AN EXPERIMENTAL AND ANALYSIS OF DIFFERENT VARIABLE COMPRESSION RATIO WITH DIFFERENT FUELS ON ENGINE

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ABSTRACT: Hydrogen, with its great energy potential and clean burning characteristics, is emerging as a viable alternative fuel at a time when the use of fossil fuels is causing growing environmental problems. Using hydrogen-enriched gasoline and compression ratios (CRs) of 15.5–17.5, this research investigates the efficiency and pollution features of a single-cylinder compression ignition engine. Based on the results, the optimal configuration is a 17.5 CR, which decreases specific fuel consumption (SFC), improves brake thermal efficiency (BTE), and decreases emissions of hydrocarbons (HC), carbon monoxide (CO), and smoke, while slightly raising nitrogen oxides (NOx). The research also looks at a Low Heat Rejection (LHR) engine configuration, which makes use of a half-millimeter coating of partly stabilized zirconia (PSZ) to reduce heat loss and improve combustion on engine parts including the piston, cylinder walls, and valves. In comparison to a typical diesel engine, the LHR engine powered by hydrogen decreased SFC by 5.7%, boosted BTE by 4.3%, and reduced UBHC and CO emissions, according to tests conducted with and without the coating, using gasoline and hydrogen, respectively. Nevertheless, there was a little increase in NOx emissions due to the higher combustion temperature. In sum, a cleaner combustion solution without significant engine modifications is offered by combining hydrogen fuel with optimized compression ratio and thermal barrier coatings; this makes it an efficient and practical alternative to diesel, which is especially relevant for sustainable fuel development in areas like India.

Key words: Hydrogen fuel, Compression ratio, Low Heat Rejection engine, Emissions reduction, Brake thermal efficiency.

1. INTRODUCTION

The growing global demand for energy, driven by rapid industrial development and population growth, has intensified the consumption of fossil fuels. These fuels, which once fulfilled around 65% of the world's energy requirements, now face two major limitations: their finite supply and their significant contribution to environmental pollution. The transportation sector alone accounts for nearly 98% of its energy needs

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from fossil fuels, making it a major emitter of greenhouse gases, particularly carbon dioxide (CO_2) and nitrogen oxides (NOx). As concerns about global warming and energy sustainability intensify, researchers are exploring alternative energy sources that are both clean and efficient.

Hydrogen stands out as a highly promising candidate among alternative fuels due to its high energy content, zero-carbon emission characteristics, and favorable combustion properties such as a wide flammability range and high flame speed. Unlike conventional fuels, hydrogen combustion primarily results in water vapor, making it environmentally friendly. Moreover, hydrogen can be produced from various renewable sources, including water electrolysis and biomass, thus offering energy security.

Recent developments in hydrogen-based dual-fuel engines, especially those operating under variable compression ratios (CR), show significant improvements in engine performance and emission control. Additionally, the implementation of thermal barrier coatings like partially stabilized zirconia (PSZ) in engine components introduces the concept of Low Heat Rejection (LHR) engines, further enhancing thermal efficiency.

This study focuses on experimentally evaluating the performance and emission characteristics of a single-cylinder diesel engine operating at different compression ratios using hydrogen as a secondary fuel. It also explores the impact of LHR engine configurations using PSZ coatings to determine the optimal setup for sustainable and efficient engine performance. in diesel engines through variable compression ratios and thermal barrier coatings to assess feasibility and optimize performance.

2. LITURETURE SURVEY:

The increasing interest in hydrogen as an alternative fuel has encouraged extensive research into its application in internal combustion engines. Hydrogen offers several benefits, including high energy density, a wide flammability range, fast flame propagation, and zero carbon emissions. Verhelst and Sierens (2001) noted that hydrogen can operate under lean conditions and provides improved thermal efficiency. However, challenges such as backfiring, pre-ignition, and elevated NOx emissions due to higher combustion temperatures still exist.

Papagiannakis and Hountalas (2004) studied dual-fuel systems, indicating that while gaseous fuels like hydrogen reduce soot and

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particulate matter, they tend to lower thermal efficiency and may increase hydrocarbon emissions. Subsequent investigations by Korakianitis et al. (2010) confirmed hydrogen's suitability for high-compression applications, owing to its high octane rating. They also found that optimizing ignition timing and mixture ratios can reduce NOx emissions.

Karim and Klat (2005) emphasized hydrogen's low ignition energy and its ability to ignite in lean mixtures, making it suitable for dual-fuel diesel engines. Ikegami et al. (2006) experimented with swirl chamber configurations and demonstrated hydrogen compression ignition without the use of spark or glow plugs. Welch and Wallace (2007) supported these findings with tests on glow plug-assisted combustion, achieving reliable ignition across varying loads.

In parallel, researchers explored Low Heat Rejection (LHR) engines, which employ ceramic coatings such as partially stabilized zirconia (PSZ) on engine components. These coatings reduce heat loss and raise in-cylinder temperatures, promoting efficient hydrogen combustion. Studies by Dogan et al. (2013) and others revealed that PSZ-coated engines operating on hydrogen showed increased brake thermal efficiency and decreased specific fuel consumption, although they exhibited a moderate rise in NOx emissions.

Overall, the literature supports the development of hydrogen-fueled engines with variable compression ratios and LHR configurations as a viable path toward cleaner and more efficient combustion. These strategies enhance performance, reduce fossil fuel dependency, and align with global efforts to mitigate climate change impacts. of hydrogen-fueled engines, particularly when combined with optimized compression ratios and ceramic coatings to enhance performance and reduce emissions.

3. Experimental Setup

3.1 Engine Description

The experimental investigation was conducted using a single-cylinder, four-stroke, water-cooled diesel engine capable of variable compression ratio adjustment. The engine was adapted to operate in dual-fuel mode by introducing hydrogen into the intake manifold, allowing it to mix with incoming air before entering the combustion chamber.

Parameter	Specification
Engine Type	Single-cylinder, 4-stroke, CI engine
Cooling System	Water-cooled
Bore	87.5 mm
Stroke	110 mm
Compression Ratios Tested	15.5, 16.5, 17.5

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Rated Power	5.2 kW at 1500 rpm
Injection Pressure	200 bar
Hydrogen Supply Pressure	10 bar
PSZ Coating Thickness	0.5 mm
Fuel Injection System	Direct injection
Fuel Types Tested	Diesel, Hydrogen-Diesel dual fuel

Hydrogen was supplied from a pressurized cylinder and regulated via a flow meter to ensure precise dosing. Compression ratios of 15.5, 16.5, and 17.5 were tested by adjusting the clearance volume using a movable cylinder head mechanism.

3.2 Low Heat Rejection (LHR)

To improve thermal efficiency, the engine was converted into a Low Heat Rejection (LHR) configuration by applying a 0.5 mm coating of partially stabilized zirconia (PSZ) on critical combustion surfaces, including the piston crown, cylinder head, and valve faces. PSZ was chosen for its excellent thermal insulation properties and high temperature resistance, which minimize heat losses and promote more stable combustion.

3.3 Instrumentation and Measurement

The test setup included an eddy current dynamometer to measure engine load and brake power, and a digital burette to accurately record fuel consumption. Emission gases such as CO, HC, NOx, and smoke opacity were analyzed using a five-gas analyzer and a smoke meter, respectively. Thermocouples and pressure transducers were installed at strategic locations to monitor combustion parameters and exhaust temperature.

3.4 Test Procedure

Tests were performed at a constant engine speed with varying loads to evaluate performance metrics like brake thermal efficiency (BTE), specific fuel consumption (SFC), and exhaust emissions. Baseline data were first collected using standard diesel fuel. Subsequent experiments used hydrogen dual-fuel operation at different compression ratios, both with and without the PSZ coating to assess the LHR effect.

4. RESULTS AND DISCUSSION

All the engine tests were carried out at the rated speed of 1500 rpm and the readings were taken only after the engine attained the stable condition. The results obtained from the rest are given below.

The comparison of brake thermal efficiency (BTE) for various hydrogen-diesel fuel blends across different compression ratios illustrates a clear trend: as the compression ratio increases, BTE improves. At maximum load, the BTE for CR 17.5 Hydrogen reaches 29.34%, closely aligning with plain diesel fuel's efficiency of

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27.84%. This increase can be attributed to better air-fuel mixing and faster evaporation, leading to more complete combustion.

Biodiesel blends, being less volatile than diesel, exhibit improved combustion characteristics at elevated temperatures, showing a greater efficiency boost at higher compression ratios. However, as biodiesel concentration increases, BTE tends to decline. Under full-load conditions, CR 17.5 Hydrogen demonstrates superior thermal efficiency compared to other mixtures due to the additional oxygen present, which enhances the combustion process.

Conversely, reducing the compression ratio results in lower BTE, primarily due to reduced compression pressure and temperature, leading to slower combustion and increased residual gas, which negatively impacts fuel efficiency. These findings suggest that higher compression ratios facilitate more effective combustion, making CR 17.5 Hydrogen a favorable option for improving engine performance without requiring major modifications.

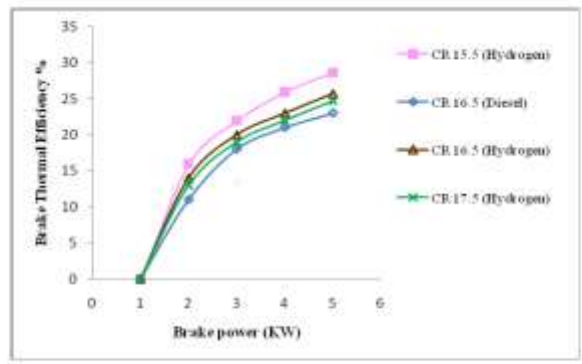

Fig 4.1 BRAKE POWER VS BRAKE THERMAL EFFICIENCY

4.1 Brake Specific Energy Consumption

The specific fuel consumption (SFC) of hydrogen-diesel blends varies with compression ratio, as illustrated in Figure 7. A higher compression ratio leads to a gradual decrease in SFC, improving fuel efficiency. At maximum load, CR 17.5 Hydrogen achieves an SFC of 15.3 MJ/kW-hr, which is 2.8% lower than diesel. This decline is attributed to better air-fuel mixing and reduced residual gas dilution, enhancing combustion efficiency.

Additionally, biodiesel's lower volatility and higher cetane number contribute to superior combustion at higher speeds, reinforcing efficiency gains. However, higher biodiesel mix percentages increase SFC due to fuel density, viscosity, and heating value variations. A lower compression ratio, on the

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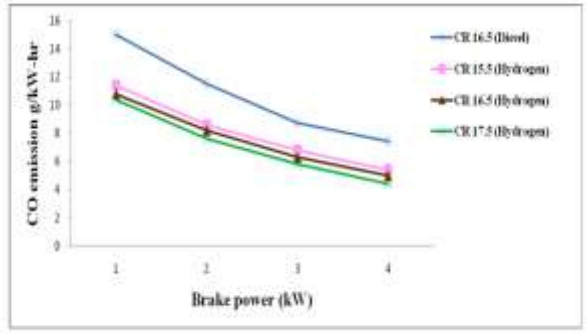
other hand, results in higher SFC due to slower combustion dynamics.

4.2Carbon Monoxide Emission

As depicted in Figure 8, CO emissions decrease with increasing compression ratio. At CR 17.5, CO emissions are 5.2 g/kW-hr, marking a 40% reduction compared to pure diesel. This decline is linked to more complete combustion, where carbon oxidation accelerates, converting more CO into CO_2.

Higher compression ratios also boost air temperature within the cylinder, further improving combustion and reducing CO emissions. However, greater biodiesel concentrations in the mix lead to higher CO emissions, regardless of the compression ratio. Under full-load conditions, CR 17.5 Hydrogen produces less CO due to its oxygen-rich composition, which supports more efficient fuel burning. Conversely, lower compression ratios increase CO emissions as residual gases dilute fresh air, reducing combustion temperature and fuel-air mixture efficiency.



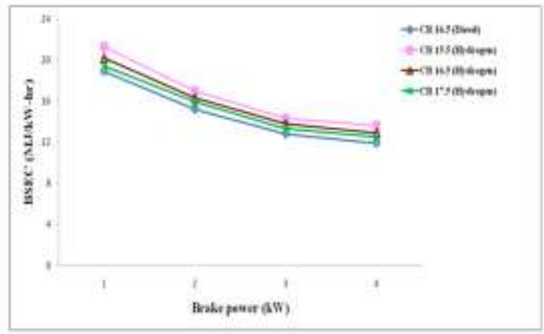


Fig 4.2 BRAKE POWER VS BRAKE SPECIFIC ENERGY CONSUMPTION and BRAKE POWER VS CARBON MONOXIDE EMISSION

4.4 Unburnt Hydrocarbon Emission

The below Figure 4.3 illustrates the variation in HC emissions across different hydrogen-diesel fuel blends with changing compression ratios. As compression ratio increases, HC emissions decrease, with CR 17.5 Hydrogen reducing HC by 14.3%. This decline is driven by higher combustion temperatures, better air-fuel mixing, and reduced charge dilution, leading to more complete combustion. Biodiesel's higher oxygen content further enhances combustion, minimizing HC emissions.

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However, higher biodiesel concentrations tend to increase HC emissions, regardless of the blend ratio. Ignition delay and fuel accumulation within the combustion chamber can also contribute to higher HC levels. A lower compression ratio leads to slower combustion, causing HC emissions to rise due to incomplete fuel oxidation.

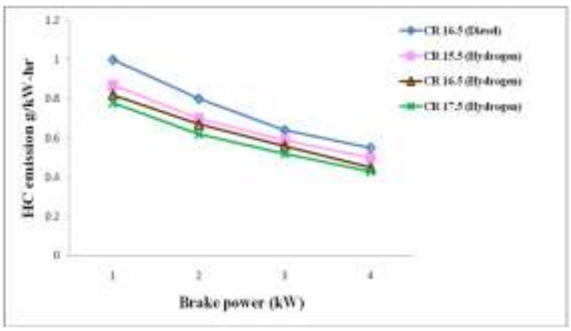

Fig 4.3 BRAKE POWER VS UNBURNT HYDROCARBON EMISSION

4.5 Oxides of Nitrogen (NOx) Emission

NOx formation is highly influenced by temperature, compression ratio, and fuel injection techniques. Figure 9 demonstrates NOx variation across different hydrogen-diesel blends, revealing a steady increase in NOx emissions with higher compression ratios. At CR 17.5, NOx levels reach 740 ppm, comparable to diesel's 734 ppm.

The rise in NOx emissions is attributed to higher combustion temperatures, increased pressure, and reduced ignition delay, all of which accelerate NOx formation. As biodiesel concentration increases, NOx emissions also rise due to higher oxygen content and greater adiabatic flame temperatures. Furthermore, the presence of double-bonded molecules in biodiesel increases flame temperatures, further contributing to NOx emissions.

Conversely, lower compression ratios result in reduced combustion temperatures and pressures, leading to lower NOx emissions. Premixed burning tends to be higher at lower compression ratios due to longer ignition delays, contributing to the reduction of NOx formation.

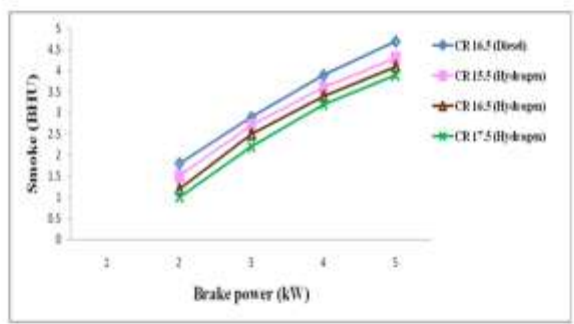

Fig 4.4 BRAKE POWER VS SMOKE OPACITY

4.4 Smoke Opacity

The smoke emissions for different hydrogen-diesel blends across varying compression ratios. As compression ratio increases, smoke production steadily declines, with CR 17.5

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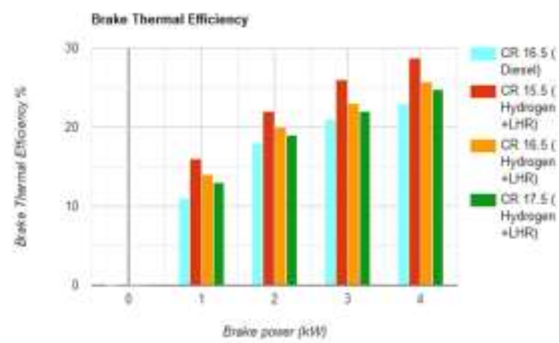
Hydrogen emitting 3.7 BSU at maximum load, marking a 12.5% reduction compared to diesel. This decrease is largely due to biodiesel's oxygen-rich composition, which enhances soot oxidation, limiting particulate emissions. Additionally, higher temperatures and pressures at greater compression ratios improve combustion, further reducing smoke. The trends align with **HC and CO emission reductions**, confirming the effectiveness of hydrogen blends in minimizing pollutants.

5 Compression ignition of Hydrogen (H2) in a direct injection diesel engine modified to operate as a Low Heat Rejection

The feasibility of using hydrogen as a primary fuel in a low-heat rejection (LHR) diesel engine has been examined. A single-cylinder air-cooled diesel engine was modified with partially stabilized zirconia ceramic components to withstand higher compression temperatures. Operating at a compression ratio of 17.5 and 1500 rpm, combustion proceeded effectively, with all tested lubricants igniting properly.

When the speed was lowered to 1450 rpm, hotspots and lubricant combustion were successfully mitigated. During hydrogen compression ignition trials, maximum compression temperatures reached around 800 K, while ceramic surfaces maintained 600–700 K. However, only intermittent hydrogen compression ignition was achieved, indicating the need for further optimization in fuel delivery and ignition stability.



Graph .5.1 BRAKE POWER VS BRAKE THERMAL EFFICIENCY

5.1 Brake Thermal Efficiency

Fig. 5.1 illustrates variations in brake thermal efficiency across different CR with LHR engines. CR hydrogen + LHR engines with ceramic coatings exhibit efficiency percentages of 29, 20, 26, 52, and 25, respectively. Zirconia brakes, due to their partial stability, enhance thermal efficiency by limiting heat transfer to the surroundings. Reduced heat loss improves engine power and efficiency.

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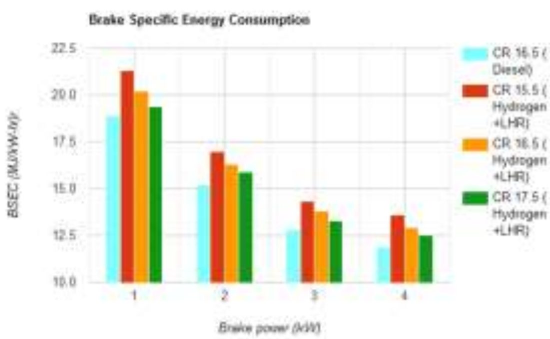
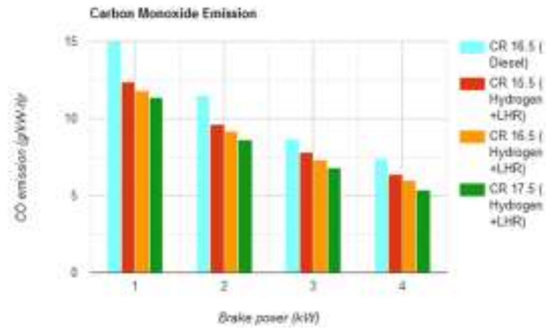
5.2 Brake Specific Energy Consumption

Internal combustion engines dissipate substantial energy through cooling and exhaust. Fig. 14 highlights differences in specific fuel energy use for standard and CR Hydrogen LHR engines. In CR 17.5 Hydrogen + LHR, consumption was 5.63% and 3.21% lower than conventional diesel. Higher biodiesel blend ratios increase SFC due to density, viscosity, and thermal properties. Lower compression ratios further elevate SFC due to slower combustion.



Graph 5.2 BRAKE SPECIFIC ENERGY CONSUMPTION



GRAPH 5.3 CARBON MONOXIDE EMISSION

5.2.3 Carbon Monoxide Emission

Fig. 5.3 compares CO emissions for CR diesel and CR hydrogen + LHR engines. Relative to CR diesel, CR hydrogen + LHR reduces CO emissions by 15.3% and 10.2%, respectively. Hydrogen injection accelerates fuel vaporization, contributing to emission reductions.

5..4 Unburnt Hydrocarbon Emission

Fig. 5.4 illustrates UBHC emissions for CR diesel and CR hydrogen + LHR engines. LHR engines emit fewer hydrocarbons than conventional engines, with reductions of 8.74% for CR diesel and CR hydrogen + LHR, and 5.32% for uncoated standard engines. Coated engines exhibit lower HC emissions due to elevated post-combustion temperatures and minimized cooling losses, enabling more complete UBHC combustion.

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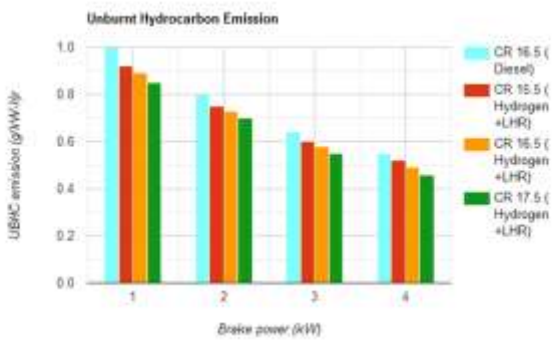
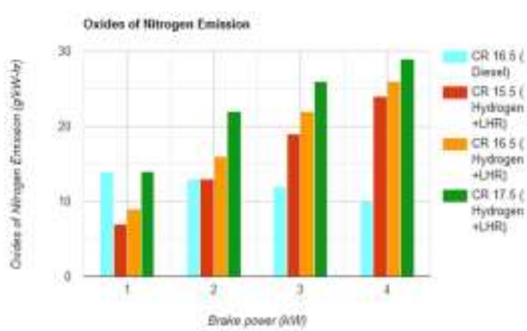


GRAPH 5.4 UNBURNT HYDROCARBON EMISSION



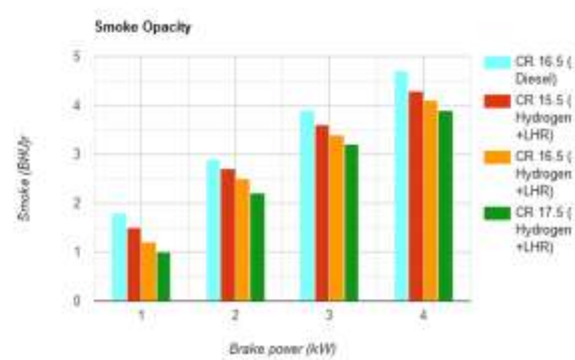
GRAPH 5.5 OXIDES OF NITROGEN EMISSION

5.5 Oxides of Nitrogen Emission

Fig. 5.5 illustrates NOx emission variations for CR diesel and CR hydrogen + LHR engines under load conditions. CR 17.5 Hydrogen + LHR exhibited a 12.34% reduction, while CR hydrogen + LHR showed a 17.53% increase compared to diesel. Higher NOx emissions in coated engines result from elevated zirconia surface temperatures post-combustion.

5.6 Smoke Opacity

Fig. 5.6 presents smoke emission differences for CR diesel and CR hydrogen + LHR engines. Under load, CR 17.5 Hydrogen + LHR reduced emissions by 5.65% and 15.28% compared to standard CR hydrogen + LHR. Increasd temperatures from sectional thermal barriers and residual carbon particles contribute to variations. Smoke emissions result from incomplete carbon combustion, while combustion chamber coatings enhance burning efficiency by increasing chamber temperatures



GRAPH 5.6 SMOKE OPACITY

5.7 Cylinder Pressure

Figure 5.7 shows the CR diesel and CR hydrogen + LHR cylindrical pressure engine

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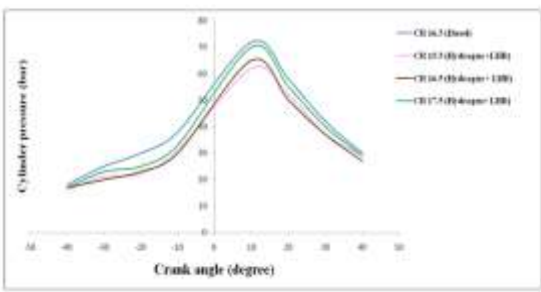
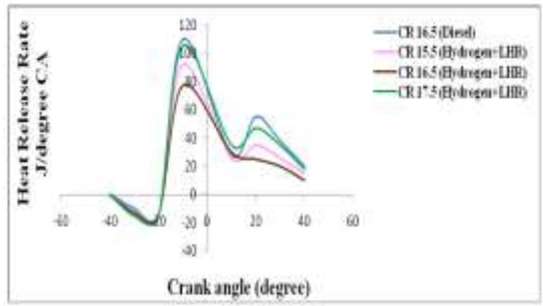
with regard to the crank angle. The total pressure rises with increased engine load. The increased CR hydrogen + LHR 17.5bar engine temperature induces a maximum stress of 73.4 bar in a conventional CI engine after TDC (71.5 bar), which is similar to diesel (13°CA). After zirconia has been coated with hydrogen, the maximum pressure increased dramatically due to the increased temperature, accelerating the in-cylinder burning process. The cylinder's high pressure gives better burning and heat release.



GRAPH 5.7 CYLINDER PRESSURE

5.8 Heat Release

Illustration 5.8 shows the CR diesel and CR hydrogen + LHR cylinder pressure test results as far as the crank angle is concerned. The Hydrogen was obvious heat release rate was lower than that of clean diesel fuel, considering the fact that CR hydrogen with LHR atomized and vaporized less than fuel combustion. The CR hydrogen heat release rate, a 12.35retard and 17.17 percent lower than the regular non-coated engine with CR hydrogen with LHR , was fuelled in ideal loading conditions.



GRAPH 5.8 HEAT RELEASE RATE

6. CONCLUSION

Hydrogen, particularly at a compression ratio of 17.5, stands out as a promising alternative fuel for CI engines, delivering higher efficiency and lower emissions without the need for modifications. The study demonstrates its capability to reduce specific fuel consumption (SFC) by 2.8%, while achieving a brake thermal efficiency (BTE) of 29.34%, making it comparable to diesel in terms of performance and fuel economy.

A key advantage of hydrogen combustion is the notable decrease in CO, HC, and smoke emissions, leading to a cleaner exhaust and a reduced environmental footprint. However, the study highlights a minor increase in NOx emissions, necessitating further refinement of emission control technologies. When coupled

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with low heat rejection (LHR) technology, hydrogen combustion achieves better thermal efficiency and optimized fuel utilization, strengthening its case as a sustainable fuel.

Unlike conventional diesel, hydrogen delivers enhanced efficiency without requiring significant modifications, positioning it as a practical and scalable solution for transitioning toward eco-friendly fuel alternatives. With its ability to cut carbon emissions while sustaining engine performance, hydrogen presents itself as a strong contender in transportation and power generation applications. As industries move toward low-emission energy solutions, hydrogen offers a pathway for cleaner and more efficient combustion technology.

Through its higher efficiency, lower emissions, and improved thermal characteristics, hydrogen at CR 17.5 emerges as a key contributor to the advancement of sustainable engine technology. Future research aimed at minimizing NOx emissions and refining fuel optimization strategies will further strengthen its feasibility for mainstream adoption, solidifying its role in next-generation energy solutions for cleaner mobility and power systems.

7. SCOPE OF FUTURE WORK

Future scope of this research should focus on optimizing biogas and LPG combustion, considering varying CO2 and butane ratios to enhance performance and emissions control. Additionally, alternative fuels like BTL, CTL, and natural gas warrant investigation.

Post-treatment systems such as HC-SCR and DOC can help reduce HC and CO emissions, while improving thermal efficiency and fuel utilization. A deeper understanding of HC variations between biogas and propane could further refine emission control strategies.

Integrating hydrogen-enriched gaseous fuel into dual-fuel combustion has shown promise for enhancing engine efficiency and reducing pollutants. Real-world testing on on-board fuel reformation will be valuable in assessing practical applications.

Engine hardware modifications, including fuel injection timing, multiple injections, EGR, and turbocharger enhancements, can be explored to optimize combustion dynamics and emissions performance in dual-fuel engine modes. These advancements can contribute to greater fuel efficiency and environmental sustainability.

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