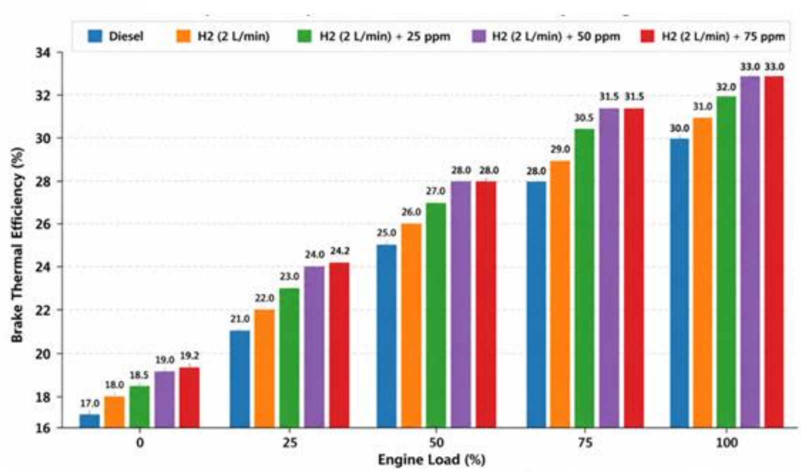


**Fig. 4.** Brake thermal efficiency (BTE) fluctuation with engine load

### IV.ii. Brake Specific Energy Consumption (BSEC)

The relationship between BSEC and engine load for diesel, $H_2$ at 2 L/min, $H_2$ at 2 L/min + 25 ppm, $H_2$ at 2 L/min + 50 ppm, and $H_2$ at 2 L/min + 75 ppm fuel mixes is shown in the figure. As can be observed, BSEC consistently decreases as engine load rises. The use of conventional diesel fuel results in the highest BSEC among all fuels tested. However, when hydrogen and nanoparticles are added to the fuel blend, energy consumption is substantially reduced. In particular, BSEC falls from about 11.8 MJ/kWh for diesel to 11.3 MJ/kWh for $H_2$ at 2 L/min, 10.9 MJ/kWh for $H_2$ at 2 L/min + 25 ppm, 10.6 MJ/kWh for $H_2$ at 2 L/min + 50 ppm, and 10.4 MJ/kWh for $H_2$ at 2 L/min + 75 ppm fuel blends under 100% load conditions. The steady decrease in BSEC with increasing nanoparticle dosage is likely due to higher efficiencies of fuel combustion, better mixing of fuel and air, quicker burning rates, and a higher rate of oxidation. Additionally, hydrogen addition improves energy conversion efficiencies by virtue of having excellent diffusivity and wider flammability ranges. Therefore, compared to pure diesel, the use of hydrogen and nanoparticles results in the lowest BSEC values, suggesting more effective energy conversion. In particular, at all load levels, $H_2$ at 2 L/min + 75 ppm generated the lowest BSEC.

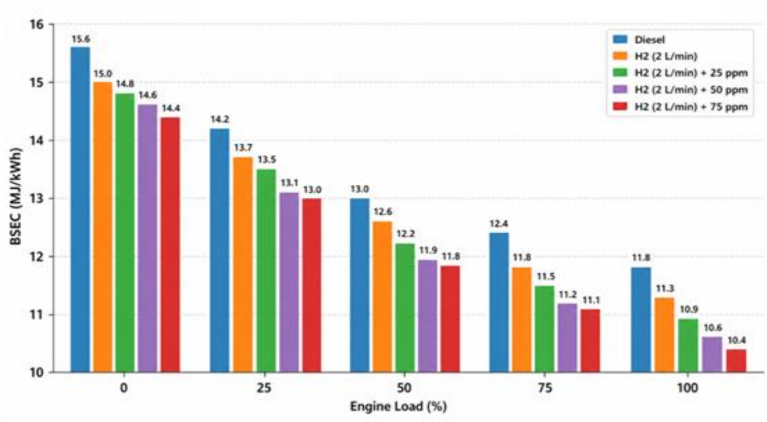


**Fig. 5.** Effect of Engine Load on Brake Specific Energy Consumption

### IV.iii. CO Emission

The graph represents the correlation between CO emissions and engine load for different fuel blends, namely diesel, $H_2$ at 2 L/min, $H_2$ at 2 L/min + 25 ppm, $H_2$ at 2 L/min + 50 ppm, and $H_2$ at 2 L/min + 75 ppm. Emissions of CO decrease as engine load increases in the case of all test blends because of increased oxidation due to high engine load. Emissions of CO are maximum in the case of diesel operation, where they start with about 0.45% vol at zero engine load and then decrease to 0.23% vol at the maximum engine load. Hydrogen fuel blend (2 L/min) shows much lower CO emissions due to the fast-burning nature of hydrogen. The use of nanoparticle additives further decreases CO emissions because of the improved combustion process. CO emissions drop from 0.23 percent in diesel to roughly 0.20 percent in H2 (2 L/min), 0.18 percent in H2 (2 L/min) + 25 ppm, 0.17 percent in H2 (2 L/min) + 50 ppm, and 0.16 percent in H2 (2 L/min) + 75 ppm. Better fuel oxidation, more air-fuel mixing, and catalytic effects from the use of nanoparticle additions could all contribute to the reduction in CO emissions. At all engine loads, it was discovered that the blend with $H_2$ at 2 L/min and 75 ppm nanoparticles had lower CO emissions than other combinations, suggesting improved combustion and more thorough carbon dioxide combustion. The effect on emission reductions of both hydrogen enrichment and 75 ppm nanoparticle additive was the highest among other blends and resulted in a total decrease in CO emissions of about 30%.

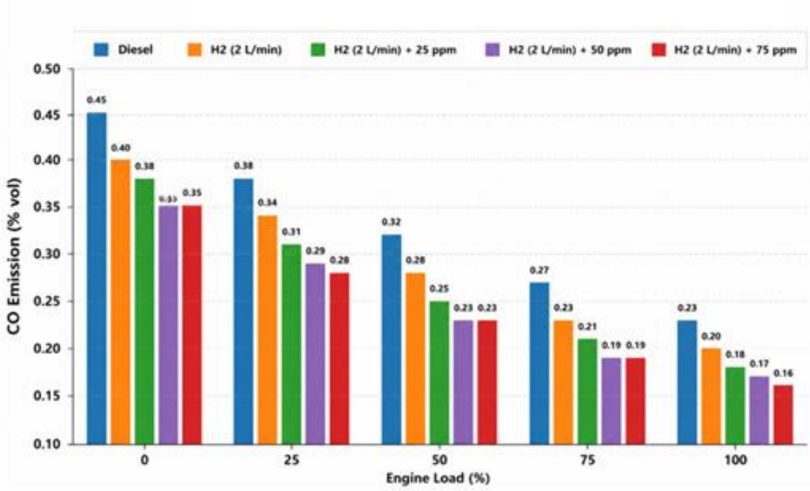


**Fig. 6.** Comparison of Carbon Monoxide (CO) Emissions under Various Engine Loads

### IV.iv. HC Emission

This plot depicts the change in the emissions of hydrocarbons (HC) with respect to engine loading for diesel, $H_2$ at 2 L/min, $H_2$ at 2 L/min + 25 ppm, $H_2$ at 2 L/min + 50 ppm, and $H_2$ at 2 L/min + 75 ppm fuel mixtures. The maximum value of HC emissions occurs in the case of diesel fuel, which decreases gradually from around 72 ppm in the case of zero loading to 42 ppm in the case of maximum loading. Due to better combustion properties of hydrogen, such as high flame propagation velocity, low ignition energy, and better fuel–air mixture, there is a reduction in HC emissions when hydrogen is added. When operated at full load, the HC emissions reduce to 42 ppm when using diesel fuel. For $H_2$ at 2 L/min fuel combination, HC emissions reduce to about 38 ppm; for $H_2$ at 2 L/min + 25 ppm, emissions reduce to about 35 ppm; for $H_2$ at 2 L/min + 50 ppm, emissions reduce to about 32 ppm; for $H_2$ at 2 L/min + 75 ppm, emissions reduce to about 32 ppm. The decrease in HC emissions is due to increased combustion temperatures, improved reaction rates, and the catalytic effect of the nanoparticle additives, which result in complete fuel oxidation. Out of all the fuel combinations used, the $H_2$ at 2 L/min + 75 ppm mixture produces the lowest HC emissions. This indicates that it offers the most efficient combustion with the least quantity of fuel escaping the combustion process. In other words, the combination of hydrogen enrichment with nanoparticle additives leads to substantial decreases in HC emissions compared to the use of diesel fuel. At full load, $H_2$ at 2 L/min + 75 ppm fuel produces a reduction of about 24% in HC emissions compared to diesel fuel.

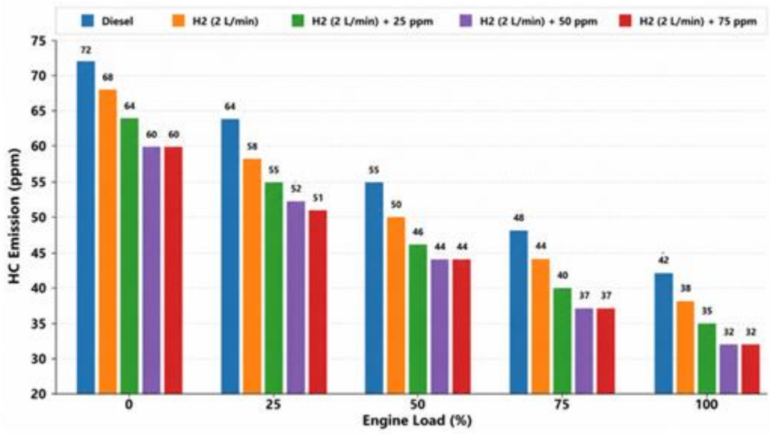


**Fig. 7.** Influence of Engine Load on Hydrocarbon (HC) Emissions

### IV.v. NOx Emissions

The nitrogen oxide (NOx) emission dependency on engine load for diesel, H2 at 2 L/m, H2 at 2 L/m + 25 ppm, H2 at 2 L/m + 50 ppm, and H2 at 2 L/m + 75 ppm fuels is shown in the graph below. In contrast to CO and HC emissions, NOx emissions progressively increase as engine load increases because of increased oxidation processes and cylinder temperature. Diesel operation corresponds to the lowest NOx emissions. At zero load, they are roughly 310 ppm; at full load, they are 680 ppm. When hydrogen is applied, there is an increase in NOx generation because burning hydrogen raises temperatures and increases heat release rates. Nanoparticles contribute to the production of NOx by improving combustion efficiency. At full load conditions, the NOx emissions rise from about 680 ppm for diesel to 730 ppm, 780 ppm, 820 ppm, and 820 ppm for $H_2$ at 2 L/m, $H_2$ at 2 L/m + 25 ppm, $H_2$ at 2 L/m + 50 ppm, and $H_2$ at 2 L/m + 75 ppm, respectively. High combustion temperatures, oxygen concentrations, and oxidation chemistry are important factors in the NOx generation process, which is the primary cause of the rise in NOx emissions in these studies. It is evident that, among all the tested fuel blends, the $H_2$ at 2 L/min + 75 ppm nanoparticle combination produces the highest $NO_x$ emissions under full-load engine operating conditions. This increase is primarily attributed to the enhanced combustion efficiency and elevated in-cylinder combustion temperature resulting from hydrogen enrichment and nanoparticle addition. The higher combustion temperature promotes the thermal $NO_x$ formation mechanism, leading to increased $NO_x$ emissions despite the improvements in combustion characteristics. Therefore, while the combined use of hydrogen and nanoparticles enhances fuel oxidation and overall engine performance, it also intensifies $NO_x$ formation at higher engine loads.

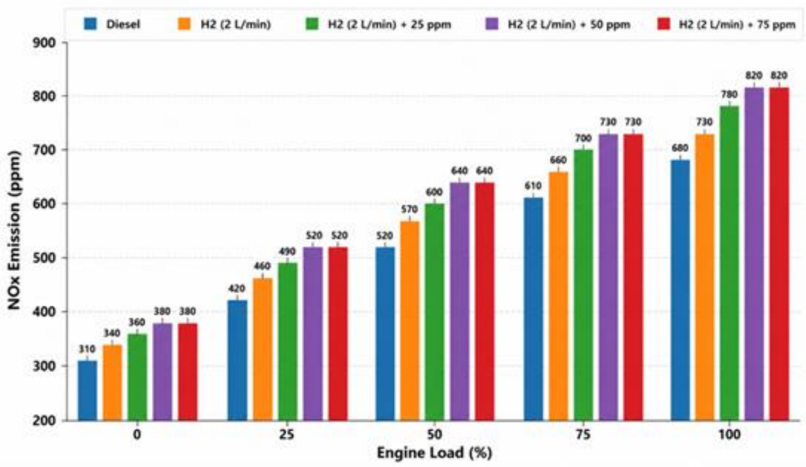


**Fig. 8.** Comparison of $NO_x$ Emissions under Various Engine Loads

## IV.vi. Smoke Emissions

The graph represents how smoke opacity changes with respect to the engine load when using different mixes of Diesel, $H_2$ at 2 L/m, $H_2$ at 2 L/m + 25 ppm, $H_2$ at 2 L/m + 50 ppm, and $H_2$ at 2 L/m + 75 ppm. Smoke opacity reduces gradually with increasing hydrogen content and nanoparticle concentration, which indicates that there is efficient combustion, thus reducing the amount of soot produced. In all the fuel mixes, the smoke opacity reduces as the engine load increases, with diesel having the highest smoke opacity values in comparison to other fuels. Traditional operation of diesel has a smoke opacity value of about 48% at no load, while full load has a smoke opacity value of around 28%. Hydrogen use decreases smoke production because it is a carbonless fuel, has high flame speeds, and is oxidized easily. Nanoparticle additives contribute to efficient combustion by improving fuel atomization, air-fuel mixture, and soot precursor oxidation. Smoke opacity decreases from about 28% with diesel to 24%, 21%, 18%, and 18% for $H_2$ at 2 L/m, $H_2$ at 2 L/m + 25 ppm, and $H_2$ at 2 L/m + 50 ppm + 75 ppm, respectively, at full engine load. These findings suggest that hydrogen fueling with the addition of nanoparticles is effective in reducing soot formation and promoting the oxidation of carbon particles. Hydrogen fueling with an $H_2$ flow rate of 2 L/m and 75 ppm nanoparticles has the minimum smoke opacity for any engine loading, demonstrating excellent performance over the use of diesel fuel. The minimum smoke opacity was achieved by hydrogen fueling and adding 75 ppm nanoparticles. For maximum load conditions, there was a reduction in smoke opacity from 28% for diesel fuel to 18% for hydrogen fueling 2 (L/m), which is about 35.7%.

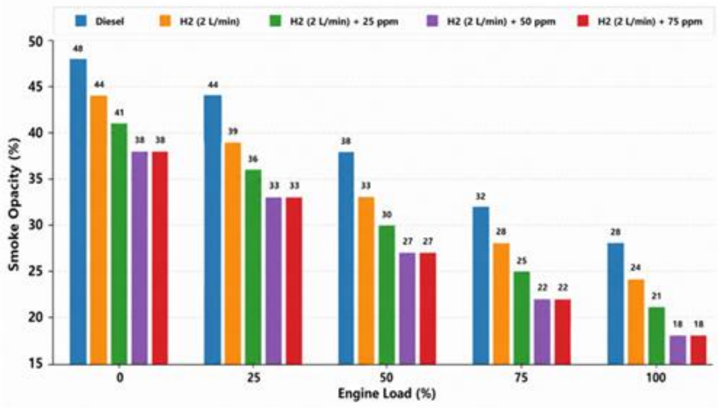


**Fig. 9.** The change of smoke opacity with engine load

### IV.vii. Cylinder Pressure (CP)

The graph shows how cylinder pressure for diesel, $H_2$ at 2 L/m, $H_2$ at 2 L/ + 25 ppm, $H_2$ at 2 L/m + 50 ppm, and $H_2$ at 2 L/min + 75 ppm varies with crank angle. Cylinder pressure increases from the beginning of the compression stroke to the end of the combustion stroke in each of the scenarios studied, after which it decreases during the expansion stroke. Among all the fuels, diesel has the minimum cylinder pressure. This can be explained by the decreased flame speed and flammability. Therefore, at 10° CA, diesel has a maximum cylinder pressure value of roughly 68 bar. Hydrogen is used to improve combustion efficiency due to its large flammability limit and quick flame speed. By adding nanoparticles, the fuel burns more intensely, increasing the cylinder's maximum pressure. At 10° CA, the greatest cylinder pressure readings for diesel, H2 at 2 L/m, H2 at 2 L/m + 25 ppm, H2 at 2 L/m + 50 ppm, and H2 at 2 L/m + 75 ppm are 68 bar, 75 bar, 82 bar, 86 bar, and 90 bar, respectively. The combination of hydrogen and nanoparticles significantly enhances the combustion process by accelerating flame propagation, increasing the rate of heat release, improving fuel atomization, and promoting improved air-fuel mixing. During combustion, all of these factors combine to greatly increase the in-cylinder pressure. Of all the fuel blends tested, the $H_2$ at 2 L/m + 75 ppm nanoparticle blend has the highest peak cylinder pressure due to its superior combustion characteristics and higher energy release rate. In comparison to neat diesel, the peak cylinder pressure increases from 68 bar to 90 bar, representing a 32.4% improvement. This increase shows that the inclusion of nanoparticles and hydrogen enrichment speeds up and completes combustion, increasing the buildup of pressure in the combustion chamber.

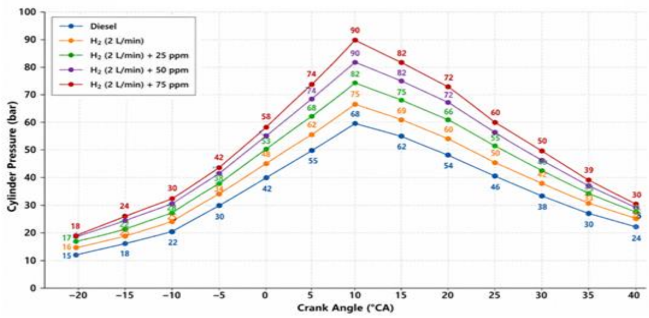

**Fig. 10.** The change of cylinder pressure with crank angle

### IV.viii. Heat Release Rate (HRR)

The graph illustrates how crank angle affects heat release rate (HRR) for fuel blends that include diesel, $H_2$ at 2 L/m, $H_2$ at 2 L/m + 25 ppm, $H_2$ at 2 L/m + 50 ppm, and $H_2$ at 2 L/m + 75 ppm. The heat release rate is initially modest during the ignition delay period, increases dramatically during the premixed combustion process, reaches its maximum value at the 10° crank angle, and then drops during the diffusion combustion and expansion processes at all operating settings. The fuel that displays the minimum heat release rate at all the combustion stages is the diesel one, which gives a maximum value of about 45 J/°CA at 10° CA. Hydrogen addition greatly improves the combustion process since it burns with a very high flame speed, needs a small amount of ignition energy, and is highly diffusive, hence giving out energy faster. The heat release rates (HRR) recorded for diesel fuel at 10° CA are about 45 J/°CA, for hydrogen (2 L/m) – 58 J/°CA, for hydrogen (2 L/m) + 25 ppm – 70 J/°CA, for hydrogen (2 L/m) + 50 ppm – 75 J/°CA, and for hydrogen (2 L/m) + 75 ppm – 82 J/°CA. The enhanced reaction process, better fuel/air combination, and catalytic effects on combustion supported by hydrogen and nanoparticles are the causes of the HRR improvement. The combination of hydrogen (2 L/m) + 75 ppm shows the most intense heat release of all the fuel mixture combinations considered for the entire combustion period as compared to the operation of diesel fuel alone. Hydrogen-enriched diesel with nanoparticles (75 ppm) has the highest heat release rate; the peak heat release increases from 45 J/°CA for diesel to 82 J/°CA, which is equivalent to an 82% increase in HRR.

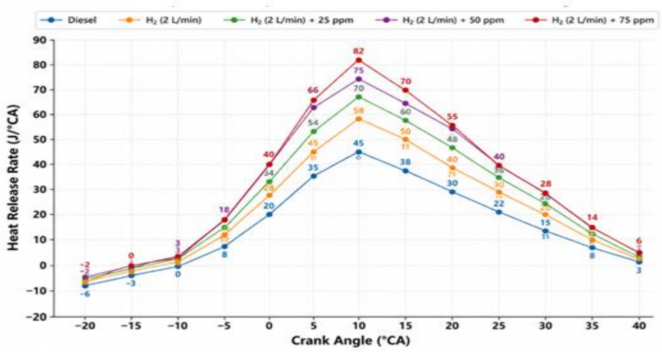

**Fig. 11.** The variation of heat release rate (HRR) with crank angle

## V. Conclusion

This experiment examined the diesel engine's performance, combustion, and emissions utilizing hydrogen enrichment 2 L/m and nanoparticle additions at varying concentrations (25, 50, and 75 ppm). It has been demonstrated that using hydrogen and nanoparticle additions jointly improved the engine's performance and combustion characteristics while also lowering the amount of most harmful gases produced during operation. Both the Brake Specific Energy Consumption (BSEC) and the Brake Thermal Efficiency (BTE) were improved over the engine's whole load range by the usage of hydrogen and nanoparticles. In terms of minimal BSEC and maximum BTE values, the combination of hydrogen 2 L/m and 75 ppm nanoparticle additives demonstrated the optimum engine performance. When compared to standard diesel combustion modes, hydrogen-enriched nanoparticle mixes showed improved in-cylinder combustion parameters. It was discovered that the maximum cylinder pressure increased from roughly 68 bar for diesel to 90 bar for the mixture of $H_2$ at 2 L/m and 75 ppm, while the maximum heat release rate increased from 45 J/°CA for diesel to 82 J/°CA, indicating faster energy release and higher combustion intensity. The emission results clearly show that as nanoparticle concentrations increased, CO, HC, and smoke opacity significantly decreased. Maximum reduction of emissions was seen in the case of the $H_2$ at 2 L/m + 75 ppm blend owing to its higher efficiency of combustion. However, because of the increased oxidation reaction rate and combustion temperature, it was discovered that the NOx emissions were significant. The findings show that using hydrogen-assisted combustion in conjunction with nanoparticles as an additive has the potential to improve diesel engine efficiency and reduce particulate matter emissions.

**Conflict of Interest:**

The authors declare that there was no relevant conflict of interest regarding this paper.

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