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Experimental Investigation on Combustion, Performance, Emissions, and Vibrations in a Diesel-Hydrogen Dual-Fuel Engine with an On-Demand Hydrogen Generation System

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Hydrogen reactor, dual fuel engine, vibration, combustion, performance, emissions.

Abstract

The study addresses the challenge of onboard hydrogen storage in transportation by proposing an innovative solution involving an on-demand hydrogen generation system. This system operates via a chemical reaction between aluminum sulphate ($Al_2(SO_4)_3$) and sodium borohydride ($NaBH_4$), producing hydrogen gas in real-time. The research examines the performance of a Variable Compression Ratio (VCR) diesel engine running in a dual-fuel mode, where hydrogen is supplied from the reactor. Engine behavior was systematically analyzed under varying operating conditions, including compression ratios of 16, 17, and 18, and engine loads ranging from no load up to 12 kg, increasing in 3 kg steps. Additionally, the hydrogen flow rate was adjusted between 0 and 15 liters per minute. The results indicate that the engine achieved its best performance, in terms of efficiency, combustion, emissions, and vibration characteristics, at a compression ratio of 18 and a hydrogen flow rate of 15 liters per minute. These findings offer valuable insights for the advancement of on-demand hydrogen reactors, highlighting their potential for integration with VCR diesel engines to promote cleaner and more sustainable transport solutions.

1. Introduction

Despite population growth of only 1.14% annually, the global demand for liquid fuels is projected to rise significantly, at 1.1% per year in transportation and 1.0% in industry by 2040 [1-3]. This increase is driven by rising energy consumption, particularly in developing nations. While diesel engines offer better thermal efficiency than gasoline engines, they produce harmful emissions like NO_x and PM [4-5]. A major shortcoming of diesel is its noise and vibration, caused by engine components, combustion, and high compression ratios [6]. Studies show that incorporating hydrogen into diesel engines can reduce vibrations [7-8]. This shift towards hydrogen fuel is driven by environmental concerns. Burning traditional fuels releases greenhouse gas emissions, while hydrogen combustion only produces water vapor [9]. As a carbon-free fuel, hydrogen eliminates emissions like CO, CO_2, hydrocarbons, and particulate matter in internal combustion engines [10]. Its unique properties make it a promising alternative fuel for the future. Hydrogen's versatility as an energy carrier stems from its numerous production methods and its high energy density per unit volume and weight compared to electricity for storage. This makes it an attractive option for applications where long-distance transportation or high energy density is crucial [11]. The high self-ignition temperature characteristic prevents direct use of hydrogen in CI engines, where ignition relies on the compressed fuel-air mixture reaching a high enough temperature to combust spontaneously [12]. Recognizing the growing gap between hydrogen supply and demand, the energy and automotive engineering sectors are actively exploring alternative methods for producing and utilizing hydrogen. Dual-fuel mode, where hydrogen is used alongside a conventional fuel like diesel, appears to be a promising approach. Studies have demonstrated several advantages of using hydrogen in dual-fuel mode. These include improved combustion characteristics due to hydrogen's wider flammability range and faster burning velocity, leading to more complete combustion [13-14]. This translates to a reduction in BSFC, a metric representing engine efficiency, by up to 15.24% compared to using only diesel at 40% load [15]. Additionally, emissions of harmful pollutants like HC, CO, and CO_2 are significantly reduced due to hydrogen's clean burning nature [16]. However, a potential drawback is the increase in NO_x emissions observed with hydrogen use. This necessitates the implementation of exhaust gas recirculation techniques to manage NO_x levels and ensure compliance with emission regulations [17]. Another promising approach involves the use of oxy-hydrogen, a mixture of hydrogen and oxygen produced through the electrolysis of water at ambient temperature. Electrolyzers work by splitting water molecules using direct current (DC) electricity. Hydrogen gas is generated at the negative electrode (cathode), while oxygen gas evolves at the positive electrode (anode) [18].

Experiments using oxy-hydrogen injection in diesel engines have yielded positive results. Researchers observed improvements in BTHE, a measure of the engine's ability to convert fuel energy into usable work, and decrease in BSFC, HC, and CO emissions [19]. However, similar to the dual-fuel mode with hydrogen, NOx emissions increase with oxy-hydrogen use. Techniques like EGR can be employed to mitigate this issue and ensure environmentally responsible operation [20]. Despite the environmental benefits of hydrogen, its widespread adoption in transportation faces significant hurdles. Seyed Ehsan Hosseini et al.[21] identify the lack of refuelling infrastructure and onboard storage as the two biggest obstacles. Developing these technologies will require substantial investments and political support. Studies exploring hydrogen use in dual-fuel mode with diesel engines show promising results. Nag et al. [22] observed a decrease in peak pressure with increasing hydrogen substitution, indicating more efficient combustion at higher engine loads. However, they also noted increased engine vibrations under these conditions. Hariharan et al. [23] found a 1% increase in BTE for neat diesel and even greater improvements for biodiesel blends when combined with hydrogen. This is attributed to hydrogen's faster burning characteristics. The impact of hydrogen on emissions is complex. Rajak et al. [24] observed an overall increase in emissions when adding hydrogen to various fuels in a single-cylinder engine. However, Jamrozik et al. [25] found that using hydrogen as a secondary fuel in a dual-fuel CI engine can reduce exhaust emissions, particularly for stationary applications where hydrogen production is readily available. Ameer Suhel et al.[26] explored the use of hydrogen gas with nano-fuels and biodiesel blends, achieving improvements in BTE and emission reduction.

However, they highlight the need for further research on the environmental impact of these nano-fuels. Alberto Boretti [27] suggests hydrogen combustion engines could be advantageous for long-distance transportation compared to battery electric vehicles. Onorati et al. [28] emphasize the critical challenges of hydrogen production, availability, and storage infrastructure. They acknowledge the economic considerations but believe hydrogen offers a promising path towards a clean energy future, particularly for internal combustion engines with established technology. Kuin et al. [29] report positive results using a hydrogen-oxygen gas generator in a diesel engine, suggesting potential for improved performance and environmental impact. Research has consistently highlighted that hydrogen offers superior environmental benefits compared to conventional fuels, such as pure diesel and biodiesel blends. Despite these advantages, traditional hydrogen production and storage methods are often impractical for mobile applications like automobiles due to issues with infrastructure and storage safety. This study introduces a novel solution: an on-demand hydrogen generation system integrated directly within the engine setup, as illustrated in Fig. 1. Unlike conventional systems that rely on external hydrogen storage, this innovative reactor generates hydrogen in real-time through chemical reactions, directly supplying it to the engine. The uniqueness of this approach lies in its ability to bypass the need for bulky and complex hydrogen storage infrastructure, making it more feasible for automotive use. This system shows promise for providing hydrogen fuel to vehicles, enabling cleaner transportation.

Nomenclature	
$Al_2(SO_4)_3$	Aluminium Sulphate
$NaBH_4$	Sodium Borohydride
$HgCl_2$	Mercury Chloride
VCR	Variable compression ratio
CI	Compression ignition
CR	Compression Ratio
Lpm	Liters per minute
Kg	kilogram

CP	Cylinder pressure
NHRR	Net heat release rate
RoPR	Rate of pressure rise
BTHE	Brake thermal efficiency
BSFC	Brake specific fuel consumption
Vol eff	Volumetric efficiency
CO	Carbon monoxide
CO_2	Carbon dioxide
HC	Hydro carbons
NO_x	Nitrogen oxides
HES	Hydrogen energy share
DAQ	Data acquisition

2. Experimental Setup and Procedure

The experiment utilized a single-cylinder, four-stroke research engine with variable compression ratio, direct injection, and water cooling as shown in Fig. 2. Diesel fuel, measured by a flow sensor, was injected into the combustion chamber from the diesel tank using injectors. A hydrogen reactor supplied hydrogen gas to the intake manifold through a flow meter. An eddy current dynamometer measured the engine's output power. For data acquisition and analysis, the engine panel and system were connected to IC Engine soft 9.0 software to monitor combustion and performance data. Exhaust emissions were analysed using an AVL Digas 444N exhaust gas analyzer. Engine vibrations were recorded by a PCB Triaxial accelerometer 356A32 mounted on the engine head. The data acquisition system (DAQ) connected the sensor cable to a system for recording vibrations. Dewesoft software X3 was used to monitor and analyze the vibration data.

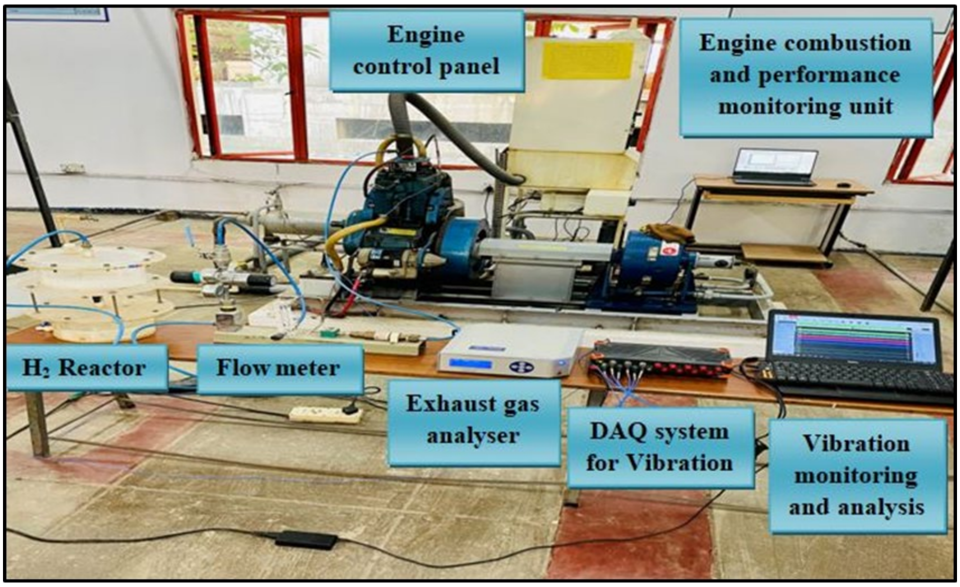

Fig. 1 *Layout of the experimental test rig*

The experiment investigated the engine's performance across a range of operating conditions. Three compression ratios were examined: 16, 17, and 18. Fig. 3 shows the setup of hydrogen reactor. Hydrogen flow rate was varied using the reactor and a flow meter. The flow meter settings were adjusted to deliver hydrogen to the engine's intake manifold at three different levels: 5, 10, and 15 LPM.The range of compression ratios and hydrogen flow rates were chosen based on preliminary trials and prior studies. These values were selected to cover a wide range of operating conditions and to investigate the effects of varying CR and hydrogen enrichment levels on engine performance and emissions. Engine load was also varied to simulate different driving scenarios. It ranged from no load (0 kg) to full load (12 kg), with increments of 3 kg for each test point.

Table 1 shows the Accuracy of measurements of the instruments used and Table 2 and 3 shows the technical specifications of test engine and vibration measurement equipment.

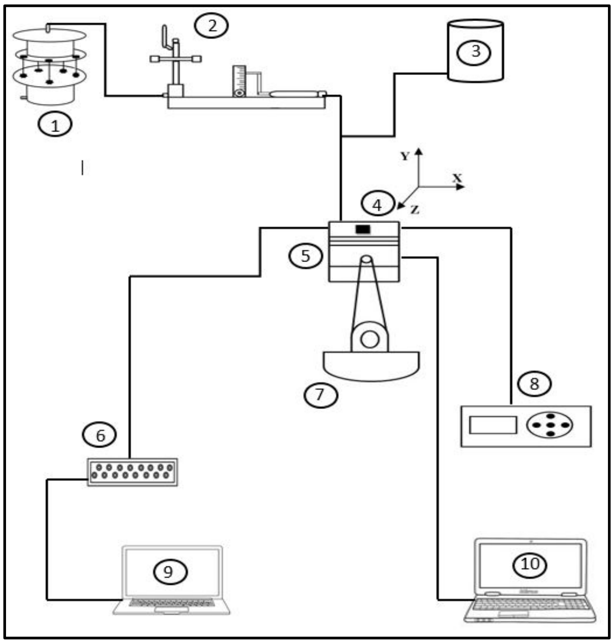

Fig. 2 *Schematic setup of experimental test reg*

Parts: 1. Hydrogen reactor 2. Hydrogen flow meter 3. Diesel tank 4. Vibration measuring sensor 5. Engine 6. Vibration measuring system 7. Crankshaft with counterweight 8. Exhaust gas analyser 9. Vibration monitoring system 10. Engine parameters measuring system

2.1 Hydrogen Generation System with Flow Rate Control

The hydrogen generation system employed in this research utilizes a two-container setup with separate reactant solutions and a controlled flow rate for delivery to the engine manifold. Here's a breakdown of the process with additional technical details:

2.1.1 Reactant Preparation

Container 1: 10 grams of sodium borohydride ($NaBH_4$) are dissolved in 1000 mL of deionised water. This solution acts as the hydrogen source.
Container 2: 5 grams of aluminium sulphate ($Al_2(SO4)_3$) are dissolved in 1000 mL of deionised water. This solution serves as the catalyst for the hydrogen generation reaction.

2.1.2 Hydrogen Generation and Flow Control

Controlled Mixing: A valve between the two containers allows for controlled mixing of the solutions. Upon opening the valve, the $NaBH_4$ solution from Container 1 gradually flows into Container 2.
Reaction Initiation: Once the solutions meet, the following reaction occurs:

$$2\ NaBH_4 + Al_2(SO_4)_3 + 6\ H_2O \rightarrow 2\ NaAlO_2 + 4\ B(OH)_3 + 12\ H_2$$

This reaction generates hydrogen gas (H_2) along with other by-products.
The hydrogen output from the reactor was consistent during the experiments, as the flow rate was controlled using a flow meter. However, maintaining consistent hydrogen production over long periods could be challenging due to potential variations in reactant concentration and reaction kinetics

2.2 Dual-Fuel Engine Conversion

To integrate the on-demand hydrogen generation system into existing diesel engines, certain modifications would be necessary. These include the installation of a custom hydrogen reactor, which generates hydrogen through a chemical reaction between sodium borohydride ($NaBH_4$) and aluminum sulphate ($Al_2(SO_4)_3$). The reactor would be connected to the engine's intake manifold, and a flow control system would regulate the hydrogen flow rate.

Additionally, safety measures were implemented during hydrogen production and injection, including hydrogen sensors to detect leaks, pressure relief valves to prevent over-pressurization, and an emergency shutdown mechanism in case of abnormal conditions. These measures ensured the safe operation of the on-demand hydrogen generation system.

Fig. 3 *Hydrogen reactor*

Table 1 *Operating range & precision of sensors*

Sensor Type Operating	Range & Precision
Load measurement	0–50 kg, ± 0.2% accuracy
Rotational speed sensor	1200–1800 rpm with ± 30 rpm
Temperature sensor	0–100 °C with ± 1% accuracy
Pressure sensor	0–350 bar with ± 0.1% accuracy
Crank angle sensor	1° resolution with ± 0.2% variation
Carbon Monoxide Sensor	0–15% with ± 0.03% accuracy
Hydrocarbon Detector	–30,000 ppm with ± 5 ppm deviation
Nitrogen Oxide sensor	0–5000 ppm ± 50 ppm accuracy

Table 2 *Engine specifications*

Parameter	Description
Engine model	Kirloskar
Cylinder Configuration	1-cylinder
Bore	87.5 mm
Stroke	110 mm
Power output	3.5 kW
Operating speed	1500 rpm
Injection pressure	200 bar
Fuel Injection Timing	30° Before TDC
CR	16:1, 17:1, 18:1
Exhaust gas analyzer	AVL DIGAS 444 N gas analyzer
Control Software	Engine soft

Table 3 *Technical specifications of vibration equipment*

Parameter	Description
Type	Dewesoft DAQ – 16 channel
Type of software	SP 12, USB based
FFT range	16000 lines of resolution
Sensors	PCB-Triaxial
Model	356A32
Sensitivity	(±10%) 100 mV/g(10.2 mV/(m/s^2))
Measurement Range	±50 g pk(±491 m/s^2 pk)
Cable Model	034k10
Mating cable length	10 ft

3. Results and Discussion

This study investigates the consequences of hydrogen enrichment on various aspects of CI engine operation, including performance, combustion characteristics, emissions, and vibration. The research employs a variable compression ratio engine, testing three distinct settings: 16:1, 17:1, and 18:1. Furthermore, hydrogen is introduced at varying flow rates to assess its influence. A detailed discussion of the findings follows:

3.1 Combustion Characteristics

3.1.1 Cylinder Pressure

Fig. 4 compares the cylinder pressure profiles of regular diesel and hydrogen-enriched diesel at three different flow rates. As expected, higher engine loads lead to increased peak cylinder pressure regardless of fuel type, due to the greater quantity of fuel being burned [31]. Hydrogen enrichment, however, results in a distinct rise in peak cylinder pressure. This is primarily due to the premixed combustion stage is intensified by the presence of hydrogen, leading to a larger amount of fuel burning before the main combustion event. Secondly, hydrogen's high diffusion coefficient promotes a more uniform mixture, improving oxygen availability for combustion [32, 33]. Furthermore, hydrogen's rapid burning characteristics contribute to a faster burning mixture and a rise in peak-in-cylinder temperature as the hydrogen proportionraises [34]. This, combined with hydrogen's low ignition energy, leads to a shift in peak pressure closer to Top Dead Centre (TDC), resulting in higher power output in hydrogen mode [35].

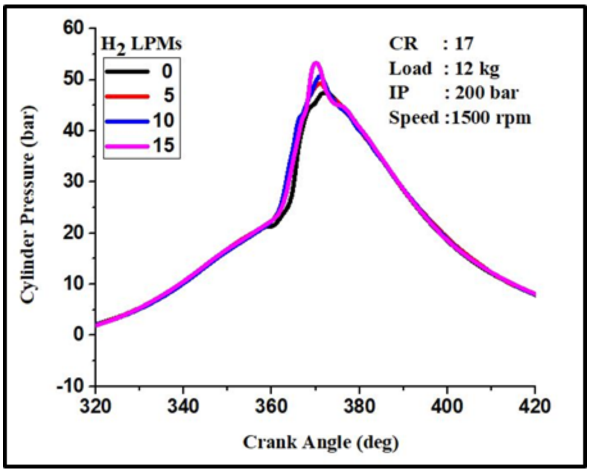

Fig. 4 *Cylinder pressure versus crank angle with different H2 flow rates*

The experiment investigated the impact of compression ratio and hydrogen flow rate on peak cylinder pressure (Pmax). As expected, increasing the compression ratio resulted in higher in-cylinder temperature and pressure, leading to faster flame propagation upon ignition [36]. Fig. 5 depicts the peak pressure (Pmax) within the combustion chamber plotted against both CR and various hydrogen flow rates. It was observed from the figure that maximum pressure increases with CR and hydrogen flow rates. Higher compression ratios led to increased combustion efficiency, which translated into observable gains in engine power and fuel economy. The peak cylinder pressure and heat release rate increased, resulting in higher brake thermal efficiency and lower brake-specific fuel consumption. These gains were more pronounced at higher CRs and hydrogen flow rates [37].

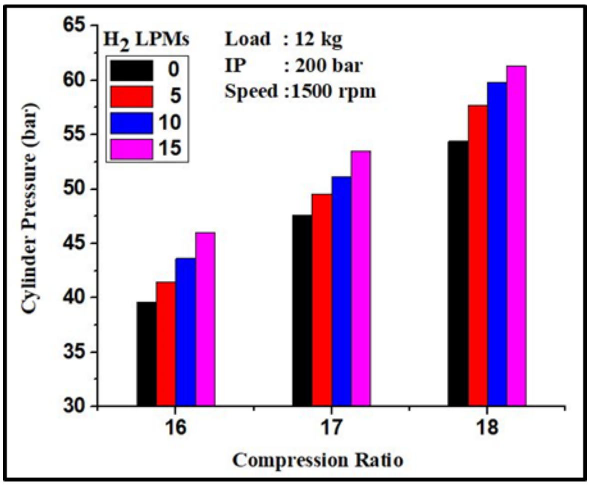

Fig. 5 *Cylinder pressure vs various compression ratios with different H2 flow rate*

3.1.2 Net Heat Release Rate (NHRR)

The NHRR represents the total amount of heat released during combustion, from ignition to completion. Fig. 6 illustrates the impact of hydrogen on the NHRR across the crank angle. Rapid burning velocity and flame propagation of hydrogen contribute to a higher peak NHRR [37].Additionally, hydrogen's lower ignition delay, compared to diesel, leads to a faster rise in NHRR. This is despite the fact that hydrogen has a higher self-ignition temperature [33]. It's important to note that hydrogen's burningrate is significantly quicker than diesel's (almost eight times faster under typical conditions at 38 cm/s for diesel) [38].

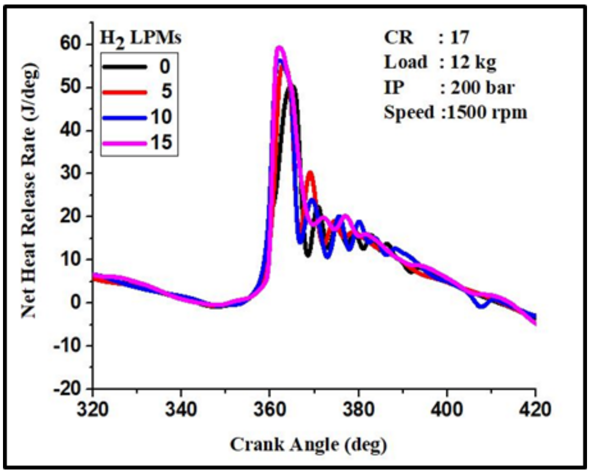

Fig. 6 *NHRR versus crank angle with different H2 flow rates*

The experiment confirmed a positive correlation between compression ratio and Net Heat Release Rate (NHRR) as shown in Fig. 7. Higher compression ratios lead to increased in-cylinder temperature and pressure, enhancing combustion efficiency and flame speed [36]. Consequently, NHRR values increased with compression ratio for all fuel conditions.

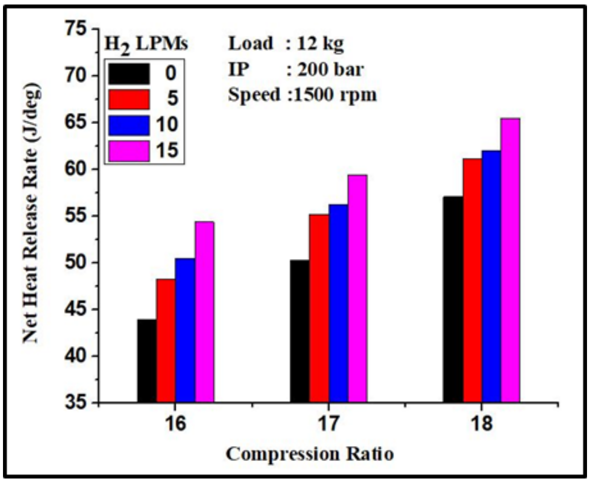

Fig. 7 *Net heat release rate versus various compression ratios with different H2 flow rates*

3.1.3 Rate of Pressure Rise (RoPR)

Fig. 8 depicts the pressure variation within the combustion chamber across the crank angle, from ignition to the expansion stroke. The experiment observed a faster rate of pressure rise at full load and constant speed with increasing hydrogen content. This rapid pressure rise is a consequence of hydrogen's fast burning characteristics, leading to more efficient combustion and a higher peak pressure within the cylinder [39]. Furthermore, increasing the hydrogen quantity significantly shortens the engine's combustion duration. This translates to a faster heat release in the peak combustion phase, further contributing to the accelerated pressure rise. Additionally, the amount of heat released during the initial combustion stage also influences the RoPR [40]. Finally, Fig. 9 illustrates how the RoPR is affected by different CR and hydrogen flow rates. Higher compression ratios provide superior pressure and temperature conditions within the cylinder, leading to faster flame propagation and consequently, a higher RoPR [33].

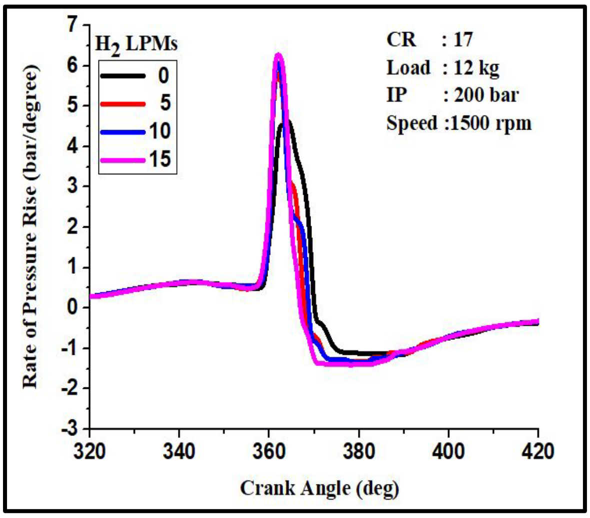

Fig. 8 *RoPR vs crank angle with different H2 flow rates*

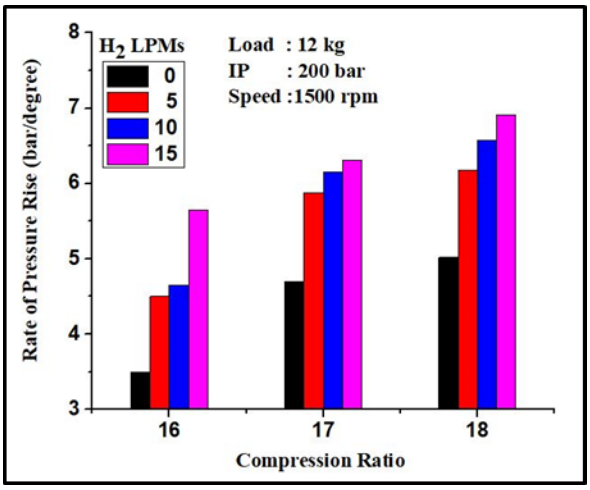

Fig. 9 *RoPR versus various compression ratios with different H2 flow rates*

3.2 Performance Characteristics

3.2.1 Brake thermal efficiency (BTHE)

Fig. 10 demonstrates the impact of hydrogen enrichment on BTHE for various engine outputs (brake power). As the figure clearly shows, BTHE increases with both higher brake power and the adding of hydrogen. This improvement can be attributed to several factors: enhanced combustion efficiency, improved air-fuel mixing, higher power output, and reduced losses [41, 42].

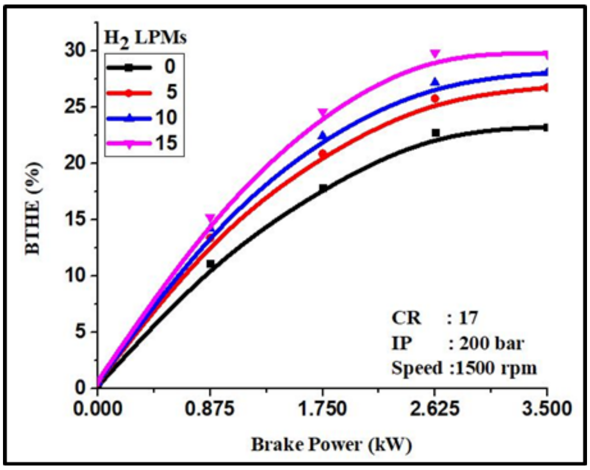

Fig. 10 *BTHE versus brake power with different H2 flow rates*

Fig. 11 further suggests that higher compression ratios lead to improved peak BTHE. This indicates that hydrogen enrichment might be even more beneficial at higher compression ratios. As the compression ratio increases, the molecules are squeezed closer together, reducing the reaction time for combustion. Additionally, the higher compression temperatures and lower minimum auto-ignition temperature of hydrogen contribute to a shorter ignition delay period [44].

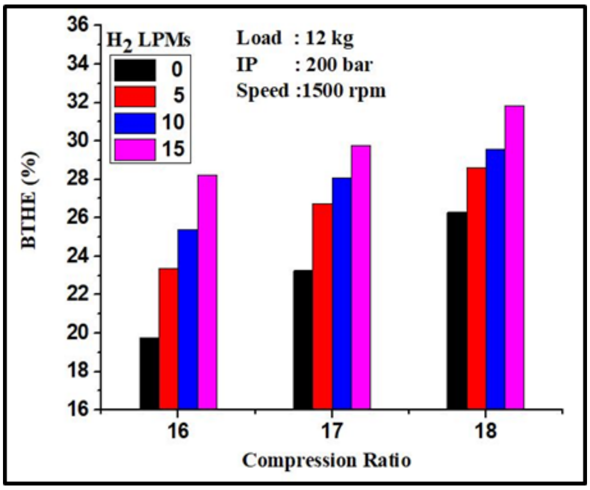

Fig. 11 *BTHE versus various compression ratios with different H2 flow rates*

3.2.2 Brake-specific fuel consumption (BSFC)

Fig. 12 demonstrates that BSFC for hydrogen-enriched diesel decreases with increasing engine power output (brake power) at all hydrogen flow rates. This improvement in fuel efficiency can be attributed to two key factors: shorter combustion Period [45, 33] and enhanced combustion [41]. It's important to note that BSFC generally has an opposite trend to Brake Thermal Efficiency (BTE) [46]. While BTE focuses on converting fuel heat into usable power, BSFC emphasizes fuel consumption for a given power output.

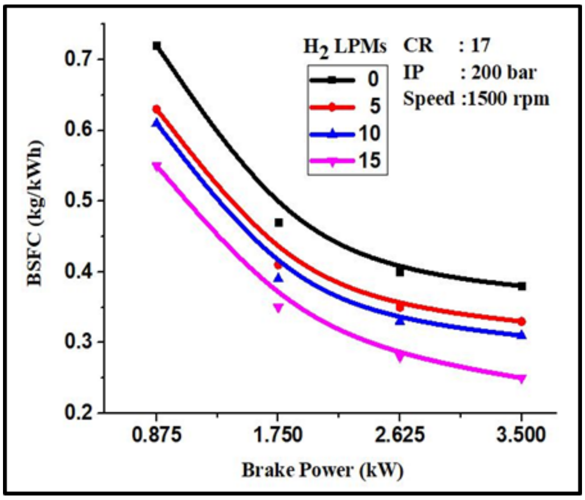

Fig. 12 *BSFC versus brake power with different H2 flow rates*

As illustrated in Fig. 13, increasing both the compression ratio and hydrogen flow rate lead to a favourable trend in BSFC. This observation suggests that the phenomenon of hydrogen enrichment might exhibit even greater advantages at elevated compression ratios. This can be attributed to the combined effects of improved air-fuel mixing and enhanced combustion efficiency facilitated by hydrogen's inherent properties at higher compression.

The study observed that engine performance metrics, such as BTHE and BSFC, improved with hydrogen enrichment across all loads. However, the improvements were more pronounced at higher loads (full load) due to better combustion efficiency and higher in-cylinder temperatures. At partial loads, the benefits were still significant but less dramatic, as the combustion process was less intense.

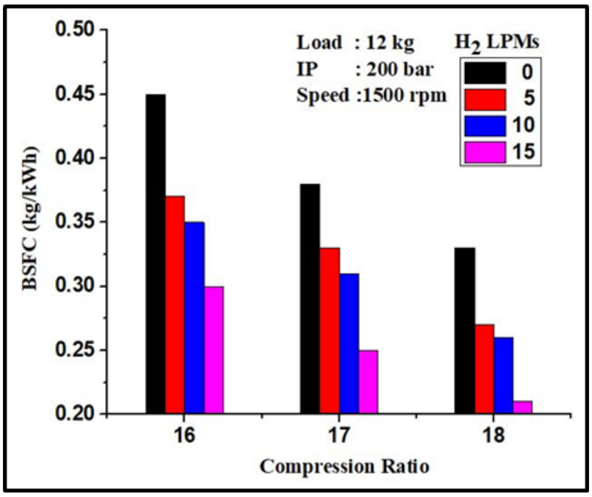

Fig. 13 *Brake specific fuel consumption versus various compression ratios with different H2 flow*

3.2.3 Volumetric Efficiency

Fig. 14 illustrates the impact of hydrogen enrichment on volumetric efficiency. This metric generally decreases with increasing engine power (brake power) for all fuel conditions. Factors contribute to this trend are high in-cylinder temperature and gas expansion at high loads [48].

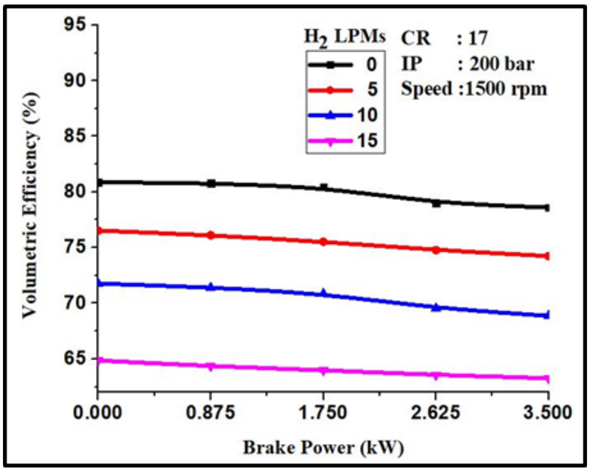

Fig. 14 *Volumetric efficiency versus brake power with different H2 flow rates*

Fig. 15 reveals a declining trend in volumetric efficiency with increasing compression ratios and hydrogen flow rates within the diesel engine. This counterintuitive behaviour can be attributed to two primary factors. Firstly, hydrogen, compared to air, has a lower inherent density. This necessitates a larger volume of hydrogen to achieve the same mass of air required for stoichiometric combustion. As a result, at higher flow rates, hydrogen can displace a significant portion of the air charge entering the cylinder, reducing the overall air intake and hence the volumetric efficiency. Secondly, higher compression ratios can exacerbate this effect by further limiting the available cylinder volume for air intake. This combination of factors leads to a decrease in the engine's ability to draw in a fresh air charge with increasing hydrogen enrichment and compression ratio.

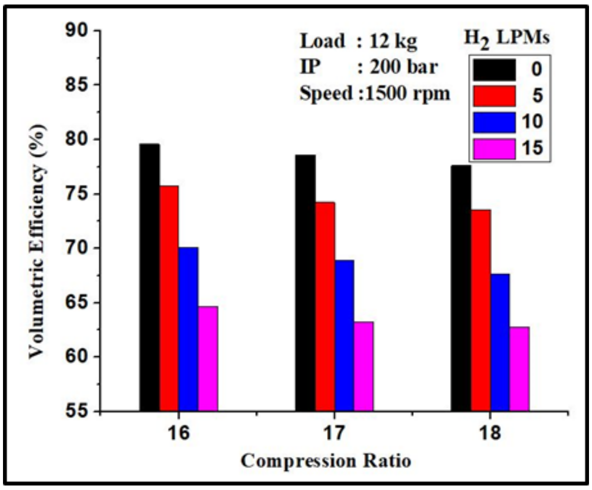

Fig. 15 *Volumetric efficiency versus various compression ratios with different H2 flow rates*

3.3 Emissions

3.3.1 Carbon Monoxide (CO)

CO, a pollutant in engine exhaust, arises from incomplete combustion of hydrocarbon fuel due to a lack of oxygen. Insufficient mixing, rich fuel ratios, and other factors contribute to CO emissions [37]. While brake power seems less influential, Fig. 16 reveals a significant CO reduction with increasing hydrogen flow rates. It's important to observe that CO emissions generally increase with higher brake power at all compression ratios. However, increasing compression ratios can also contribute to lower CO by promoting the complete burning of fuel droplets.

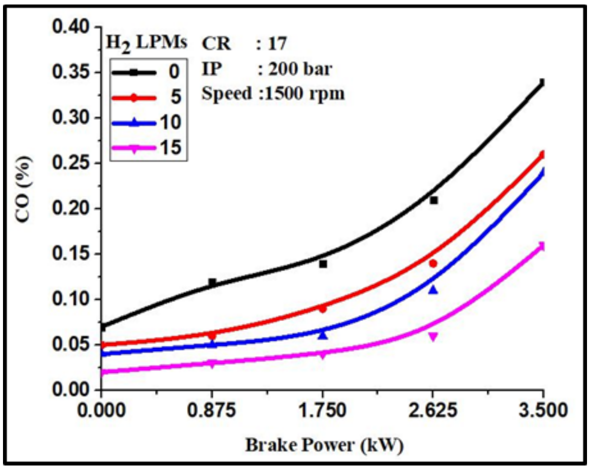

Fig. 16 *CO versus BP with different H2 flow rates*

Increasing compression ratios and hydrogen flow rates are likely to contribute to a decreasing trend in CO emissions observed in Fig. 17. Higher compression ratios lead to more complete combustion of the fuel-air mixture, leaving less unburned carbon monoxide (CO) in the exhaust. Additionally, hydrogen burns cleaner than diesel, and introducing hydrogen into the engine reduces the overall carbon content in the fuel mixture. This dual effect explains the potential for lower CO emissions with these changes. Similar trends are noticed with Jaikumar et al [33].

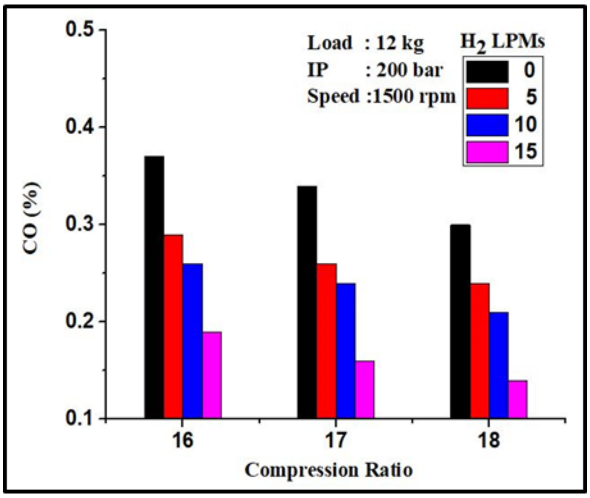

Fig. 17 *Carbon monoxide versus various compression ratios with different H2 flow rates*

3.3.2 Hydrocarbon (HC)

HC emissions are another pollutant of concern in engine exhaust. These unburned hydrocarbons result from incomplete combustion within the cylinder due to factors like Non-uniform Air-Fuel Mixture and cylinder wall temperature [51, 52].

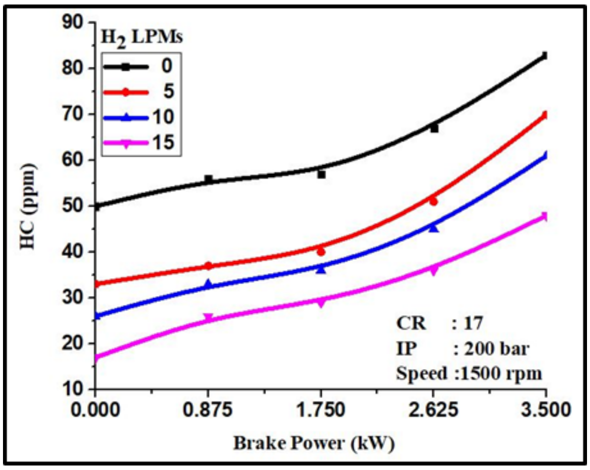

Fig. 18 *HC versus BP with different H2 flow rates*

As shown in Fig. 18, HC emissions generally decrease with increasing brake power, likely due to improved combustion efficiency at higher engine loads. The introduction of hydrogen offers a significant advantage in HC reduction like no carbon content, faster burning velocity and reduced carbon-based fuel.

Fig. 19 shows HC decreases by increasing CR due to fact that the higher compression ratios produce hotter compressed air, which encourages more rapid and complete combustions [44].

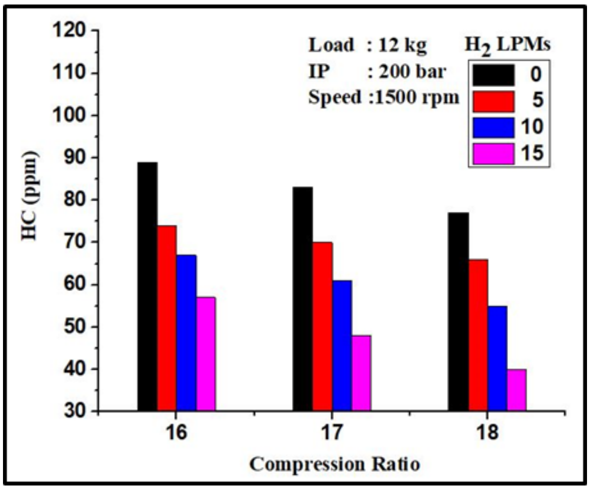

Fig. 19 *Hydro carbons versus various compression ratios with different H2 flow rates*

3.3.3 Nitrogen Oxides (NO_x)

In diesel engines, high temperatures and oxygen levels within the cylinder contribute to the formation of nitric oxide (NO_X) emissions, as shown in Fig. 20. This makes NO_X a useful indicator of how well hydrogen substitution works. While adding hydrogen speeds up combustion and increases the temperature of the burning gases, it can also lead to higher NO_X emissions. This is because the faster burning and increased efficiency caused by hydrogen also contribute to rapid temperature rise and flame spread [44]. Additionally, hydrogen's much higher lower heating value (LHV) compared to diesel further elevates peak cylinder temperatures, promoting NO_X formation [56].

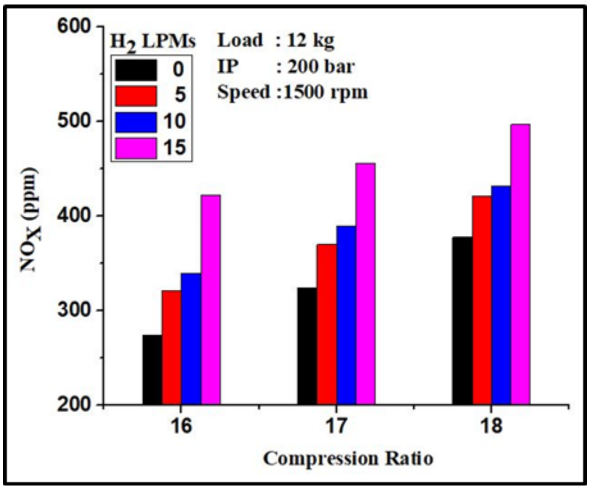

Fig. 20 *NOx versus various compression ratios with different H2 flow rates*

It was observed that NO_x increased with increasing compression ratios and hydrogen substitution rates because operating temperatures are high [44].

3.3.4 Carbon Dioxide

Diesel engines produce CO_2 emissions when the fuel burns and carbon atoms combine with oxygen. As Fig. 21 shows, adding hydrogen to the fuel lowers CO_2 emissions compared to using just diesel. There are two reasons for this. First, hydrogen improves fuel combustion, allowing more complete burning and less CO_2 production. Second, unlike diesel, hydrogen itself doesn't contain any carbon atoms, so its combustion doesn't generate CO_2 directly.

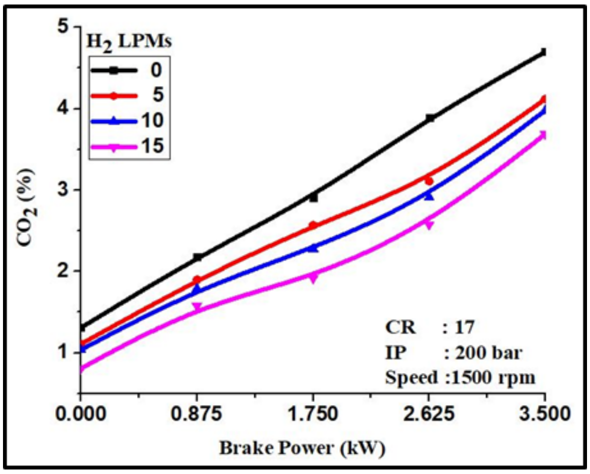

Fig. 21 *CO2 versus BP with different H2 flow rates*

Fig. 22 suggests a correlation between increasing compression ratios, hydrogen flow rates, and a decrease in CO_2 emissions. The main reasons for this trend: Higher compression ratios lead to a hotter and denser environment in the engine cylinder. This promotes more complete combustion of the fuel mixture, resulting in less unburned fuel and consequently lower CO_2 emissions. Hydrogen itself doesn't produce CO_2 during combustion, only water vapour. Introducing hydrogen into the engine dilutes the amount of traditional diesel fuel being burned. Since diesel fuel combustion produces CO_2, this dilution effect lowers the overall CO_2 emissions from the engine.

Beyond the reduction in emissions, the environmental impact of sourcing and using chemical reactants ($NaBH_4$ and $Al_2(SO_4)_3$) should be considered. While hydrogen combustion produces only water vapor, the production of these reactants may have ecological implications, such as energy consumption and waste generation during their manufacture. However, the overall environmental benefit of reduced greenhouse gas emissions from the engine could outweigh these concerns, especially if the reactants are produced using renewable energy sources.

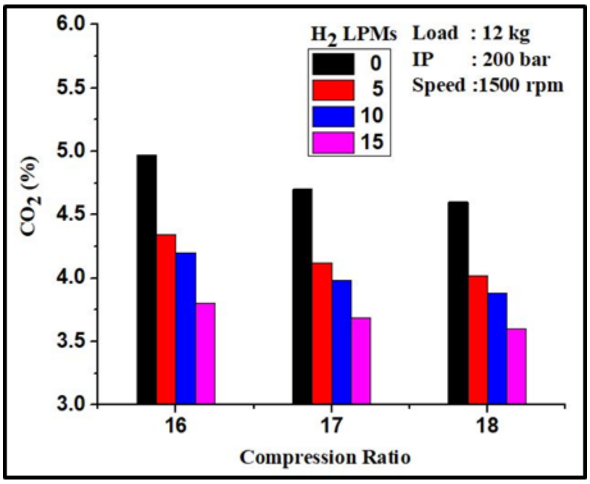

Fig. 22 *CO2 versus various compression ratios with different H2flow rates*

3.4 Vibrations

This study investigated how adding hydrogen to diesel fuel affects engine vibrations. A diesel engine was run at full load (12kg) and constant speed (1500 rpm) while vibrations were measured using a sensor mounted on the engine head. The tests used pure diesel and hydrogen blends with flow rates of 5, 10, and 15 liters per minute. Vibration data from the hydrogen blends were compared to pure diesel, which served as the baseline. Vibrations were recorded in real-time (time domain).

In general, engine vibrations stem from two main factors: the weight of engine parts (inertia) and fluctuations in pressure within the engine [59]. When fuel burns in the combustion chamber, pressure rises rapidly. This pressure pushes against the engine's internal walls and pistons, causing vibrations [60]. In diesel engines, variations in cylinder pressure are considered the primary culprit for vibration [61].

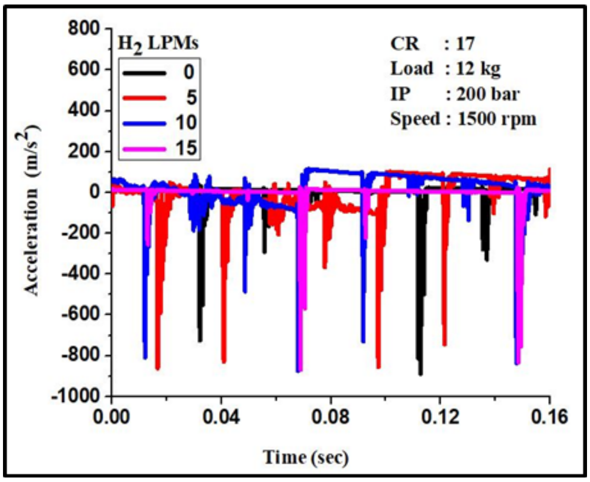

Fig. 23 *Time domain vibrations of engine head for different H2 flow rates*

The experiment's results, shown in Fig. 23, reveal that vibrations are lowest at a hydrogen flow rate of 15 liters per minute (lpm) compared to pure diesel and other hydrogen rates. This is likely because hydrogen's faster combustion shortens the ignition delay period [62]. Shorter ignition delay leads to a less mixing-controlled combustion phase, potentially reducing the acceleration of engine block vibrations. The relationship between cylinder pressure variations and engine vibrations is inversely proportional, meaning lower pressure variations lead to lower vibrations. Figure 24 shows the vibrations measured in all three directions (X, Y, and Z axes). The Y-axis recorded the highest vibration due to the piston's up-and-down movement within the cylinder. The crankshaft translates this vertical motion into a back-and-forth motion (longitudinal), resulting in the second-highest vibration on the X-axis. Vibrations on the Z-axis, typically caused by the engine's auxiliary equipment, were the lowest [62, 63].

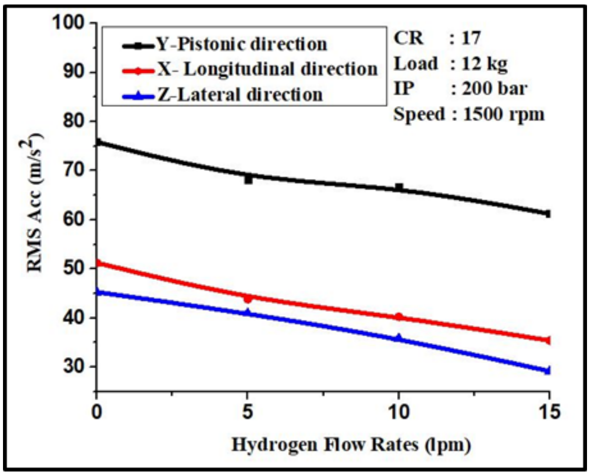

Fig. 24 *Vibrations vs different H2 flow rates in three directions*

While the previous results showed reduced vibration with higher hydrogen flow rates, it's important to consider the complex factors at play. Despite the increased in-cylinder pressure caused by hydrogen's high energy content and fast burning (reduced ignition delay and faster flame propagation), the overall vibration is lower [64,65]. This seemingly contradictory outcome can be explained by the numerous influences on engine vibration, as highlighted in prior research [66-69]. These factors include the movement of the pistons and crank mechanism, timing gear inputs, engine body vibrations, cooling flow, gas intake and exhaust, fuel injection, inertia of camshaft components, and even the impact of cylinder head parts. The interplay of these factors likely contributes to the overall decrease in vibration observed with higher hydrogen use.Fig. 25 shows the decreasing trends in engine vibrations with increase in compression ratio and hydrogen flow rates. A higher compression ratio can, in some cases, lead to a smoother and more even combustion process. This can potentially reduce the impulse forces acting on engine components, leading to lower vibrations. However, a very high compression ratio can also cause knocking, which can increase vibrations. Hydrogen has a higher burning velocity compared to diesel. This faster burn can potentially lead to a more controlled combustion event, reducing pressure fluctuations and vibrations within the engine.

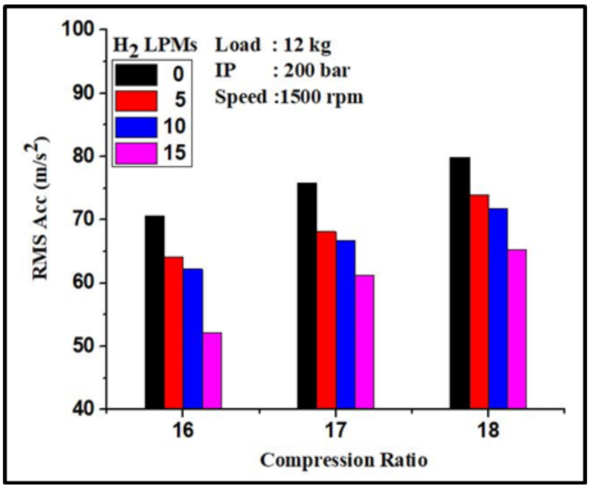

Fig. 25 *Vibrations vs various compression ratios for different H2 flow rates*

4. Conclusions

This research studied the effect of hydrogen enrichment on a CI engine with a variable compression ratio. The engine was effectively modified to incorporate a hydrogen reactor, enabling the production of hydrogen gas and its injection into the intake manifold.Tests were conducted at different CR and various engine loads by adjusting hydrogen flow rates. The following are the conclusions drawn from the work:

- Burning hydrogen with diesel at CR18 increased cylinder pressure, NHRR, and RoPR. The highest values were recorded at a hydrogen flow rate of 15 liters per minute: 61.33 bar pressure (12.8% increase), 65.48 J/degree heat release (14.4% increase), and 6.91 bar/degree pressure rise (37.6% increase).
- Engine efficiency (BTE) improved significantly (31.8% increase) with hydrogen enrichment at CR18 and 15 lpm flow rate. Additionally, fuel consumption (BSFC) decreased continuously as compression ratio and load increased (reduction of 0.21, representing a 36.4% improvement).
- Air intake efficiency (volumetric efficiency) also improved at CR18 and 15 lpm flow rate (increase of 62.8%, or 23.6%).
- Hydrogen enrichment (15 lpm) at CR18 and full load led to a reduction in CO by 0.14 (53.3%) and carbon dioxide (CO_2) emissions by 3.6 (21.7%).
- While hydrogen combustion typically increases NO_x emissions due to high temperatures, this study observed a decrease (31.5%) with hydrogen addition (15 lpm) at CR18 and full load. Similarly, hydrocarbon (HC) emissions also decreased by 48.1% under these conditions.
- Hydrogen's fast burning rate promoted better combustion, resulting in lower vibration compared to pure diesel. The lowest vibration (52.17 m/s^2 acceleration) was observed at CR16 with hydrogen enrichment (15 lpm).

Scaling this system for heavy-duty engines or commercial vehicles presents several technical challenges. The reactor would need to be scaled up to meet the higher hydrogen demand of larger engines, and heat management would become critical due to the increased heat generation. Space constraints and durability under harsh operating conditions are additional considerations. Future research should focus on addressing these challenges to enable the widespread adoption of on-demand hydrogen generation in heavy-duty applications.In overall implementing on-demand hydrogen generation in real-life applications presents several challenges. These include the safe storage and handling of chemical reactants ($NaBH_4$ and $Al_2(SO_4)_3$), ensuring the durability of the reactor over long-term use, and integrating the system into existing vehicle architectures without compromising space or weight. Addressing these challenges will be critical for the practical adoption of this technology.

Future studies could focus on scaling the system for multi-cylinder engines and other vehicle types, such as heavy-duty trucks and buses. The challenges of scaling up include ensuring consistent hydrogen production, managing heat dissipation, and integrating the system into existing vehicle architectures.

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Conflict Of Interest

The authors declare no conflict of interest, financial or otherwise.

Authors' Contribution

The authors confirm contribution to the paper as follows: ***Study conception and design:*** *Shaik Subani, Domakonda Vinay Kumar;* ***Data collection:*** *Shaik Subani, Domakonda Vinay Kumar;* ***Analysis and interpretation of results:*** *Shaik Subani, Domakonda Vinay Kumar, Farooq Shaik, Noor Alam;* ***Draft manuscript preparation:*** *Shaik Subani, Domakonda Vinay Kumar, Farooq Shaik, Noor Alam; All authors reviewed the results and approved the final version of the manuscript.*

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