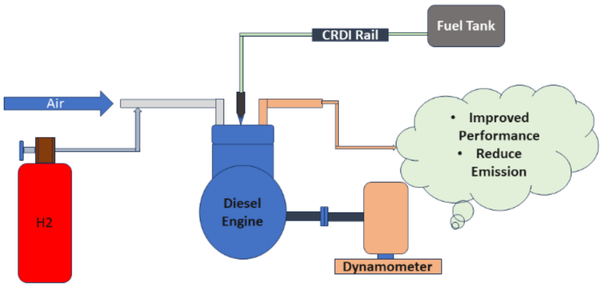
Global NEST Journal, Vol 26, No 8, 06256

Analysis of the performance, combustion and emission of Hydrogen Induction in a CRDI engine

Anandkumar Gunasekaran[1]*, Selvaraju Ponnusamy Nallusamy[2], Ramakrishnan Sambasivam[1] and Silambarasan Rajendran[3]
[1]Department of Automobile Engineering, Madras Institute of Technology, Chennai, Tamil Nadu, India.
[2]Department of Automobile Engineering, Rajalakshmi Engineering College, Chennai, Tamil Nadu, India.
[3]Department of Mechanical Engineering, Annapoorana Engineering College, Seeragapadi Salem-636308, Tamil Nadu, India.
[3]Department of Mechanical Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, Tamil Nadu, India.
[3]Centre for Research Impact & Outcome, Chitkara University Institute of Engineering and Technology, Chitkara University, Rajpura, 140417, Punjab, India.
Received: 12/06/2024, Accepted: 16/07/2024, Available online: 24/07/2024
*to whom all correspondence should be addressed: e-mail: anand8285@gmail.com
https://doi.org/10.30955/gnj.06256

Graphical abstract



Abstract

Since hydrogen gas is a plentiful element in the universe, using it as fuel for IC engines has the potential to reduce pollution while also improving the engine performance. Hydrogen gas as fuel has many advantages, including a high energy density, a rapid flame speed, clean burning, and a short quenching distance. When compared to pure diesel as fuel, alternative fuels like biodiesel (a mixture of lemon and orange peel oils) are utilised in this experiment to reduce exhaust emissions. In addition to biodiesel, hydrogen induction is used in dual fuel technology to boost the power of engine while minimising emissions and improving the fuel efficiency and fuel economy. Hydrogen gas is utilised, the engine consumes less biodiesel fuel, thereby reducing the fuel cost. According to experimental findings, a reduction in the brake-specific energy consumption of 23.48% and a rise in brake thermal efficiency of 33.4% are observed for pure diesel along with 6lpm of hydrogen gas. Therefore, hydrogen is a potential fuel to drive the internal combustion engine to produce more power and by minimising the exhaust gas emissions.

Keywords: Hydrogen Energy Share, Dual fuel Technology, Hydrogen CRDI Engine, Improve Efficiency, Reduce Emissions.

1. Introduction

Reverend W. C. used hydrogen as fuel way back in 1820. Regarding the utilisation of hydrogen gas to provide moving power in equipment, he worked on a study. While vacuum engines couldn't last, hydrogen and air are burnt to produce power to move the piston [Sørensen, Bent 2011]. The hydrogen gas is utilised as a fuel for IC engine to generate electricity with zero emissions and water as a byproduct is still being researched. Leading automakers are currently conducting extensive research to create electricity from hydrogen because it can be produced using sustainable energy sources [Sharma, Sunita and Sib Krishna Ghoshal 2015]. The primary motivating forces behind hydrogen research are the exhaustion of the non-renewable fossil fuels and the rising need for energy. This reduces the human dependency on fossil fuel to convert it into heat energy. An extensive study on hydrogen as a fuel is motivated by its capacity to attain high energy efficiency without producing harmful emissions [Berry, Gene D *et al.* 1996]. In comparison to alcohol, biodiesel, compressed natural gas, and other alternative fuels, hydrogen gas is the best. Hydrogen gas can be used to generate energy in fuel cells or by introducing hydrogen into internal combustion engines. Considering that hydrogen gas has a higher auto-ignition temperature and higher-octane number, researchers are focusing on hydrogen induction in both petrol and diesel engines [Montoya *et al.* 2018]. Compression ignition (CI) engines can be converted to use hydrogen induction by either making simple engine modifications or changing the engine's operating characteristics. Several ignition-triggering systems turn on the hydrogen induction in compression engines (CI) for combustion [Masood and Ishrat 2008]. Hydrogen storage is a disadvantage of using hydrogen as an energy source. Because of its reduced weight and strong flammability, hydrogen must be handled carefully to prevent leaks into the atmosphere. Nonetheless, as stated by Quadflieg, "There is no doubt that hydrogen as energy will continue its great preference for the next century, particularly with respect to environmental preservation" [Quadflieg 1988].

A representation of many forms of hydrogen production are available at present time. When combined with flue gas to create valuable compounds like polymers, ammonia, and methanol, hydrogen is an effective desulfurization reactant. Modern steam methane reforming technology is a more economical means to produce hydrogen and CO_2 gas, both of which are greenhouse gas emissions contributors. By 2030, the researcher would create new methods for producing hydrogen from renewable energy [KOnECznA *et al.* 2021]. Green hydrogen is now the most environmentally friendly and will be widely accessible soon. Future fuel cell automobiles and hydrogen internal combustion engines may be more practical and cost-effective thanks to research into novel hydrogen storage materials and techniques. Depending on the condition of the gas and the intended use, hydrogen can be stored using a variety of techniques [Züttel 2004].

In general, high-pressure cylinders are preferred for storing hydrogen in its gaseous condition. To store compressed gas, hydrogen gas must be compressed to extremely high pressures, often between 300 and 700 bar. Although high-pressure tanks are big and heavy, compressed gas storage is comparatively easy and cheap. Cryogenic tanks are used to store liquid hydrogen below 21.2 K in natural settings. The least dense material is liquid hydrogen, which weighs only 71g.

A method called common rail direct injection uses high-pressure fuel to optimise fuel atomization for better combustion. It offers excellent control over the pressure, timing, and fuel injection duration, resulting in enhanced combustion and minimal exhaust emissions. A comprehensive explored on the regulation of specific matter utilising a CRDI engine is compared to a traditional CI engine was conducted by Mohankumar and Senthilkumar [Mohankumar and Senthilkumar 2017]. According to Shahir *et al.* [2015], who studied the emission characteristics of CRDI and CI engines, the concentration of hazardous gases and particulate matter is dramatically reduced because of high-pressure fuel injection and advanced injection time. Common rail direct injection systems consist of the following components, common rail (or accumulator), the high-pressure fuel pump, electronic actuated fuel injector, ECU, sensors, etc. From fuel tank the fuel is pumped through the fuel filter and the high-pressure pump delivers it to the common rail at desired pressure. The accumulator is used to maintain the fuel pressure constant and the fuel is injected by actuating the solenoid in the injector (As the solenoid is energized the valve is lifted and fuel is sprayed on the walls of combustion cylinder chamber). The major advantage of the CRDI engine is fuel atomization is good and leads to better combustion, this reduces the exhaust emission and enhances the engine performance. It also reduces the noise and vibrations of the engine.

In dual fuel mode, Gananmoorthi and Vimalananth [Gnanamoorthi and Vimalananth 2020] studied the impact of high-flow hydrogen fuel in CRDI engines. It was conducted in a 5-kW water-cooled single-cylinder IC engine, and the engine's performance was monitored as the hydrogen gas flow rate was changed from 4 to 8 lpm. To start the ignition of the pre-mixed hydrogen and air combination, diesel is injected at 23^{o} BTDC as the pilot fuel. At an ideal hydrogen flow of 30 lpm, it was recorded that the brake thermal efficiency of the engine was increased to 30.7% and the BSEC was decreased by 23.5%. Like this, the hazardous emissions from the hydrogen diesel dual fuel were reduced; CO was lowered by 22.3% and UHC by 33%.

In addition to using diesel as a pilot fuel, Srikanth Vadlamudi *et al.* [2023] observed the exhaust emissions and efficiency of CRDI engines running on hydrogen and compressed natural gas. The maximum cylinder pressure in dual fuel mode was 74 bar, which improved combustion. Adding hydrogen reduces the amount of diesel fuel used, which lowers specific fuel consumption and lowers engine emissions. Effects of biodiesel combined with hydrogen and producer gas in CRDI engines were studied by Halewadimath *et al.* [2022]. Maximum BTE is noted for hydrogen flow rates of 9 lpm. They used producer gas that had been hydrogen gas-enhanced and methyl ester of neem oil. To evaluate various performance and combustion characteristics, experiments were carried out with diverse hydrogen induction timing and injection duration. A compression ignition engine was modified into a CRDI engine by Yunus Khan *et al.* [2021], who also tested hydrogen injection and biodiesel (ceiba pentandra oil). When biodiesel was injected at 900 bar, it resulted in an 18.5% decrease in UHC emissions and a 17% reduction in CO when compared to a conventional CI engine. The engine's lifespan is increased by direct injection of hydrogen, which also eliminates backfiring and pre-ignition. The low ignition energy of hydrogen makes backfiring and pre-ignition more common, which is a significant disadvantage of port fuel injection of hydrogen [van Wijk and Noordelijke 2017].

Hydrogen's potential as a clean energy source has roots dating back to 1820, with modern research focusing on its role in fueling internal combustion engines for electricity generation. Major automakers are investing heavily in hydrogen research to mitigate reliance on fossil fuels and curb emissions. Despite challenges like storage and handling, hydrogen is anticipated to dominate energy preferences for its environmental benefits. Advances in production methods, including "green hydrogen," promise sustainable energy solutions. Common rail direct injection (CRDI) systems have revolutionized combustion efficiency and emission control in internal combustion engines. Integration of hydrogen into CRDI engines has shown significant reductions in emissions and improved fuel efficiency. Studies explore various hydrogen-enhanced CRDI engine strategies, from optimization of injection timing to dual-fuel approaches. Results indicate enhanced engine performance and reduced emissions, offering promising avenues for sustainable transportation solutions.

2. Materials and methods

2.1. Materials

The experimental setup utilizes a 1-cylinder, 4-stroke diesel engine, chosen for its simplicity and ease of modification. Integrated into the system are components of a Common Rail Direct Injection (CRDI) system, including the CRDI pump, common rail, and solenoid injector, enabling precise control over fuel delivery. Additionally, a hydrogen gas cylinder and flow meter are incorporated, offering a means to introduce hydrogen as a supplemental fuel for combustion optimization. The fuel blend consists of 75% diesel, 12.5% lemon peel oil, and 12.5% orange peel oil, aiming for a sustainable and environmentally friendly alternative. Monitoring and analysis are facilitated by an exhaust gas analyzer (AVL Digas 444) and smoke meter, providing insights into emission levels and combustion efficiency, essential for evaluating the performance and environmental impact of the system.

2.2. Methods

Hydrogen is stored in a high-pressure cylinder. A pressure regulator reduces the pressure of the hydrogen gas before it enters the mass flow meter. The mass flow meter measures the amount of hydrogen gas flowing into the system. A flame arrester is installed to prevent any flames from traveling back upstream into the hydrogen supply line.

A high-pressure pump increases the pressure of the hydrogen gas before it goes to the common rail. A solenoid valve controls the flow of hydrogen gas to the injector. The hydrogen injector injects the hydrogen gas into the engine's intake manifold. Air is filtered by an air filter before it enters the engine. The air-fuel mixture is then drawn into the engine's cylinders by pistons. The engine in this setup is connected to an eddy current dynamometer which is a type of dynamometer that uses electromagnetic fields to absorb energy from a rotating shaft. This allows researchers to measure the engine's performance. The exhaust gases from the engine are expelled through the exhaust gas outlet.

A data acquisition system (DAC) is used to collect data from the various sensors in the setup, such as the mass flow meter and the dynamometer. An engine control unit (ECU) is responsible for controlling the engine's operation, such as the amount of fuel injected and the timing of ignition.

Overall, this experimental setup allows researchers to study how hydrogen induction affects the performance of internal combustion engines. By measuring the flow rate of hydrogen, the power output of the engine, and the emissions produced, researchers can gain insights into the potential of hydrogen as a fuel for internal combustion engines.

3. Properties of Hydrogen as fuel and Biodiesel

The most prevalent atom in the universe and the basic form of all molecules is hydrogen. It is stable in both the forms of liquid in water (H_2O) and gas (H_2). Coming on to properties of hydrogen it is given below Table 1

Table 1. Various properties of diesel, petrol and Hydrogen

Property	Petrol	Diesel	Hydrogen
Density (kg/m^3)	750	830	0.089
Molecular weight	~120	~180	2.016
Auto-ignition temperature (K)	630	520	858
Volumetric energy content (MJ/m^3)	33	35	10.7
Lower heating value (MJ/kg)	44.5	42.5	150
Quenching distance (mm)	~2	-	0.64
Flammability limits (vol %)	1-7.6	0.6-5.5	4-7.6
Stoichiometric air-fuel ratio	14.7	14.5	34
Minimum ignition energy (mJ)	0.24	0.24	0.02
Laminar flame speed (m/s)	0.4	0.4	~1.85

In contrast to other fossil fuels like diesel and petrol utilised in the transportation industry, hydrogen fuel has unique chemical and physical properties (as seen in table 1). At room temperature, hydrogen is a gas, whereas petrol and diesel are liquids. At ambient pressure and temperature, hydrogen gas has a minimum density compared to diesel and petrol because of its small molecular weight. As hydrogen contains no carbon, burning hydrogen generates very minimal carbon exhaust emissions. Although hydrogen has a low energy density per cubic metre (10.7 MJ/m^3), it has the highest energy density per kilogramme of fuel (120 MJ/kg). Because hydrogen has a low boiling point, it is typically stored in a compressed state in a cylinder.

Due to its strong reactivity with ambient air, hydrogen mixes with air quickly and is ready for burning at a high flame velocity of 1.85 m/s. Compared to fossil fuels, it has a shorter flame quenching distance due to its higher energy content and flame velocity. The main disadvantage of utilising hydrogen gas as fuel in IC engine is the higher auto-ignition temperature (850 K). Research Octane Number of hydrogen (130) is relatively very high compared to diesel and petrol due to this hydrogen internal combustion engine has high resistance towards engine knocking [Aleiferis *et al.* 2012].

Due to its high flammability range, a hydrogen internal combustion engine has a higher thermal efficiency. The engine operates in a lean mixture of hydrogen and air. Comparable to other fossil fuels, hydrogen ignites with a relatively low energy need (0.02 mJ). Because hydrogen has a far lower density than air, hydrogen internal combustion engines are safe. As a result, hydrogen is a superior alternative fuel for IC engine because in the event of a hydrogen gas leak, the gas will rise above the atmosphere.

Generally, fuel is delivered into the cylinder in 2 different ways, either direct injection (DI) or port fuel injection (PFI). In the PFI method, inside the intake manifold fuel is sprayed and the air-fuel mixture enters the engine cylinder through the intake manifold. In the PFI method, the fuel mixture has a maximum auto-ignition temperature, so fuel is ignited by a spark plug or using pilot fuel diesel or homogenous charge compression ignition are techniques followed. But in the case of PFI injection, there is a greater chance of back-firing, pre-ignition, and knocking, this damages the engine and engine components. This is because of the small quenching distance and low ignition energy of hydrogen. Recently a lot of research is taking place on the direct injection of hydrogen because it eliminates the backfiring and pre-ignition and increases the lifespan of the engine. In direct injection engine, the hydrogen gas is sprayed straight inside the engine cylinder at high pressure and the source of ignition are glow plug or pilot fuel is used.

4. Experimental setup

The experiment was performed by first converting a 1 cylinder, 4 stroke diesel engine into CRDI engine and hydrogen gas induction setup is incorporated for the modified engine setup mentioned in Table 2. The volume flow meter is utilised to regulate the flow of hydrogen gas from the tank into the combustion chamber. H_2 gas is inducted along with the intake manifold; it quickly combines with air and as biodiesel is injected directly inside the engine cylinder. Biodiesel is injected at high pressure due to common rail (CRDI setup), Due to high pressure, the atomisation of fuel is better, and this leads to complete combustion.

The below given table 2 shows the engine specification used in the experiment. It consists of a water-cooled engine with the four stroke, single cylinder, compression ignition engine. This engine is modified into CRDI engine by adding CRDI pump, common rail and solenoid injector actuated using an ECU. Biodiesel was injected at a pressure of 500 bar and injection timing as 27° BTDC and regulated by an ECU setup. Figure 1 shows the experimental setup used in this research.

Table 2. Engine specifications for the current work

Engine Name	Kirloskar SV1 Engine
Number of Cylinders	1
Number of Stokes	4
Maximum Torque	37.4Nm @ 1800rpm
Maximum Power	5.9kW (8bhp)
Bore diameter (mm)	87.5
Stoke length (mm)	110
Engine Displacement	661cc
Compression Ratio	17.5
Engine Cooling Method	Water Cooling

The diesel and biodiesel fuel are used in this study, comparative analysis of performance, combustions and emission are performed. The different types of fuel to hydrogen ratio are given below in the Table 3.

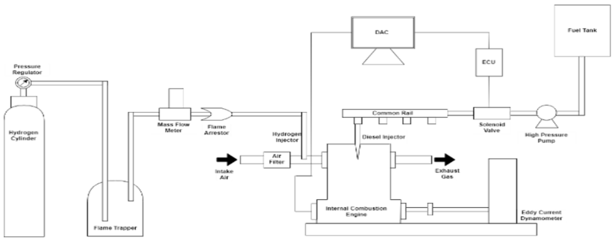


Figure 1. Hydrogen Induction Experimental Setup

From the above blend (Orange and Lemon peel oil) BTE close to diesel and it reduces the emission gases. Blend is then used as fuel along various hydrogen energy share ratio. The below Table gives the energy share of blend and hydrogen gas.

Table 3. Volume percentage of Fuels and Hydrogen.

Fuel Name	Fuel Content
Diesel	100% Diesel
D + 4lpm of H2	100% Diesel + 4LPM of Hydrogen gas
D + 6lpm of H2	100% Diesel + 6LPM of Hydrogen gas
D + 8lpm of H2	100% Diesel + 8LPM of Hydrogen gas
Biodiesel	75% Diesel + 12.5% Lemon peel oil + 12.5% Orange peel oil
BD + 4lpm of H2	75% Diesel + 12.5% Lemon peel oil + 12.5% Orange peel oil + 4LPM of Hydrogen gas
BD + 6lpm of H2	75% Diesel + 12.5% Lemon peel oil + 12.5% Orange peel oil + 6LPM of Hydrogen gas
BD + 8lpm of H2	75% Diesel + 12.5% Lemon peel oil + 12.5% Orange peel oil + 8LPM of Hydrogen gas

5. Analytical calculations

The engine performance parameters such as brake power (BP), brake thermal efficiency (BTE), brake specific energy consumption (BSEC), brake specific fuel consumption (BSFC), and hydrogen energy share (HES) are evaluated by the following equation,

$$\mathrm{BrakePower}(\mathrm{BP})=\frac{2\pi \mathrm{NT}}{60000}(\mathrm{kW}) \tag{1}$$

$$\mathrm{BrakeThermalEfficiency}(\eta)_{\mathrm{Diesel}}=\frac{\mathrm{BP}\times 3600}{\mathrm{m_D LHV_D}}\times 100\% \tag{2}$$

$$\mathrm{BrakeThermalEfficiency}(\eta)_{\mathrm{Dual}}=\frac{\mathrm{BP}\times 3600}{\mathrm{m_D LHV_D}+\mathrm{m_{H_2} LHV_{H_2}}}\times 100\% \tag{3}$$

$$\mathrm{BrakeSpecificFuelConusmption}(\mathrm{BSFC})_{\mathrm{Diesel}}=\frac{\mathrm{m_D LHV_D}}{\mathrm{BP}}\left(\frac{\mathrm{kJ}}{\mathrm{kWh}}\right) \tag{4}$$

$$\mathrm{BrakeSpecificEnergyConsumption}(\mathrm{BSEC})_{\mathrm{Dual}}=\frac{\mathrm{m_D LHV_D}+\mathrm{m_{H_2} LHV_{H_2}}}{\mathrm{BP}}\times\left(\frac{\mathrm{kJ}}{\mathrm{kWh}}\right) \tag{5}$$

$$\mathrm{HydrogenEnergyShare}(\mathrm{HES})=\frac{\mathrm{m_{H_2} LHV_{H_2}}}{\mathrm{m_D LHV_D}+\mathrm{m_{H_2} LHV_{H_2}}}\times 100\% \tag{6}$$

$$\dot{\mathrm{m}}_{\mathrm{H_2}}=\delta_{\mathrm{H_2}}\times \dot{\mathrm{v}}_{\mathrm{H_2}} \tag{7}$$

6. Results & Discussion

6.1. Performance Characteristic

The brake thermal efficiency of the engine and brake-specific fuel consumption for all the blends are compared below.

6.1.1. Brake Thermal Efficiency vs Load

The brake thermal efficiency is an important performance parameter; it gives the percentage of chemical energy of fuel that is converted to work. The BTE for neat diesel is compared with biodiesel fuel along with hydrogen gas induction at different flow rates and plotted versus load. From the Figure 2 it is seen an induction of hydrogen increases the BTE of the engine slightly because of the faster flame speed and higher energy density of H_2 gas. It is observed that the diesel with H_2 induction at 6lpm had a higher BTE of 33.4% compared to only diesel of 32.2%. Similarly, biodiesel with H_2 induction at 8lpm has closest to diesel, BTE of 33.2%. Therefore, hydrogen gas is a potential fuel that can be used along with diesel and biodiesel to maximise the efficiency of diesel engines.

6.1.2. Brake Specific Energy Consumption vs Load

Brake specific energy consumption is used to denote the amount of energy needed for one kilowatt per hour. If the fuel used in the engine is not pure, then it is better to compare specific energy consumption rates because the fuels in the blend have different heat content. As seen from the figure the energy consumption by fuel decreases as we introduce the hydrogen gas into the engine cylinder. This means the engine requires less fuel along with hydrogen to produce the required power to sustain the load. Diesel with a hydrogen flow rate of 6lpm shows the least fuel consumption as seen from Figure 3, this leads to better fuel efficiency and fuel economy.

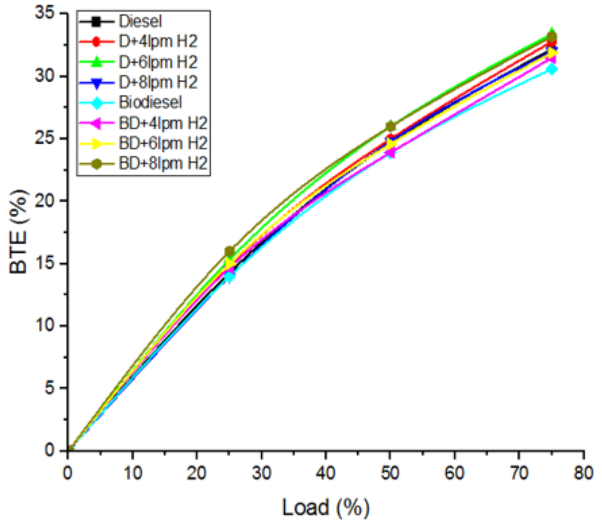


Figure 2. BTE vs Load

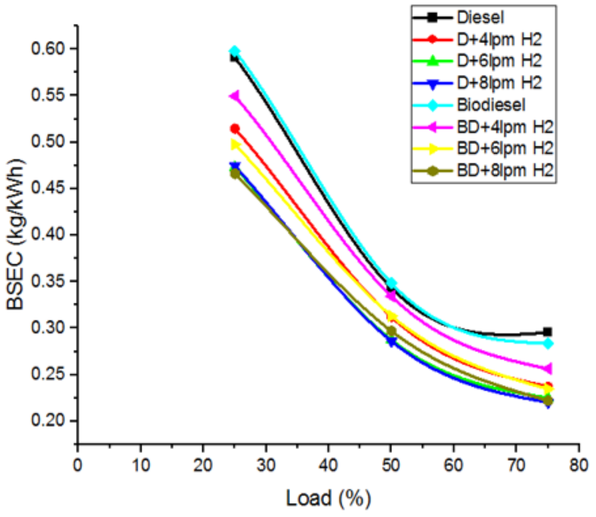


Figure 3. BSEC vs Load

6.1.3. Hydrogen Energy Share vs Load

Figure 4 shows the relation between hydrogen energy share versus load. It was determined that the HES rises as hydrogen content increased. However, increasing the load of the engine causes HES to drop. Diesel with 8 LPM of hydrogen results in a maximum HES value of 34% at no load condition. The hydrogen flow rate at 8 LPM with a load of 75% resulted in a further decrease in the HES value of 15.41%. Under low load conditions, the diesel engine's combustion cylinder is injected with rich fuel mixture, which explains why hydrogen's energy share was larger at low load conditions. The rise in HES was brought about by hydrogen's increased calorific value, which was three times greater than that of diesel.

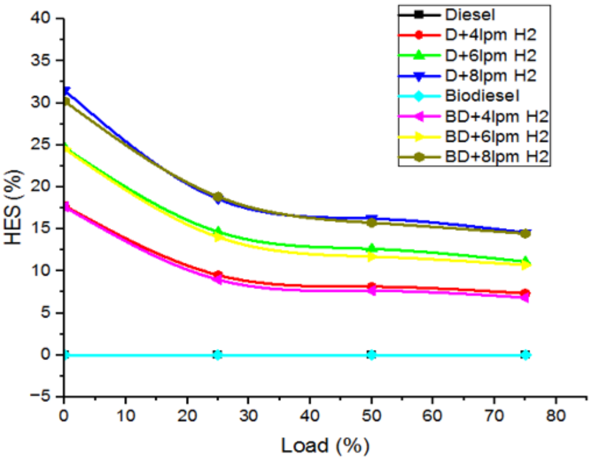


Figure 4. HES vs Load

6.2. Combustion Characteristic

Combustion parameters of engine contributes a major role in evaluating the efficient working of engine and it is responsible for the NO_X production from engine.

6.2.1. In-cylinder Pressure vs Crank angle

The figure depicts the relation of the peak pressure inside the engine cylinder and crank angle of diesel and blend with different rate of hydrogen gas. From Figure 5 the peak pressures of diesel with 6lpm of hydrogen gas has maximum pressure of 72 bar. Peak pressure is caused by the rising in-cylinder temperature under load, which also reduces the time it takes for the fuel to ignite. The period of premixed combustion decreases due to less ignition, which decreases peak pressure. Reduced ignition delay minimizes premixed combustion's duration, which lowers peak pressure. In order for the engine to achieve its highest peak pressure, the ignition delay plays a crucial role at part load.

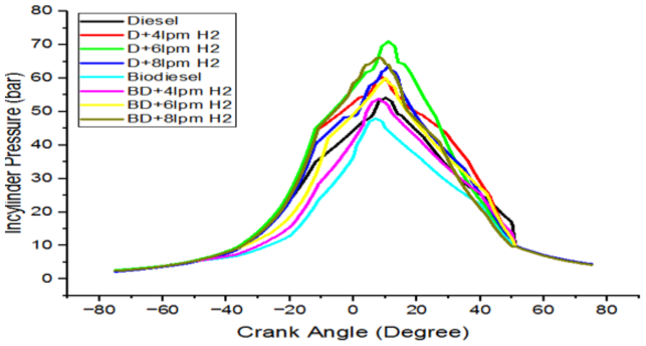


Figure 5. In-cylinder Pressure vs Crank Angle

6.3. Emission Characteristic

As the world moves towards environmentally friendly it is important to reduce the harmful emissions from the engines. With the help of alternative fuels, emissions can be reduced and the emissions from engines consist of NOx, CO_2, CO, UHC, etc. Emissions are a major concern, therefore comparisons of different fuels on emission characteristics are discussed below. The emission gas analyzer is utilised to evaluate the various emission parameters and the smoke meter is utilised to evaluate the smoke.

Table 4. Exhaust gas analyser features

Equipment	Measurement	Range	Accuracy
AVL Digas 444	CO	0-10% vol	±0.02% vol
	UHC	0-10000ppm	1%
	NOx	0-5000ppm	1%
	CO_2	0-20% vol	±0.1% vol
AVL Smoke meter	Smoke	100%	±0.2%

6.3.1. Oxides of Nitrogen Emissions vs load

As the in-cylinder temperature rises at increased load, the NO_X emission for diesel fuel increases, as shown in the Figure 6. The amount of O_2 gas in the engine cylinder will have an impact on how much NOx is released from the engine. Here, the presence of sufficient O_2 in the combustion chamber at a high temperature causes the NO_X emission to increase as the blend increases. The induction of Hydrogen along with diesel increases the in-cylinder temperature therefore NO_X is increased. So after-treatment devices are used to minimize NO_X.

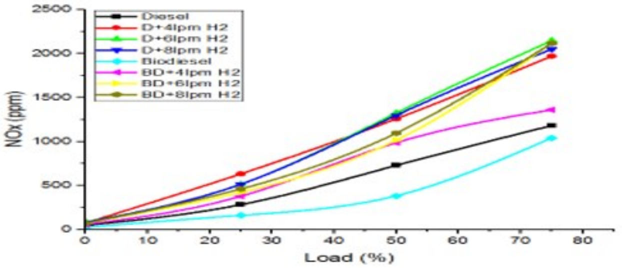


Figure 6. NOx vs Load

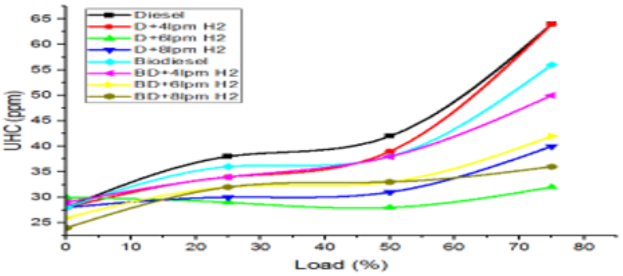


Figure 7. UHC vs Load

In the above Figure it is observed induction of H_2 gas along with biodiesel and diesel escalates the NOx emission due to higher cylinder pressure and good combustion. It is also observed that biodiesel (lemon and orange peel) has the lowest NOx emission of 1000 ppm at a load of 75%.

6.3.2. Unburnt Hydrocarbons vs load

The above graph in Figure 7 shows the relation between unburned hydrocarbon and load. In the case of only diesel as fuel, the emission of UHC is maximum compared to biodiesel and hydrogen induction. Diesel with 6lpm of hydrogen has the lowest emission of UHC of 30 ppm at 75% load. The H_2 gas lean mixture was then used in the combustion process, supporting the stabilised combustion process. This stabilized process resulted in a decrease in flame quench in the combustion layer. Rapid pyrolysis or oxidation produces efficient combustion and lowers the emission of UHC when H_2 is present.

6.3.3. Carbon monoxide emission vs load

According to the current experimental findings, as compared to 100% diesel at a lower load, the induction of hydrogen gas with air prone to reduce CO emissions. The minimum CO emissions were determined from Figure 8 to be 0.048% for a biodiesel with 8lpm of hydrogen engine with less low load, and 0.05% for a Diesel with 6lpm hydrogen flow quantity with air. Since the hydroxyl radical is utilised in CO oxidation and is very quick than processes that employ O_2, large volumes of H_2O or H_2 could have a startling effect on the rate of oxidation.

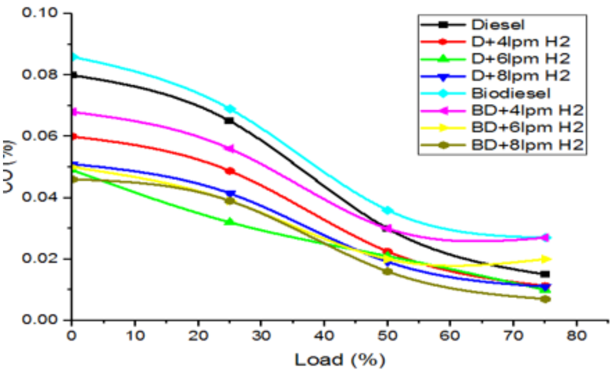


Figure 8. CO vs Load

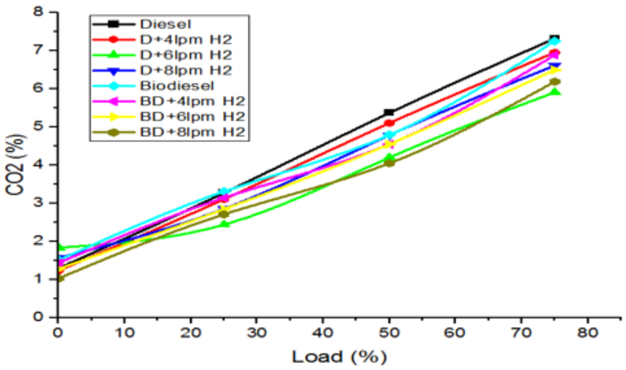


Figure 9. CO_2 vs Load

6.3.4. Carbon dioxide emission vs load

The experimental findings indicate that, in comparison to plain diesel, which has a maximum CO_2 emission level at all loads, the supply of hydrogen at different flow rates with diesel and biodiesel minimizes CO_2 green-house gas. This was due to the quick and complete combustion that requires more oxygen, which was insufficiently accessible in the neat diesel engine within the allotted time and led to incomplete combustion. So, compared to the clean diesel engine, different hydrogen gas flow volumes with air had lower emissions of carbon dioxide (CO_2). And as the hydrogen flow rate increases the emission of carbon dioxide reduces significantly at all loads observed from Figure 9. Diesel with 6lpm of hydrogen flow rate and biodiesel with 8lpm of hydrogen has the least emission of carbon dioxide at different loads of the engine.

6.3.5. Smoke vs load

Smoke emissions are caused by fuel and air mixes that are either too rich to ignite or too lean to ignite automatically and maintain a spreading flame. High temperature and high-pressure lead to soot production, which primarily occurs in the rich mixture zone of each fuel spray at maximum temperature and high pressure. Modest oxygenation of the fuel could lower higher rich regions and lower the production of primary smoke. Diesel fuel has a lower hydrogen-to-carbon ratio than petrol, and adding hydrogen raises that ratio and causes lighter hydrocarbon structures to form via means of chemical bonds, which is also what caused the lowered smoke emission. From Figure 10, it is concluded at high load, diesel with 6lpm has the lowest smoke of 25% compared to other fuel types. This is because complete oxidation takes place and only a few particles get formed as soot.

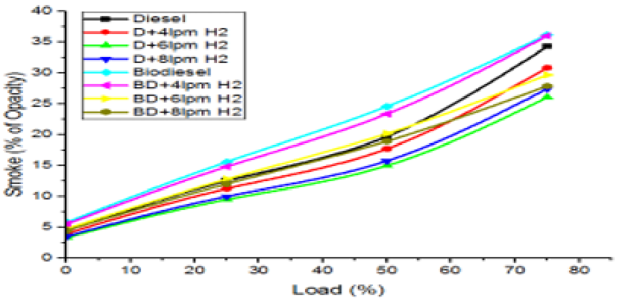


Figure 10. Smoke vs Load

7. Conclusion

The investigated results of the dual-fuel technology in the currently modified engine shows the properties of the CRDI engine's combustion, performance and exhaust emissions. Engine properties are influenced by the hydrogen gas and air supply. By inducting H_2 gas along with diesel and biodiesel in a dual fuel mode, the amount and induction duration of the hydrogen gas induction during the combustion phase were successfully controlled. An extreme increase in hydrogen gas induction in the manifold delayed the combustion phase, while a 20 to 40% hydrogen energy sharing had little effect on emissions and combustion. The availability of H_2 gas leads to greater fuel efficiency due to H_2 gas has a larger calorific value and better burning characteristics than conventional CI engine under various load conditions. The following are observations recorded in above experimental investigation,

- Brake thermal efficiency is maximum for diesel with 6lpm of H_2 gas and the value is 33.4% and blend with 8lpm of H_2 gas has almost near BTE of 33.2%. By inducing hydrogen gas, the efficiency of the engine enhances and performance of engine increases.
- As increasing the hydrogen gas induction, the fuel consumed by engine decreases, there is a reduction of 33.4% of fuel quantity, at diesel along with 8lpm of H_2 gas. The hydrogen flow rate at 8 LPM with a load of 75% resulted in a further decrease in the HES value of 15.41%.
- Maximum in-cylinder pressure of combustion cylinder of diesel with 6lpm of hydrogen gas is measured as 72 bar.
- Hydrogen induction reduced the exhaust gas emissions, diesel along with 6lpm of H2 gas has least unburned hydrocarbons, similarly it has very less emission of CO and smoke. But NO_x gas emissions are increased by induction of hydrogen due to high in cylinder temperature and pressure.

Conflict of Interest

The authors have no conflicts of interest to disclose

Funding

No funding was received.

Acknowledgement

"We would like to express our sincere gratitude to [**Centre for Excellence in Automobile Technology**] for providing access to their state-of-the-art facilities and resources, which were instrumental in the completion of this research. The expertise and support extended by the staff at [Centre for Excellence in Automobile Technology] were invaluable in conducting experiments, analysing data, and interpreting results. This research would not have been possible without their assistance. We are also thankful for which facilitated our engagement with [Centre for Excellence in Automobile Technology]. We acknowledge the role of [**Centre for Excellence in Automobile Technology /Directors**] and all members of the research centre for their contributions to this work. Their dedication to advancing scientific knowledge has greatly enriched our research experience."

References

Aleiferis, Pavlos G., and Martino F. Rosati. "Controlled autoignition of hydrogen in a direct-injection optical engine." *Combustion and Flame* 159, no. 7 (2012): 2500-2515.

Berry, Gene D., Alan D. Pasternak, Glenn D. Rambach, J. Ray Smith, and Robert N. Schock. "Hydrogen as a future transportation fuel." *Energy* 21, no. 4 (1996): 289-303.

Gnanamoorthi, V., and V. T. Vimalananth. "Effect of hydrogen fuel at higher flow rate under dual fuel mode in CRDI diesel engine." *International Journal of Hydrogen Energy* 45, no. 33 (2020): 16874-16889.

Halewadimath, S. S., Nagaraj R. Banapurmath, Virupaxappa S. Yaliwal, M. Guru Prasad, S. S. Jalihal, Manzoore Elahi M. Soudagar, Haseeb Yaqoob, Muhammad Abbas Mujtaba, Kiran Shahapurkar, and Mohammad Reza Safaei. "Effect of manifold injection of hydrogen gas in producer gas and neem biodiesel fueled CRDI dual fuel engine." *International Journal of Hydrogen Energy* 47, no. 62 (2022): 25913-25928.

Khan, TM Yunus, Manzoore Elahi M. Soudagar, S. V. Khandal, Syed Javed, Imran Mokashi, Maughal Ahmed Ali Baig, Khadiga Ahmed Ismail, and Ashraf Elfasakhany. "Performance of common rail direct injection (CRDi) engine using Ceiba Pentandra biodiesel and hydrogen fuel combination." *Energies* 14, no. 21 (2021): 7142.

KOnECznA, REnAtA, and Justyna Cader. "Hydrogen in the strategies of the european Union member states." gospodarka *surowcami mineralnymi* 37, no. 3 (2021): 53-74.

Masood, M., and M. M. Ishrat. "Computer simulation of hydrogen–diesel dual fuel exhaust gas emissions with experimental verification." *Fuel* 87, no. 7 (2008): 1372-1378.

Mohankumar, S., and P. Senthilkumar. "Particulate matter formation and its control methodologies for diesel engine: A comprehensive review." *Renewable and Sustainable Energy Reviews* 80 (2017): 1227-1238.

Montoya, Juan P. Gómez, Andrés A. Amell, Daniel B. Olsen, and German J. Amador Diaz. "Strategies to improve the performance of a spark ignition engine using fuel blends of biogas with natural gas, propane and hydrogen." *International journal of hydrogen energy* 43, no. 46 (2018): 21592-21602.

Quadflieg, H. "From research to market application? Experience with the German hydrogen fuel project." *International journal of hydrogen energy* 13, no. 6 (1988): 363-374.

Shahir, V. K., C. P. Jawahar, and P. R. Suresh. "Comparative study of diesel and biodiesel on CI engine with emphasis to emissions—a review." *Renewable and Sustainable Energy Reviews* 45 (2015): 686-697.

Sharma, Sunita, and Sib Krishna Ghoshal. "Hydrogen the future transportation fuel: From production to applications." *Renewable and sustainable energy reviews* 43 (2015): 1151-1158.

Sørensen, Bent. "Hydrogen and fuel cells: emerging technologies and applications." (2011).

Vadlamudi, Srikanth, S. K. Gugulothu, Jibitesh Kumar Panda, B. Deepanraj, and PR Vijaya Kumar. "Paradigm analysis of performance and exhaust emissions in CRDI engine powered with hydrogen and Hydrogen/CNG fuels: A green fuel approach under different injection strategies." *International Journal of Hydrogen Energy* 48, no. 96 (2023): 38059-38076.

van Wijk, A., and Noordelijke Innovation Board. "The Green Hydrogen Economy now in the Northern Netherlands." *Groningen, the Netherlands* (2017).

Züttel, Andreas. "Hydrogen storage methods." Naturwissenschaften 91 (2004): 157-172.