

Impact of Multi-Walled Carbon Nano Tubes in Diesel Engine Combustion with Hydrogen as Supplementary Fuel

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Abstract

The objective of this experiment is to investigate the effect of multiwalled carbon nanotubes, combined with hydrogen as a supplementary fuel, on the efficiency, combustion, and emissions of a diesel engine test rig. In three phases, tests were conducted. In the initial attempt, pure diesel and hydrogen at 0.047, 0.077, 0.101, and 0.121 kg per hour (F1-F5). In the second phase, diesel with 60 ppm concentration of MWCNT and hydrogen at 0.047, 0.077, 0.101, and 0.121 kg per hour (F6-F10). In the third phase, diesel with 90 ppm concentration of MWCNT and hydrogen at 0.047, 0.077, 0.101, and 0.121 kg per hour (F11-F15). It was recorded that the output thermal efficiency improved with hydrogen injection at 0.121kg per hour in all three phases, to 27.65%, 23.47%, and 25.97% compared to diesel, diesel with 60 ppm, and diesel with 90 ppm. The specific fuel consumption was reduced by 32.43%, 23.52% and 25.71%, respectively. CO emissions are reduced by 37.5%, 50%, and 27.27% in three phases, and CO₂ emissions are reduced by 16.66%, 35%, and 11.11%, respectively. Hydrocarbon emissions were mitigated by 40%, 55% and 65% compared to baseline fuels. Smoke emissions were also reduced by 56%, 70% and 76%, whereas nitric oxide emissions were increased by 38.64%, 11.03% and 28.6% among the three phases compared to baseline fuels. As cylinder peak pressure are concerned in phase 1 the pressure was increase by 29.12%, in the second phase and third phase the pressures are recorded highest value of peak pressure of 85 bar at 371 crank angle and net heat release was increased by 46.14%, 16.18% and 5.2% at crank angle 363 deg, in the third phase for all the hydrogen injection rates heat release was found very high.

Keywords: hydrogen; multiwall carbon nano tubes(MWCNT); nitric oxide; particulate matter; sonication.

Introduction

The exergetic assessment was done using jet fuel and hydrogen fuel on a turbojet engine. Parametric analysis concluded that exergy efficiency was reduced 1.67% when hydrogen fuel was used. With hydrogen operation, the ecological and environmental effect will be improved. Balli et al., (2018). Research was conducted using diesel and diesel plus hydrogen mixtures on an air-cooled engine at full load, and hydrogen was injected at 5, 10, 15 and 20%, after which the volumetric efficiency was compared. Batmaz (2013). A thermodynamic bi-zonal model used for the analysis in K9K Renault engine operated at 2000 rpm and energy substitution was upto 55% results recorded that hydrogen enhanced fuel atomization, accelerated mixture formation and vaporization with shorter ignition delay Cernat et al. (2020) and Pana et al. (2021). The supplementary fuels hydrogen and producer gas in an engine operating 1500 rpm and combustion parameters were studied at different load conditions the cycle pressure was increased when hydrogen was used nearly 30%. Still, when producer gas was used the pressure was reduced, Dhole et al. (2014, 2016a, 2016b).

Experiment was conducted on two different chambers hemispherical and re-entrant with dual fuel injection with hydrogen at 8 lpm and neem methyl ester was used to understand performance and emissions with an injection pressure of 600-1000 bar, results recorded peak pressure and heat energy and brake efficiency was increased by 3.02% and reduction in emissions were observed whereas there was an increase in nitric oxide emissions Halewadimath et al. (2020). Due to flammability, faster diffusion rates and rapid characteristics of combustion and also enhances fuel burning in compression ignition engine hydrogen was considered as alternative fuel. The performance and emissions were focused by injecting hydrogen-rich air at a flow rate of 25 lpm under an EGR system, and results recorded

decrement of emissions significantly. Hoang and Pham, (2020), supplying hydrogen-rich air through the intake manifold using an integrated EGR system improved combustion efficiency and reduced particulate matter and NO_x emissions. The enhanced combustion was attributed to hydrogen's high diffusivity, wide flammability limits, and fast burning velocity, which enable more complete combustion of the fuel–air mixture. Apart from performance and emission studies, some researchers have investigated the dynamic behaviour of engines operating with hydrogen-assisted fuels, Javed et al. (2016).

Researchers focussed on specific fuel consumption and emissions by injecting small quantities of hydrogen along with intake air into the inlet manifold of a diesel engine and the results were demonstrated reduction in specific fuel consumption by 11.53% and increment of BTE 4.85%, emissions were also decreased whereas slight increase in nitric oxide emissions with minimal change in combustion characteristics, Kamaraj et al. (2020). Studies focussed on supplementary fuel as hydrogen in diesel engine with a share of 30% of energy as like split injection first diesel then hydrogen, engine running at 100 rpm and the parameters were analysed at loads 40%,60% 75% and 100%. At partial loads, the performance and emissions were reduced, but NO was increased at full load. Hydrogen was injected at 25%,50%, and energy share through the intake manifold when the engine was running at 750 to 2100 rpm to analyse engine output parameters. Results recorded a reduction in emissions, whereas nitric oxide emissions were increased Karagöz et.al., (2015, 2016).

Experiments are conducted using a hydrogen energy supplement at 0.2- 0.8 litres per minute to understand engine output parameters. Results have shown reduced emissions at 0.8 lpm of hydrogen, whereas nitric oxide emissions are increased at higher loads, Koten et al. (2018). The impact of hydrogen and di-tert-butyl peroxide (DTBP) are used to control nitric oxide emissions in a single cylinder engine with an rpm of 1500. Experiments were conducted with and without (DTBP). Results were recorded for 14% hydrogen 1% (DTBP). The temperature was decreased, and heat release was decreased by 10% and 2%, respectively. Studies evaluated ignition delay in a hydrogen diesel dual fuel engine with and without (DTBP). The delay values were compared with the Hardenberg–Hase equation and its modified form, the ignition delay values 6.6-21.22% and 1.2-11.96%, respectively. In addition, 5% DTBP significantly reduced the ignition delay, and the polytropic index was increased during combustion. Further, the studies have extended the effect of di-tert butyl peroxide additive in a hydrogen–diesel dual–fuel engine to improve performance and reduce emissions. Results recorded that the addition of 1-5% DTBP with 40% energy of hydrogen substitution significantly increased brake thermal efficiency at low load conditions. The addition of DTBP of 4% reduced NO emissions up to 33.82%, Kumar et.al.(2020a,2020b,2020c).

To predict combustion parameters, brake thermal efficiency, and mean gas temperature on a dual fuel engine using hydrogen, LPG and their mixtures as supplementary fuels. Using empirical equations, spray mixing, flame propagation, and equilibrium combustion products are processed. The values obtained are compared to the experimental values of multi cylinder turbocharged and single cylinder engines. The predicted values have shown close agreement with experimental readings. Studies focused on ignition delay on a 4D cylinder turbocharged diesel engine operable on hydrogen, LPG and mixtures of these as secondary fuels. The conduction of experiments and ignition delay were compared with the existing values. Results recorded the variations of about 6.56-14.6% for dual fuel and 33.3% for pure diesel. It's understood from the results that ignition delay depends on fuel type, gaseous fuel concentration, charge temperature, and oxygen concentration. Further studies have expanded to combustion characteristics of the same engine and same fuels as secondary, the results have demonstrated for 30% hydrogen substitution increased pressure and combustion duration compared to diesel operation similarly LPG substitution enhanced pressure but heat release was declined in the first combustion phase, but the hydrogen LPG mixture (70:30) proved better performance with effective impact on combustion parameters and reduced combustion duration Lata, D. B. et. al, (2010,2011a,2011b).

Exhaust gas recirculation (EGR) along with hydrogen was studied on a single-cylinder dual-fuel system. In this study, the energy shares of hydrogen 0%,10% and 30%, and EGR rates from 0-10%. Results recorded without affecting the brake thermal efficiency, the emissions NO, CO₂, CO, THC and PM are reduced by 27.4,33.4,32.3 and 20%, Nag, et al. (2019). Tamanu methyl ester (TME) ethanol blends with hydrogen induction were studied to improve performance and reduce emissions. Ethanol could be blended with biodiesel up to 30% have reduced emissions and improved performance without modifying the engine Parthasarathy, et al. (2015). Researchers focused on gaseous fuels to reduce emissions and consumption of liquid fuels, using natural gas, biogas, producer gas, methane, LPG and propane. Results declared that the dual fuel concept effectively reduced NO and PM emissions, and specific fuel consumption was increased at part loads; engine performance was improved at higher loads (Sahoo et al., U.K. 2009).

Studies investigated the usage of hydrogen diesel fuel combustion in a modified diesel engine at different engine speeds and injection strategies. Results recorded a reduction of smoke emissions and an increase in nitric oxide emissions. To

control nitric oxide emissions, water was injected into the intake manifold, and a reduction of 50% and an efficiency of 37% was recorded Serrano, et.al (2019). Air fuel ratio significantly improves the efficiency of the engine and reduces the emission effect on the environment. It also improves the performance and emission parameters as the engine speed is increased, as hydrogen diffusion and air fuel homogeneity enhance the combustion process. Simultaneously, material selection and engine components, valves play an important role, Sing, L. K. (2015). Investigations have been done on a hydrogen–diesel dual fuel model with different hydrogen energy shares. Increasing the hydrogen consumption reduced the fuel consumption, and in turn improved performance, whereas nitric oxide emissions were increased significantly. Suzuki, et.al (2015).

Studies focused on engine simulation software. The combustion chamber was modelled using both the standard and modified configurations in AVL-FIRE at 2000 rpm. It was observed that the modern combustion chamber improved mixture formation and evaporation rate compared to the standard combustion chamber. Increased pressure, temperature, flame velocity and net heat release rate were observed; CO and NO emissions were also reduced by 6% and 32%, respectively, for the modern combustion chamber. Temizer, et al. (2021). Researchers used microalgae bio diesel, hydrogen and hydroxyl gas in a diesel engine, and the results show that emissions are reduced, but brake power and torque were also reduced, while CO₂ was also increased. Uludamar, E. (2018).

A diesel–bio gas dual fuel engine with hydrogen as a supplement has been studied from 5-20% to improve performance and emissions. At higher loads, the hydrogen impact was greater when compared to low loads in terms of peak pressure and heat energy. The author also used exergy analysis to identify irreversibility in engine processes Verma et al., (2018). Substantial research has been conducted on dual fuel to improve the performance and emissions, however only limited studies have focusses on nanoparticles. In this research multi-walled carbon nano tubes at 60 and 90 ppm dosages per one litre with the injection of hydrogen at 0.047, 0.077, 0.101, and 0.121 kg per hour during suction stroke at a pressure of 2bar was investigated and the same hydrogen injection was done for pure diesel was experimented.

Table 1 Summary of introduction

Fuel / Strategy	BP	BTE	BSFC / SFC	ICP / HRR	HC	CO	NOx	CO ₂	Smoke / PM	Ref
Hydrogen fuel in turbojet engine (exergy study)	↑	↑	↓	↑	↓	↓	↑	↓	↓	Balli et al. (2018)
Hydrogen fuel in diesel engine	↑	↑	↓	↑	↓	↓	↑	↓	↓	Batmaz (2013)
Hydrogen influence on vaporization & combustion	—	↑	↓	↑	↓	↓	↑	↓	↓	Cernat et al. (2020a)
Hydrogen as alternative automotive diesel fuel	↑	↑	↓	↑	↓	↓	↑	↓	↓	Cernat et al. (2020b)
Hydrogen + producer gas dual fuel	↑	↑	↓	↑	↓	↓	↑	↓	↓	Dhole et al. (2016a)
Ignition delay & combustion duration study	—	↑	↓	↑	↓	↓	↑	↓	↓	Dhole et al. (2016b)
Mathematical modelling of H ₂ dual fuel engine	↑	↑	↓	↑	↓	↓	↑	↓	↓	Dhole et al. (2014a)
Performance & emissions using H ₂ + producer gas	↑	↑	↓	↑	↓	↓	↑	↓	↓	Dhole et al. (2014b)
Hydrogen enriched producer gas (HPG) in CRDI engine	↑	↑	↓	↑	↓	↓	↑	↓	↓	Halewadimath et al. (2020)
Hydrogen + EGR emission reduction strategy	—	↑	↓	↑	↓	↓	↓	↓	↓	Hoang & Pham (2020)
Hydrogen dual fuelling with nanoparticles	↑	↑	↓	↑	↓	↓	↑	↓	↓	Javed et al. (2016)
On-site hydrogen generation CI engine	↑	↑	↓	↑	↓	↓	↑	↓	↓	Kamaraj et al. (2021)
Hydrogen enrichment at different engine loads	↑	↑	↓	↑	↓	↓	↑	↓	↓	Karagöz et al. (2015)
Hydrogen–diesel dual fuel combustion study	↑	↑	↓	↑	↓	↓	↑	↓	↓	Karagöz et al. (2016)
Hydrogen performance & emission characteristics	↑	↑	↓	↑	↓	↓	↑	↓	↓	Koten (2018)
Hydrogen + DTBP additive effect on NOx	↑	↑	↓	↑	↓	↓	↓	↓	↓	Kumar & Lata (2020a)
DTBP additive ignition delay analysis	—	↑	↓	↑	↓	↓	↓	↓	↓	Kumar et al. (2020b)
DTBP additive performance & emissions	↑	↑	↓	↑	↓	↓	↓	↓	↓	Kumar et al. (2020c)
Hydrogen + LPG dual fuel engine	↑	↑	↓	↑	↓	↓	↑	↓	↓	Lata & Misra (2010)
Ignition delay study (H ₂ + LPG)	—	↑	↓	↑	↓	↓	↑	↓	↓	Lata & Misra (2011)
Combustion parameters H ₂ + LPG	↑	↑	↓	↑	↓	↓	↑	↓	↓	Lata et al. (2011)
Hydrogen diesel dual fuel with EGR	↑	↑	↓	↑	↓	↓	↓	↓	↓	Nag et al. (2019)
Hydrogen + ethanol–biodiesel blend	↑	↑	↓	↑	↓	↓	↑	↓	↓	Parthasarathy et al. (2015)
Dual-fuel gaseous engine review study	—	—	—	—	↓	↓	↑	—	↓	Sahoo et al. (2009)
Hydrogen/diesel ratio with water injection	↑	↑	↓	↑	↓	↓	↓	↓	↓	Serrano et al. (2019)
Hydrogen fuelled engine design study	—	↑	↓	↑	↓	↓	↑	↓	↓	Sing (2015)
Multi-cylinder hydrogen/diesel engine	↑	↑	↓	↑	↓	↓	↑	↓	↓	Suzuki et al. (2015)
Combustion chamber geometry with hydrogen	↑	↑	↓	↑	↓	↓	↑	↓	↓	Temizer & Cihan (2021)
Hydroxyl & hydrogen addition with biodiesel	↑	↑	↓	↑	↓	↓	↑	↓	↓	Uludamar (2018)

Materials and Methods

To understand the functional groups and surface chemical characteristics of multiwall carbon nanotubes the analysis of Fourier Transform Infrared Spectroscopy was conducted. The obtained spectrum was examined for the selected wavenumber range to understand the bonding features of MWCNT shown in Figure 1. The graphite structure of MWCNT at band 1644 cm^{-1} which corresponds C=C stretching vibrations of sp^2 -hybridized carbon [Carbon 46 (2008) 833–840]. The graphite framework of carbon was observed may also be attributed to aromatic C=C skeletal vibrations at peak 1541 cm^{-1} . The functional groups carbonyl, carboxyl, and hydroxyl groups on the surface of nanotubes were observed as the peaks are observed at 1746 cm^{-1} , 1368 cm^{-1} , and 1007 cm^{-1} [Carbon 46 (2008) 833–840, *Advanced Materials* 17 (2005) 17–29]. The broad band 3279 cm^{-1} corresponds O–H stretching which signifies hydroxyl groups and adsorbed moisture. The C–H stretching vibration of aliphatic groups were observed at peak 2919 cm^{-1} . The peak at 2340 cm^{-1} corresponds to atmospheric CO_2 absorption, which is not intrinsic to the MWCNT sample.

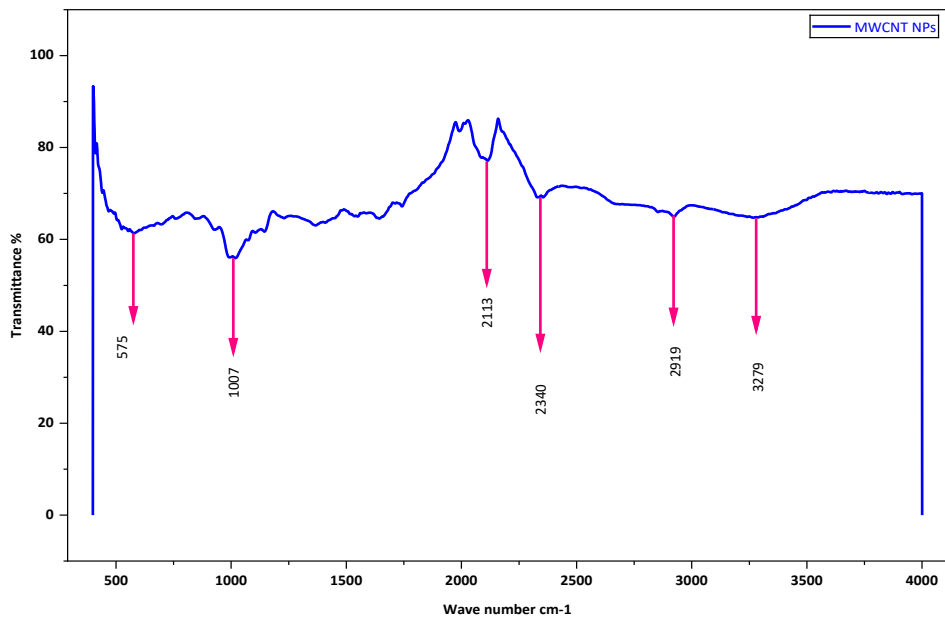


Figure 1 Fourier transform infrared spectroscopy spectrum.

Table 2 FTIR phase identification

Peak position cm^{-1}	Assignment	Phase indicated
3279	O–H Stretching	Surface hydroxyl groups/ adsorbed
2919	C–H Stretching	Aliphatic hydrocarbon groups
2340	CO_2 Asymmetric stretching	Atmospheric CO_2
2113	Combination / overtone band	Carbon framework vibration
1746	C=O stretching	Carbonyl/ carboxyl groups
1644	C=C Stretching	Graphite carbon structure
1541	C=C Skeletal vibration	Aromatic carbon frame work
1368	C–O Stretching	Oxygen containing functional groups
1007	C–O Stretching	Alcohol / ether groups
575	c-c skeletal vibration	Carbon nanotube framework

Figure 2 demonstrates the pattern of XRD of multi-walled carbon nanotubes confirming the successful formation of graphite carbon peaks. From the pattern at $2\theta = 25\text{--}26^\circ$ a dominant peak corresponds (002) to graphite carbon which in turn indicates well organized graphene layers within MWCNT structure. It was understood that this peak indicates the presence of nanoscale crystallinity and partially structural disorder which is normally observed in synthesized MWCNT through catalytic route. The broadening indicates defects and curvature of graphene walls and a finite crystalline dimension of nanotubes. At $2\theta \approx 42\text{--}44^\circ$ a weaker diffraction feature was observed and attributed to (100) graphitic carbon which in turn supports graphitic nano framework. The synthesized MWCNT possesses good purity phase as strong impurity peaks were not observed at higher diffraction region such as (Fe, Co, or Ni particles). The weak bands are observed at $45\text{--}55^\circ$ region which are the traces of amorphous carbon or residual metallic catalyst remnants. The

diffraction profile demonstrates a partially crystalline graphitic structure with characteristic carbon ordering, which is advantageous for enhancing thermal conductivity, catalytic activity, and combustion enhancement when used as fuel nano-additives in diesel-based systems. The observed graphitic crystallinity may facilitate improved heat transfer and oxygen adsorption during combustion, thereby contributing to enhanced oxidation behaviour.

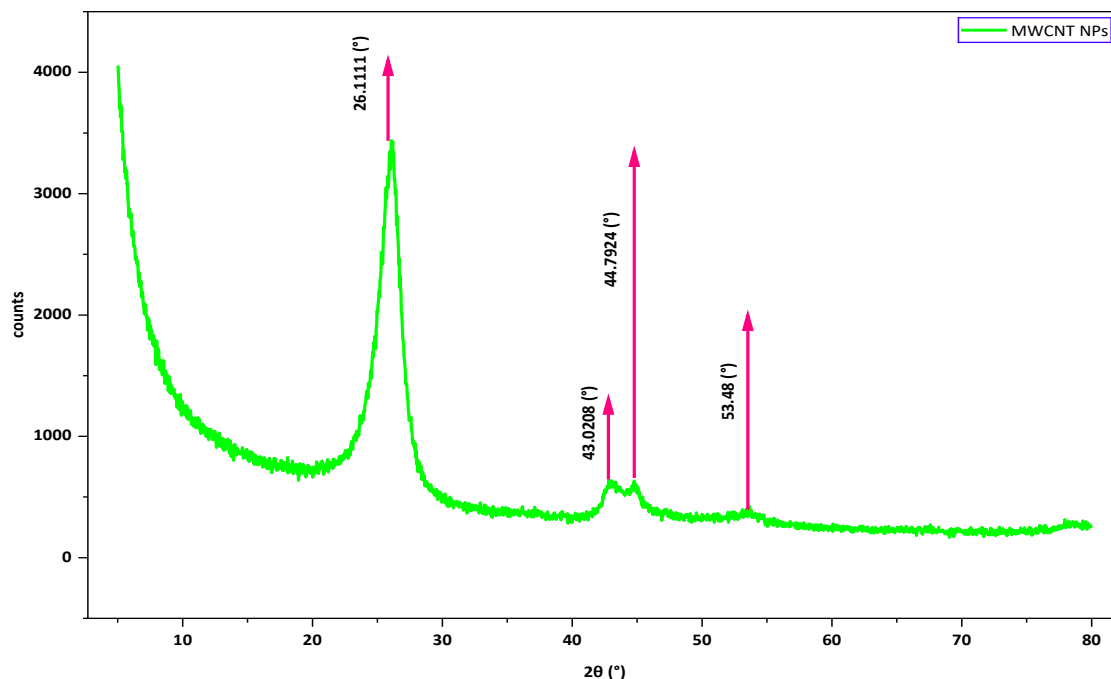


Figure 2 X-Ray diffraction of MWCNT.

Table 3 XRD profile parameters.

Position 2θ	Height [cts]	FWHM Left [°2θ]	d- spacing [Å°]	Rel.Int.%
26.1111	2764.47	0.4546	3.4128	100.00
43.0208	264.79	0.4546	2.10254	9.58
44.7924	240.3	0.3897	2.02341	8.69
53.48	67.52	0.7793	1.71319	2.44

FESEM Images of Multiwalled carbon nano tubes

Figure 3 depicts the morphology of synthesized MWCNT, which was tested using field emission scanning electron microscopy. The obtained image confirms the presence of entangled and fibrous tubular nanostructures of MWCNT. These tubes are oriented randomly and interconnected network which is a characteristic morphology of MWCNT. These nanotubes exhibit high aspect ratio and cylindrical morphology which signifies concentric graphite walls. The strong van der Waals forces between adjacent nanotubes which reflect as agglomerated nanotubes. Despite of partial agglomeration the framework of tubes are clearly distinguishable and demonstrating structural integrity and continuity of nanotube network. The image further exhibits porous and interconnected structure which provides effective surface area and enhanced adsorption characteristics. This sort of morphology is very much beneficial in fuel additive applications as it increases the surface interaction which promotes better fuel atomization, enhanced heat transfer and catalytic oxidation in the combustion process as there is no presence of bulky particles too.

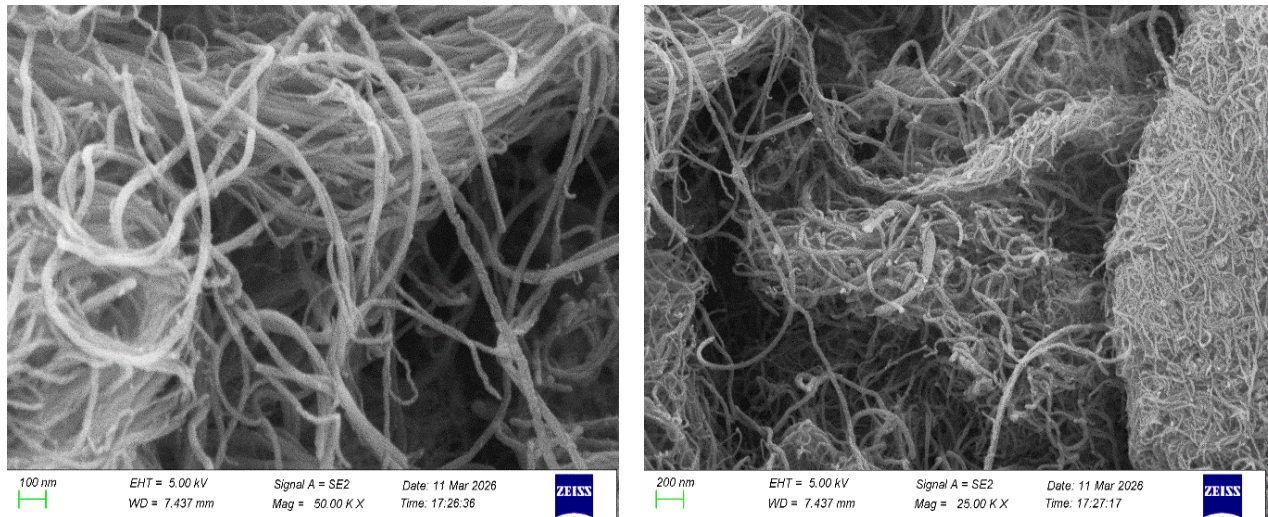


Figure 3 SEM images of MWCNT.

Figure 4 demonstrates the surface plot analysis of the multiwalled carbon nanotubes (MWCNTs), which revealed a highly irregular and heterogeneous topographical structure characterized by noticeable surface roughness and nanoscale height variations. The three-dimensional surface profile revealed interconnected nanotube networks with localized agglomerated regions, attributed to strong van der Waals interactions between adjacent nanotubes. Such surface irregularities indicate a high effective surface area, which is advantageous for enhanced physicochemical interactions. The observed topography further suggests the existence of a porous and non-uniform surface architecture, which may facilitate improved adsorption behaviour and enhanced catalytic activity during combustion applications. The elevated surface features and valleys observed in the surface plot indicate the presence of nanoscale structural complexity, which increases the number of active sites for fuel–nanoparticle interactions.

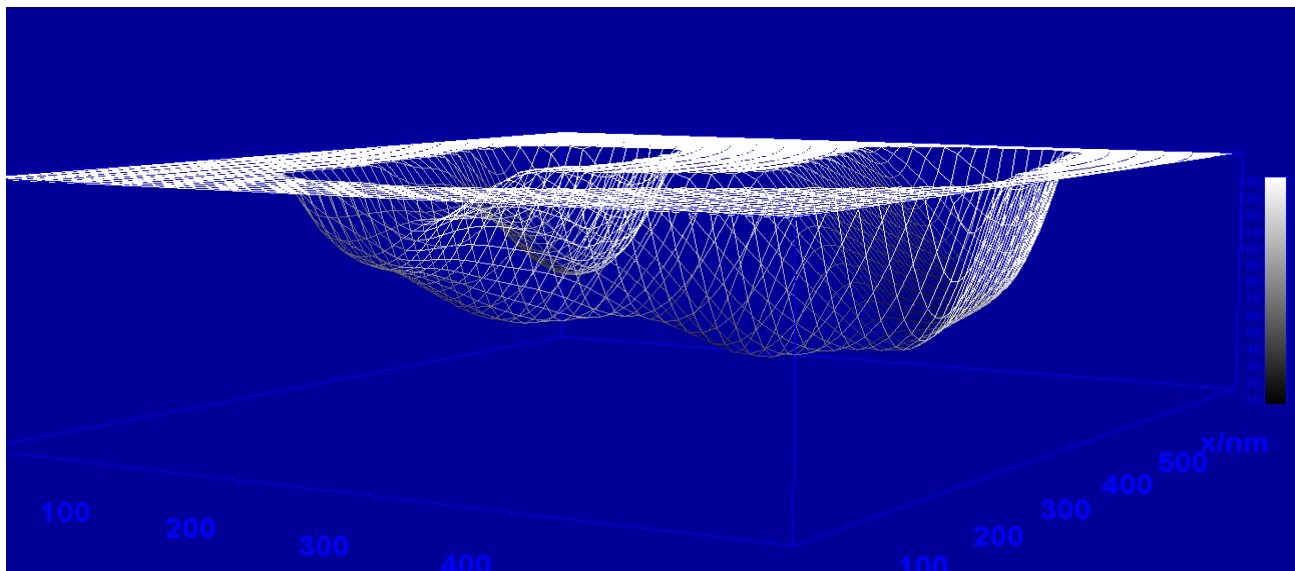


Figure 4 Surface plot of MWCNT at 100 nm.

Additionally, the rough surface texture of MWCNTs may improve dispersion and interfacial contact within fuel blends, thereby enhancing heat transfer and oxidation behaviour. The interconnected nanoscale morphology observed from the surface profile confirms the structural integrity of the nanotube network. It supports its suitability as a combustion-enhancing nano-additive in diesel engine applications. Overall, the surface plot confirms that the multiwalled carbon nanotubes exhibit a rough, porous, and interconnected nanoscale morphology with significant surface heterogeneity, which is expected to contribute positively toward combustion improvement, emission reduction, and fuel oxidation enhancement.

Methodology

The experimental investigation was conducted in three sequential phases to evaluate the individual and combined effects of hydrogen enrichment and multi-walled carbon nanotubes (MWCNTs) on the combustion, performance, and emission characteristics of the diesel engine. Phase 1 established the baseline performance of neat diesel and hydrogen-enriched diesel. Neat diesel was used as the reference fuel (F1), while hydrogen was subsequently introduced at mass flow rates of 0.047, 0.077, 0.101, and 0.121 kg h⁻¹, corresponding to test fuels F2–F5, respectively. The hydrogen was supplied to the engine through the designated hydrogen delivery system and its flow rate was controlled and monitored using a calibrated flow-measuring device. All other engine operating and measurement conditions were maintained identical to those used for the reference diesel condition.

In Phase 2, the effect of MWCNT addition and its combined interaction with hydrogen was investigated. MWCNTs were dispersed in neat diesel at a concentration of 60 ppm to obtain the F6 nanofuel. The MWCNT–diesel mixture was prepared using an appropriate dispersion procedure to minimize particle agglomeration and ensure uniform distribution throughout the fuel. The 60 ppm MWCNT fuel was subsequently tested with hydrogen supplementation at 0.047, 0.077, 0.101, and 0.121 kg h⁻¹, designated as F7–F10, respectively. Phase 3 followed the same experimental procedure using a higher MWCNT concentration of 90 ppm. Neat diesel containing 90 ppm MWCNT was designated F11, while F12–F15 represented the corresponding MWCNT–diesel fuel supplemented with hydrogen at 0.047, 0.077, 0.101, and 0.121 kg h⁻¹, respectively. Thus, a total of 15 fuel conditions were evaluated, enabling systematic assessment of the effects of hydrogen flow rate at two different MWCNT concentrations.

For each experimental condition, the prepared fuel was introduced into the engine under the same prescribed operating conditions, and sufficient time was allowed for the engine to reach steady-state before data acquisition. The fuel consumption, air-flow rate, engine load, and relevant temperature and pressure parameters were recorded using calibrated measurement instruments. Combustion characteristics were evaluated from the measured in-cylinder pressure data, while exhaust emissions were determined using the installed gas and smoke meter. The measured parameters were subsequently compared with those obtained using neat diesel to quantify the influence of MWCNT addition, hydrogen enrichment, and their combined application.

To ensure experimental reliability, the same fuel preparation, engine warm-up, stabilization, measurement, and data-recording procedures were followed for all 15 test conditions. Measurements are repeated under each condition, and the mean values should be reported together with the corresponding uncertainty or standard deviation. The experimental matrix is summarized in a systematic basis for evaluating the effects of MWCNT concentration (0, 60, and 90 ppm) and hydrogen flow rate (0, 0.047, 0.077, 0.101, and 0.121 kg h⁻¹) on engine performance, combustion behaviour, and exhaust emissions.

Diesel engine performance characteristics were evaluated to quantify the influence of multiwall carbon nanotubes (MWCNT) diesel blends on engine output key parameters under steady state operating conditions using standard diesel engine test rig in fig 5. Experimentation was conducted on Kirloskar TV1 engine, the injection of fuel with is at 23 bTDC with an injection pressure of 250 bar for all the test runs. The engine was allowed to reach steady state for 20 to 25 minutes prior to data acquisition to attain steady state operating conditions. Experimentation was done with neat diesel and subsequently with Nanoparticle blends at a dosage of 60 and 90ppm along with hydrogen. At each load the engine was stabilized for 5 min after performance parameters were recorded, fuel consumption was measured using a burette and stopwatch method while air flow was determined by means of an air box and a U tube manometer. Brake torque was measured by eddy current dynamometer.

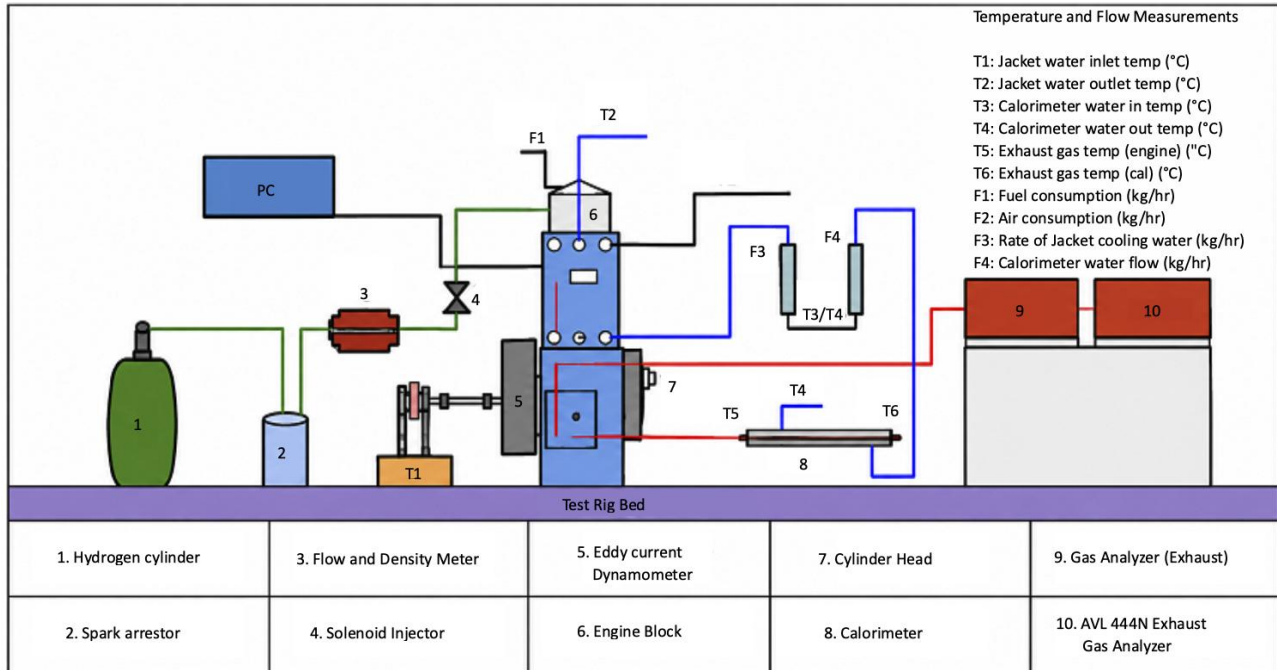


Figure 5 Test rig schematic diagram.

Table 4 Engine specifications

Component of engine	Specification
Power output	5.20kW
Speed	1500rpm
Internal diameter	87.50mm
Length of the stroke	110.00mm
Conrod length	234.00mm
Ratio of compression	17.50:1
Displacement of the Engine	661cc

Error Analysis

Using Standard Deviation (Variance) Method

Unpredictability in conduction of experiment is crucial for evaluating reliability and reproducibility of measured values. The overall error is incurred due to calibration of instruments, observational limits, environmental conditions and the procedures of the experiment are summarized in the table 4, resulting an overall error of 3.268% using root –sum-square approach.

The uncertainty of a dependent variable y with respect to independent variables x is expressed as:

$$V(Y, Xi) = F(X_1 + (VX_1), X_2 + V(X_2), \dots, X_n + V(X_n)) - F(X_1, X_2, \dots, X_n) \quad (1)$$

Using Taylor series expansion, the combined uncertainty is given by:

$$V_c(Y) = \sqrt{\left(\left(\frac{\partial Y}{\partial X_1} V X_1\right)^2 + \left(\frac{\partial Y}{\partial X_2} V X_2\right)^2 + \dots + \left(\frac{\partial Y}{\partial X_n} V X_n\right)^2\right)} \quad (2)$$

The experimentation considers all parameters are statistically independent and sensitive coefficients are taken as unity, therefore the overall error reduced to the standard variance program form:

$$\sigma_{total} = \sqrt{(\sigma^2_1 + \sigma^2_2 + \dots + \sigma^2_n)} \quad (3)$$

Unpredictability

The repeatability values of the measured parameters are considered as standard deviations

Table 5 Uncertainty values

Parameter	Uncertainty
Operating speed (S)	±0.6
Applied Load (L)	±0.2
Peak Pressure (cylinder) (P)	±0.1
Mass flow of fuel (F)	±1.0
Mass of air flow (A)	±0.4
Tail pipe temperature (EGT) (E)	±0.2
Consumption of fuel (specific) (B)	±1.2
Carbon monoxide (C)	±0.2
Hydro Carbon emissions (H)	±0.2
Nitric Oxide emissions (N)	±0.2
Smoke emission (SM)	±0.1
Speed of the stirrer (SS)	±1.0
Density of fuel (FD)	±0.001
Flash point (FP)	±2.0
Kinematic viscosity (KV)	±0.1
Calorific value (CV)	±0.2
Hydrogen mass flow (MF)	±0.1
Density (Coriolis meter) (CM)	±0.0005
Cetane number (CN)	±1.0

Squaring each uncertainty:

$$\sigma_{total} = \sqrt{[(0.6)^2 + (0.2)^2 + (0.1)^2 + (1)^2 + (0.4)^2 + (0.2)^2 + (1.2)^2 + (0.2)^2 + (0.2)^2 + (0.2)^2 + (0.1)^2 + (1.0)^2 + (0.001)^2 + (2.0)^2 + (0.1)^2 + (0.2)^2 + (0.1) + (0.0005) + (1.0)^2]} \\ = \pm 3.268$$

Within any experimental investigation error analysis is crucial for revealing the magnitude of uncertainties associated with the measurement. Errors can occur due to various causes, including calibration, instrumentation, observation, environmental circumstances and test planning. Table 5 provides the percentage uncertainty for each individual parameter, and the total percentage of uncertainty was determined using equation1 to be ±3.268%.

Combustion Analysis Procedure

For combustion analysis, a piezoelectric pressure sensor mounted on the cylinder head was connected to a charge amplifier, in turn connected to a data acquisition system, which measures the in-cylinder pressure during the combustion process. The inside cylinder pressure was synchronized, and the crank angle signal was recorded using a data acquisition system, which is incorporated with combustion analysis software. The peak cylinder pressure and the actual crank angle were directly taken as a result of the pressure crank angle graph. The cumulative heat release was generated by taking the integration of the heat release rate within the range of the crank angle.

Emission Analysis Procedure

Emission evaluation was carried out on the diesel engine test rig operated with diesel as base line fuel, diesel- Nano blends and diesel. Nanoparticles were uniformly dispersed in diesel at the desired concentrations, and the engine was operated at a constant speed under different load conditions. Prior to measurement, the engine was allowed to attain a steady state condition. Exhaust emissions of hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO₂), and oxides of nitrogen (NO/NO_x) were measured using a calibrated multi-gas exhaust analyser as shown in Figure 6. Smoke opacity was determined by using standard smoke meter shown in Figure 6. At each point emission readings were recorded after analyser stabilization and averaged over a fixed sampling period. Each test was repeated for to ensure

repeatability. The observed emissions were correlated with operating parameters such as load and fuel flow rate to evaluate the combined influence of nanoparticles on exhaust emissions characteristics.



Figure 6 Emission measuring equipment.

Experimental Setup

The test engine used for the experiment is a common-rail direct-injection engine with a pressure sensor to capture the peak cycle pressure as a function of crank angle. The necessary instrumentation, AVL 444 five-gas analyser, along with the smoke meter, was connected to measure emissions and smoke.



Figure 7 Engine test rig.



Figure 8 Sonicator.

Table 6 Properties of fuels

Sample/ Properties	Density at 25 °C	LCV Calorific Value	HCV Calorific Value	Flash Point	Fire Point	Kinematic Viscosity at 40 °C	Dynamic Viscosity @400°C
Unit	kg/m ³	kJ/kg	kJ/kg	(°C)	(°C)	(cSt)	(cP)
ASTM Standard	D287	D 4809	D 4809	D93- 58T	D93- 58T	D445	D445
Pure Diesel	830	42000	46000	52	59	2.5	2.1
MWCNT 60ppm	835	42500	46500	58	62	2.7	2.3
MWCNT 60ppm	840	43500	47000	60	67	2.9	2.5

Results

The output thermal efficiency was improved for hydrogen injection at 0.121kg per hour in all the three phases with 27.65,23.47% and 25.97% when compared to diesel, diesel with 60ppm and diesel with 90ppm. The specific fuel consumption was reduced by 32.43%,23.52% and 25.71%, respectively. As cylinder peak pressure are concerned in phase 1 the pressure was increase by 29.12%, in the second phase and third phase the pressures are recorded highest value of peak pressure of 85 bars at 371 crank angle and net heat release was increased by 46.14%,16.18% and 5.2% at crank angle 363 deg, in the third phase for all the hydrogen injection rates heat release was found very high. CO emissions are decreased by 37.5%,50% and 27.27% co₂ emissions are reduced by 16.66%,35% and 11.11%, respectively, in three phases. Hydrocarbon emissions were mitigated by 40%,55% and 65% compared to baseline fuels. Smoke emissions were also reduced by 56%,70% and 76%, whereas nitric oxide emissions were increased by 38.64%, 11.03% and 28.6% among the three phases compared to baseline fuels.

Specific fuel consumption calculates the fuel consumed to produce a unit brake power which in turn provides fuel economy and the insights of effectiveness of combustion process. In the present research at different loads the performance and emissions are studied with an auxiliary fuel of hydrogen blended with MWCNT. Figure 9 demonstrates the variation of specific fuel consumption(BSFC) for the fuel blends F1-F15 at full load. A comparative analysis of brake specific fuel consumption was performed between F1 –F5, F6-F10 and F11–F15, considering F1, F6 and F11 as reference fuel for comparison in three phases. A notable decline in BSFC was recorded with a value of 32.43%,23.52% and 25.71% in the three phases, respectively, with a hydrogen injection rate of 0.121kg h⁻¹. The same trend was followed at 25,50 and 75% loads. The reduction in specific fuel consumption at a hydrogen flow rate of 0.121kg/ hour is due to an enhanced combustion mechanism. As hydrogen possesses a high heating value (120MJ/kg), low ignition energy, high flame speed and wide flammability limits compared to diesel. At moderate flow rates, participation of hydrogen in combustion is more rapid in the premixed combustion phase, which promotes more complete oxidation of the diesel spray. This will lead to more combustion efficiency and a reduction in unburned hydrocarbons. Since specific fuel consumption is inversely proportional to brake thermal efficiency, improvement in combustion characteristics directly reduces the mass of diesel required to produce a given brake power output. Multiwalled carbon nanotubes further intensify this improvement, which act as a nano-catalytic combustion promoter due to high surface area, good thermal conductivity and also oxygen buffering capacity Mesri et al. (2021).

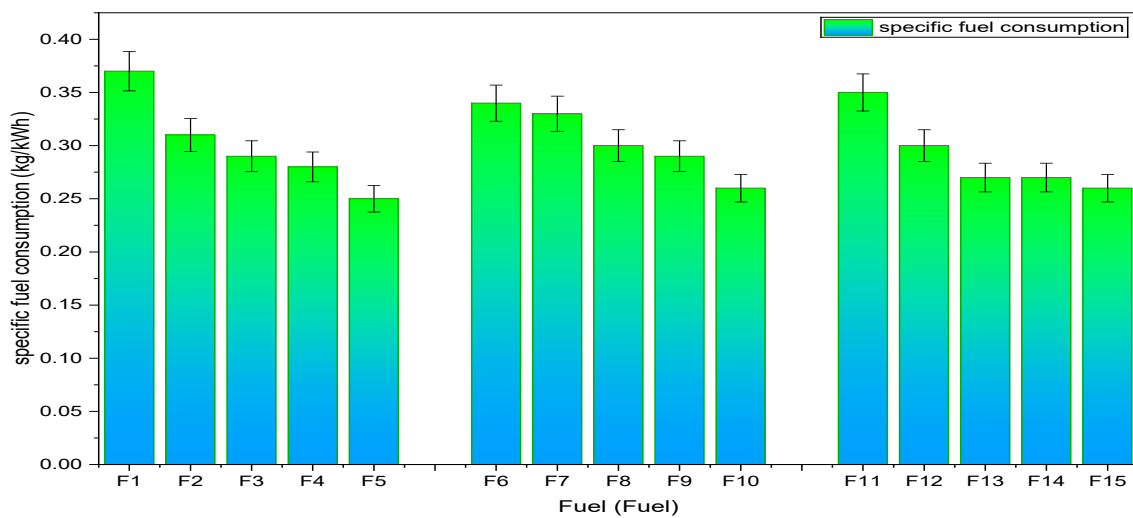


Figure 9 Variation of specific fuel consumption.

The most important and key parameter in the combustion process is brake thermal efficiency which signified the conversion of chemical energy to brake power. In this research the variation of efficiency with different loads blended diesel with multiwalled carbon nanotubes with and without hydrogen as supplementary fuel.

Figure 10 represents the variation of brake thermal efficiency (BTE) for the fuel blends F1-F15 at full load. A comparative analysis of brake thermal efficiency was performed within F1 –F5, F6-F10 and F11 –F15 considering F1, F6 and F11 as reference fuel for comparison in three phases. A notable increment in BTE was recorded with a value of 38.22% %,30.68% and 35.08% in the three phases, respectively, with a hydrogen injection rate of 0.121kg/h^{-1} . The same trend was followed at 25,50 and 75% loads also. The gradual increase in brake thermal efficiency at 0.121kg/hr was due to combustion kinetics and effective utilization of energy within the cylinder. The hydrogen was injected with 2 bar pressure at 90°CA after top dead centre during the suction stroke without disturbing the air intake inside the cylinder to avoid agglomeration during the suction stroke. Because of the high heating value of hydrogen, flammability limits, high diffusivity, and a more homogeneous mixture, which accelerates the initial stages of combustion initiated by pilot injection. The rapid flame propagation shortens combustion duration, improves completeness of oxidation and shifts a larger portion of the heat release towards the optimal crank angle close to top dead centre Kamaraj *et al.* (2021)

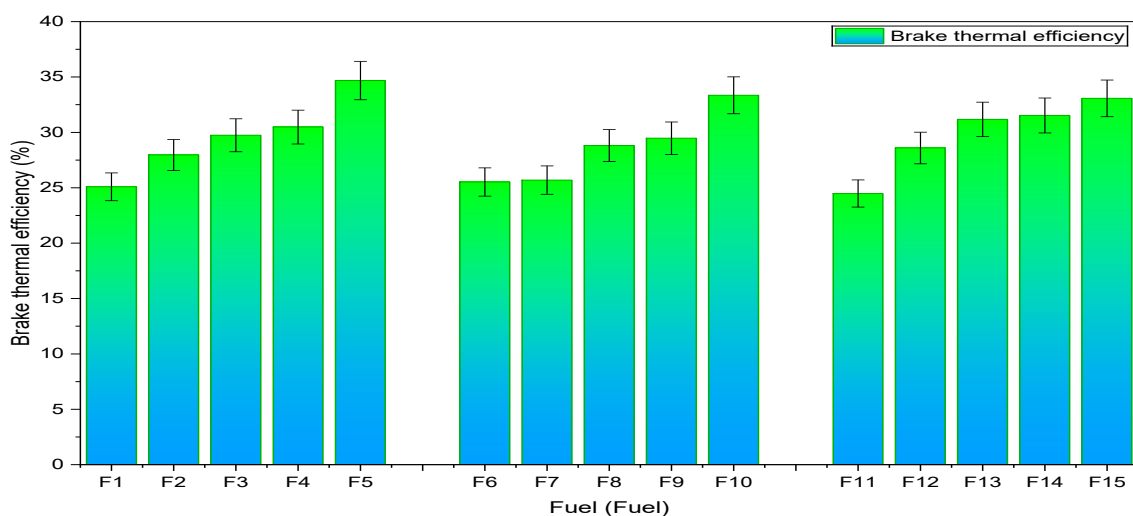


Figure 10 Variation of brake thermal efficiency.

Cylinder pressure is a fundamental parameter that reflects the in-cylinder combustion process and energy release characteristics of the engine. The variation of cylinder pressure with crank angle provides valuable insights into ignition

delay, combustion phasing, and peak pressure development. In the present study, cylinder pressure profiles are analysed under different engine operating parameters to evaluate the influence of hydrogen enrichment and MWCNTs nanoparticle addition. Figure 11 represents the variation of peak cylinder pressure for all the tested fuels pure diesel with and without hydrogen, multiwall carbon nano tubes of 60ppm and 90ppm with and without hydrogen. In all three phases, the cylinder pressure was increased with a flow rate of 0.121 kg per hour compared to base fuels, diesel, diesel with multiwall 60 and 90 ppm. This gradual increase occurred when different flow rates of 0.047, 0.077, 0.101 and 0.121 kg per hour were used. This gradual increase and maximum at 0.121 kg per hour might be due to enhanced combustion reactivity and faster heat release characteristics. Hydrogen promotes rapid premixed combustion once initiated by pilot injection due to high flame speed, wide flammability limits and low ignition energy. These parameters accelerate the early combustion phase and improve the cycle peak pressure inside the combustion chamber. Due to the hydrogen injection, a more homogeneous mixture formation is responsible for high diffusivity, which ensures more uniform combustion and thereby an increase in pressure near top dead centre. Simultaneously, MWCNT improves the atomization process and shortens the ignition delay due to high thermal conductivity and catalytic surface activity Lata et al. (2011)

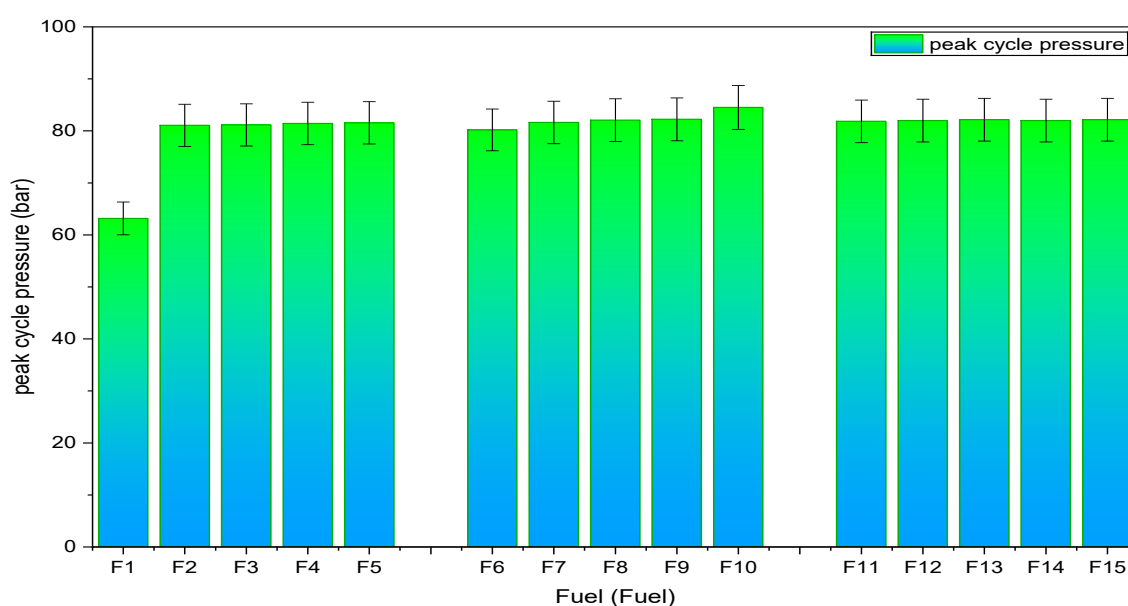


Figure 11 Variation of peak cycle pressure.

Figure 12 demonstrates the variations in heat release rate for the diesel and blended with diesel are tested with and without hydrogen. Among all the cycles for a flow rate of 0.121 kg/hr achieved maximum heat release rate. When hydrogen was injected the net heat release rate and cumulative heat release rate was increases and inturn improved brake thermal efficiency near the optimal crank angle region. Simultaneously the this higher cumulative heat release rate is directly proportional to specific fuel consumption.

The redictopm in specific fuel consumption is due to improvement in combustion performace which is attributed to high flame speed , wide flammability limits due to hydroge and shorter ignition delay which inturn enhanced premixed combustion phase. The incomplete combustion is possible due to the injection of hydrogen as it imoroves the mixture homogeneity. The addition of multiwall carbon nanotubes improves atomization process and inturn it is helpful in secondary braekup of mixture particles which leads to better mixing. These results are in accordance with D.B. et al Latha(2011).

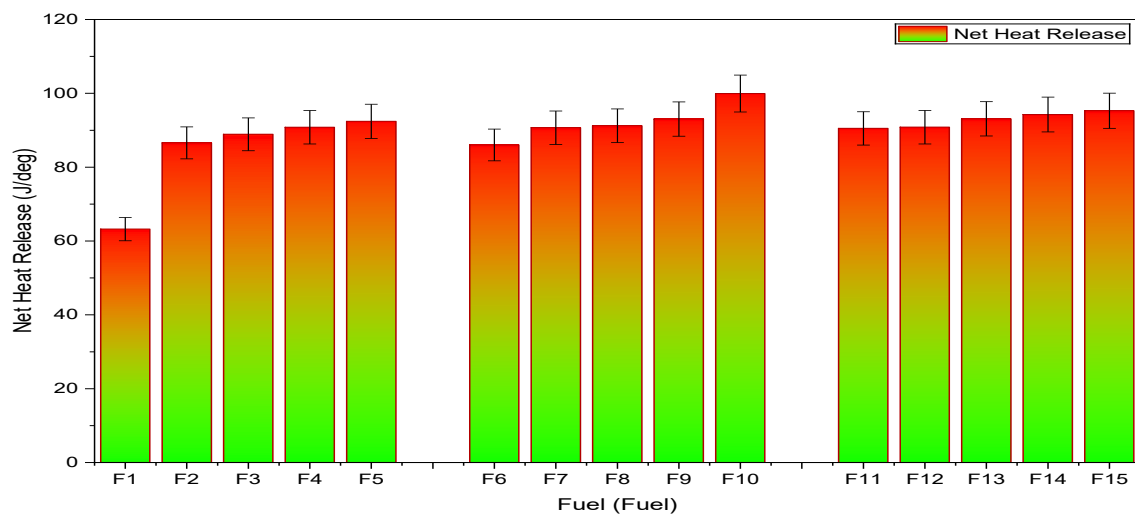


Figure 12 Variation of heat release rate.

When carbon-based liquid fuels are burned incompletely, hazardous carbon monoxide emissions are emitted. Fig. 13 demonstrates the carbon monoxide and carbon dioxide emissions at full load. It is understood and confirmed from the findings and discussion that the brake thermal efficiency, net heat release, and cylinder pressure are enhanced by hydrogen supplementation with multiwalled carbon nanotubes in diesel operation. Due to improved homogeneity of the mixture, the elevated cylinder temperatures cause the intermediate species of carbon monoxide emissions to decrease significantly through the oxidation process. The carbon monoxide was reduced by 37.5%, 50% and 27.27% with an injection rate of 0.121 kg per hour compared to base reference fuels, diesel, diesel with 60 ppm MWCNT and 90 ppm MWCNT (multiwalled carbon nano tubes). Carbon dioxide emissions are also reduced but comparatively less 16.66%, 35% and 11.11% respectively. The reason might be due to enhanced atomization and catalytic properties of MWCNTs convert CO to CO₂, consequently carbon dioxide emissions increase slightly, indicating more complete combustion Ashok et al. (2021).

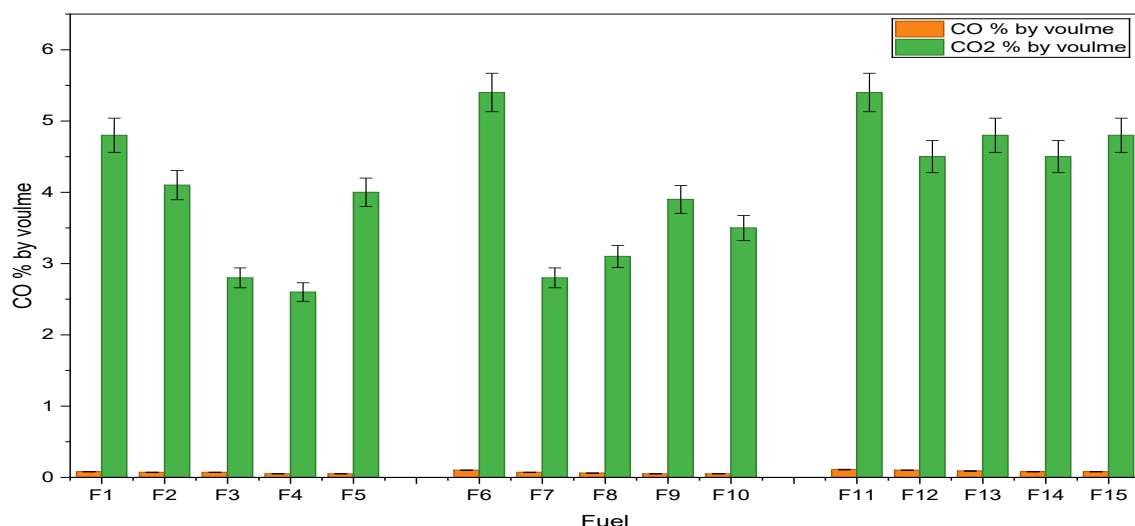


Figure 13 Variation in carbon emissions.

Figure 14 validates the variation of hydrocarbons and nitric oxide emissions. The observed increase in brake thermal efficiency, peak cylinder pressure, and net heat energy rate under hydrogen-enriched MWCNT–diesel operation indicates intensified premixed combustion and elevated in-cylinder temperature. The hydrocarbon emissions were reduced by 40%, 55% and 65%, respectively, in three phases. The reduction in hydrocarbons might be enhanced in an oxidation environment by minimising the wall quenching effect, improving homogeneity and accelerating intermediate

species. The catalytic and atomization properties of multiwalled carbon nanotubes enhance combustion completeness, particularly at 90ppm concentration. Conversely, the elevated peak temperatures and oxygen availability strongly promote thermal nitric oxide formation through the Zeldovich mechanism, increasing nitric oxide emissions. It was observed that Nitric oxide rise at 90ppm is attributed to higher combustion intensity and greater residence time for elevated temperature rise. Due to these reasons, the nitric oxide emissions were increased by 38.64%, 11.03% and 28.6% respectively for the three phases Kumar et al. (2020)

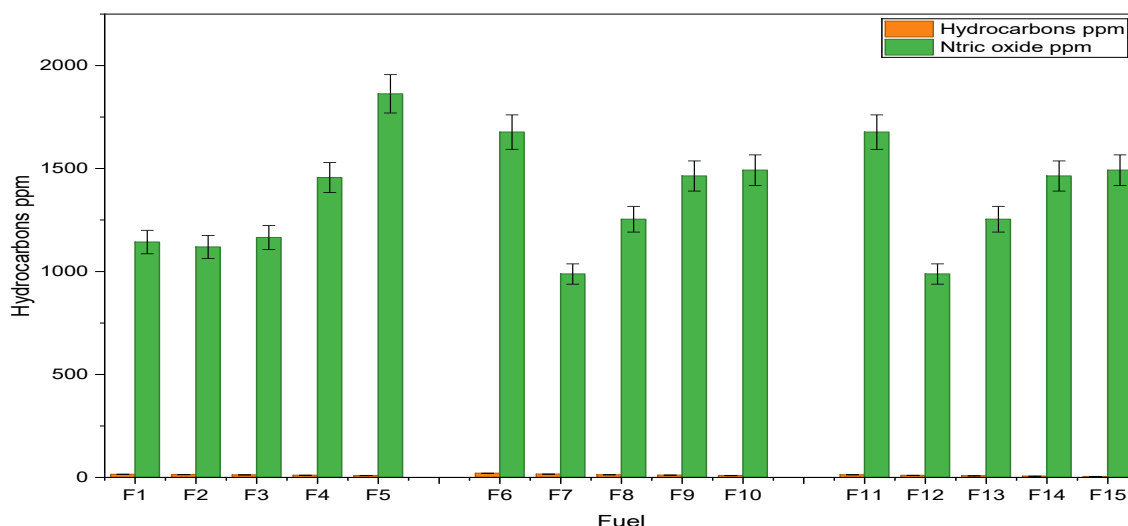


Figure 14 Variation in hydrocarbons and nitric oxide emissions.

Due to incomplete combustion of hydrocarbon fuels the formation of smoke occurs. The smoke constituents are strongly affected by fuel composition, mixing of fuel and air, combustion temperature and conditions of operation. During peak loads the availability of less oxygen and the formation of smoke at high levels. Improved mixing, atomization and enhanced oxygen the smoke emissions are controlled. Figure 15 Demonstrates the variation of smoke opacity. The smoke opacity was reduced by 56%.70% and 76% res [actively for the three phases with a hydrogen injection rate of 0.121kg /hr. The substantial decrement is primarily due to the carbon-free nature of hydrogen, which reduces the availability of carbon for soot precursor formation. Due to high diffusivity and flame speed of hydrogen, the air fuel mixture homogeneity is enhanced and the combustion phase is shortened, thereby suppressing locally rich zones responsible for soot nucleation. In addition to the elevated temperature in the combustion chamber, an increase in radical OH concentration promotes active soot oxidation. The hydrogen when combined with multi-walled carbon nanotubes, enhanced atomization, the synergetic interaction results in significant suppression of particulate formation Manigandan Manigandan et al. (2019).

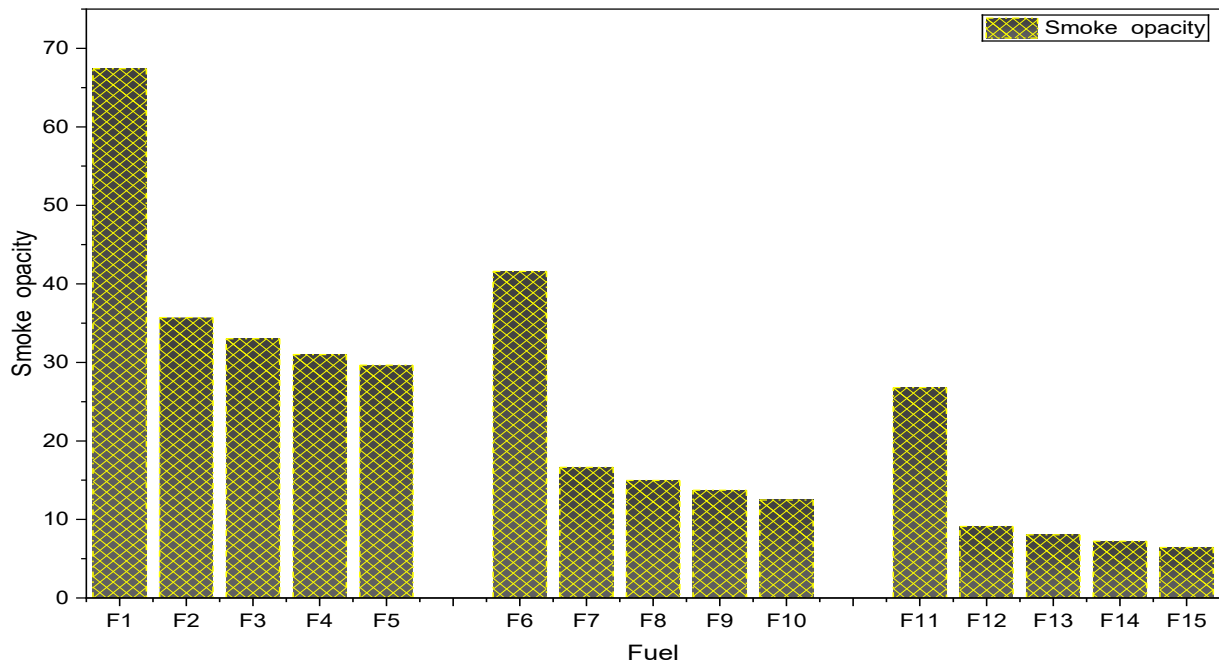


Figure 15 Variation in smoke emissions.

Conclusion

Experimental evaluation was carried out in different cycles to access the impact of hydrogen gas in diesel fuel blended with multiwall carbon nanotubes to understand performance, combustion and emissions. In the first cycle pure diesel with different flow rates 0.047, 0.077, 0.101, and 0.121 kg h⁻¹ (F1–F5) of hydrogen was executed. In the second cycle diesel blended with 60ppm dosage of MWCNT with the same flow rates of hydrogen considered in the cycle1. In the second phase, diesel blended with 60 ppm MWCNTs was tested under the same hydrogen flow rates (F6–F10). In the third phase, diesel blended with 90 ppm MWCNTs was evaluated with hydrogen induction rates of 0.047, 0.077, 0.101, and 0.121 kg h⁻¹ (F11–F15) to investigate the combined influence of nanoparticle concentration and hydrogen supplementation on engine characteristics.

It was recorded that the brake thermal efficiency increased with hydrogen induction at a flow rate of 0.121 kg h⁻¹ across all three experimental phases. The maximum enhancement in brake thermal efficiency was recorded as 27.65%, 23.47%, and 25.97% for the respective fuel combinations when compared with pure diesel, diesel blended with 60 ppm MWCNTs, and diesel blended with 90 ppm MWCNTs. Among the tested conditions, hydrogen supplementation at 0.121 kg h⁻¹ exhibited the most notable improvement in engine efficiency. The results indicated a consistent increase in brake thermal efficiency under higher hydrogen induction rates.

The brake specific fuel consumption (BSFC) was observed to decrease by 32.43%, 23.52%, and 25.71%, respectively, across the three experimental phases. Similarly, CO emissions were reduced by 37.5%, 50%, and 27.27%, while CO₂ emissions decreased by 16.66%, 35%, and 11.11%, respectively. The reductions in fuel consumption and exhaust emissions were consistently observed under the tested operating conditions. These findings indicate noticeable variations in fuel utilization and emission characteristics across the three fuel phases.

Unburned hydrocarbon (UHC) emissions were reduced by 40%, 55%, and 65% compared with the corresponding baseline fuels across the three experimental phases. Similarly, smoke emissions decreased by 56%, 70%, and 76%, indicating a considerable reduction in exhaust opacity. However, nitric oxide (NO) emissions increased by 38.64%, 11.03%, and 28.6% relative to the baseline fuels, respectively. The observed emission characteristics varied across the three fuel phases under the tested operating conditions.

The cylinder peak pressure and net heat release characteristics exhibited noticeable variations across the three experimental phases under hydrogen induction. In the first phase, the cylinder peak pressure increased by 29.12% compared with the baseline fuel condition. In the second and third phases, the highest cylinder peak pressure of 85 bar

was recorded at 371° CA, indicating enhanced combustion pressure development. Furthermore, the net heat release rate (NHRR) increased by 46.14%, 16.18%, and 5.2%, respectively, across the three phases, with the maximum heat release observed at approximately 363° crank angle. In the third phase (90 ppm MWCNT blend), significantly higher heat release was observed at all tested hydrogen injection rates. The combustion profile demonstrated notable variations in pressure development and heat release behaviour with increasing hydrogen supplementation and nanoparticle concentration.

Despite the promising outcomes, the use of MWCNTs presents certain limitations that warrant further investigation. Their tendency to agglomerate and sediment can compromise fuel stability and combustion repeatability, highlighting the need for optimized surfactant concentrations and effective functionalization strategies. Nanoparticle deposition near the injector nozzle may contribute to clogging, wear, and altered injection characteristics, emphasizing the importance of injector optimization and long-term stability assessment. Non-uniform nanoparticle–fuel mixing may also introduce variability in combustion behaviour and should be addressed through improved dispersion techniques. In addition, the relatively high cost of MWCNTs and concerns regarding nanoparticle handling and environmental impacts remain important considerations for large-scale implementation. The limited availability of long-duration engine data further emphasizes the need for comprehensive investigations of durability, deposit formation, wear, and emission stability. Addressing these challenges through cost-effective material synthesis, optimized fuel formulations, and extended engine testing will strengthen the feasibility of MWCNT-based fuels for practical applications.

Future studies should focus on improving the long-term dispersion and stability of nanoparticles in diesel using suitable surfactants such as Tween 80 and Span 80. Functionalization of nanoparticles may further enhance fuel compatibility and suppress agglomeration, thereby improving combustion performance. Systematic optimization of nanoparticle dosage, hydrogen flow rate, injection pressure, and injection timing is required to achieve an improved NO_x–PM trade-off. The combined application of nanoparticles, hydrogen, EGR, and after-treatment technologies should be explored for further emission reduction. Advanced combustion diagnostics, including mass fraction burned (MFB) and in-cylinder pressure analysis, can provide deeper insight into combustion mechanisms. Long-term engine durability, wear, and tribological studies are essential to establish practical applicability. Future research should also address the safe handling, environmental impact, and disposal of nanoparticles. The development of hybrid nanomaterials, particularly MWCNT–metal oxide combinations, offers a promising pathway toward simultaneously improving efficiency and reducing emissions.

Nomenclature

ASTM	— American Standard Testing Method
BP	— Brake Power
BTE	— Brake Thermal Efficiency
CP	— Cylinder Pressure
CR	— Compression ratio
CHRR	— Cumulative Heat Release Rate
CO	— Carbon Monoxide
CO ₂	— Carbon Dioxide
DE	— Diesel engine
EDX	— Energy dispersive x-ray
FESEM	— Field emission scanning electron microscope
FTIR	— Fourier transform infrared
H ₂	— Hydrogen
HC	— Hydrocarbons
MFB	— Mass Fraction Burned
HRR	— Heat Release Rate
NO _x	— Oxides of Nitrogen
PM	— Particulate matter
PCP	— Peak Cylinder Pressure
SFC	— Specific Fuel Consumption
XRD	— X- ray diffraction
MWCNTs	— multi-walled carbon nanotubes

Compliance with ethics guidelines

The authors declare they have no conflict of interest or financial conflicts to disclose.

This article contains no studies with human or animal subjects performed by the authors.

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