



Performance and Emission Analysis of CI Engines Fueled by Hydrogen-Biogas Blends

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ABSTRACT

This study explores the potential of hydrogen-enriched biogas as a sustainable fuel for compression ignition (CI) engines, aiming to enhance performance and reduce emissions. Experiments were conducted using biogas blended with 10%, 20%, and 30% hydrogen, evaluating engine performance across 0%, 50%, and 100% loads, and utilizing 3, 4, and 5-hole injector nozzles. Results indicate that a 30% hydrogen blend significantly improved engine performance at full load, increasing thermal efficiency and reducing hydrocarbon (HC), carbon monoxide (CO), and smoke opacity emissions, while noting an increase in nitrogen oxide (NOx). The enhanced combustion characteristics of hydrogen, including higher flame speed and calorific value, facilitated more complete combustion. Injector nozzle optimization, particularly with a 5-hole configuration, improved fuel atomization and mixing, resulting in lower brake specific fuel consumption (BSFC). This research demonstrates the viability of hydrogen-enriched biogas as a promising alternative fuel, emphasizing the need for optimized operating parameters to balance performance and emissions in CI engines.

1. Introduction

The global energy crisis and environmental concerns have led to increased interest in alternative fuels for internal combustion engines. As fossil fuel reserves continue to deplete and greenhouse gas emissions increase, researchers and policymakers are actively seeking sustainable energy solutions to mitigate these challenges. Biogas, a renewable energy source produced through the anaerobic digestion of organic matter, has gained significant attention as a potential substitute for conventional fossil fuels [1]. Biogas, primarily composed of methane and carbon dioxide, offers several advantages, including its renewable nature, potential for waste management, and reduced carbon footprint compared to fossil fuels. However, the direct application of biogas in compression ignition (CI) engines poses several challenges. The lower energy density and slower flame propagation of biogas compared to traditional fuels can result in reduced engine performance and efficiency [2]. These limitations have prompted researchers to explore various strategies for enhancing the combustion characteristics of biogas in CI engines, with hydrogen enrichment being a promising technique. Hydrogen enrichment has garnered considerable interest in the field of alternative fuels owing to its potential to improve engine performance and reduce emissions. The addition of hydrogen to biogas can potentially enhance its combustion characteristics owing to its unique properties, including its high energy content, low ignition energy,



and wide flammability limits [3]. These attributes make hydrogen an attractive additive to improve the overall combustion process and address some of the inherent limitations of biogas as fuel. The concept of hydrogen enrichment aligns with the growing interest in hydrogen as a clean energy carrier and its potential role in decarbonizing the transportation sector [4]. As the world transitions towards a low-carbon future, hydrogen is increasingly recognized as a versatile energy vector that can complement other renewable energy sources and contribute to reducing greenhouse gas emissions across various sectors. Previous studies have investigated the effects of hydrogen addition on various engine parameters, providing valuable insights into the potential benefits of this approach.[5]. reported improved thermal efficiency and reduced CO emissions in a dual-fuel engine operating on natural gas with hydrogen enrichment. Their findings demonstrated the positive impact of hydrogen addition on combustion efficiency and pollutant formation [6]. These studies highlight the potential of hydrogen enrichment to address the key challenges associated with alternative fuels in internal combustion engines. Despite the promising results obtained in previous studies, the specific effects of hydrogen enrichment in biogas on CI engine performance and emissions remain unexplored. This research gap necessitates a comprehensive investigation to understand the potential benefits and challenges associated with this fuel combination in CI engines. The complex interactions between hydrogen, biogas, and CI engine combustion warrant a detailed analysis to optimize the fuel composition and engine operating parameters. The present study aimed to bridge this knowledge gap by evaluating the effects of hydrogen enrichment in biogas on the emission characteristics and performance parameters of CI engines. By systematically varying the hydrogen content in biogas and analyzing key engine metrics, this study aims to provide insights into the optimal hydrogen-biogas blend ratios for improving engine performance and reducing emissions. This study explored a range of hydrogen concentrations to determine the threshold at which significant improvements in engine characteristics can be achieved without compromising the safety or durability of the engine. Furthermore, this study assessed the impact of hydrogen enrichment on various emission components, including carbon monoxide (CO), carbon dioxide (CO₂), unburned hydrocarbons (HC), and nitrogen oxides (NO_x). Understanding the trade-offs between different pollutant species is crucial for developing strategies to meet increasingly stringent emission regulations while maintaining or improving engine efficiency. The results of this study are expected to provide valuable insights into alternative fuels and engine technology. By elucidating the relationships among hydrogen enrichment, biogas composition, and CI engine performance, this study aims to provide a foundation for future developments of sustainable transportation solutions. The findings may have implications for the design of more efficient and cleaner CI engines and inform policy decisions regarding the promotion of hydrogen and biogas as alternative fuels. In conclusion, this study explored the potential of hydrogen enrichment in biogas as a means of enhancing the performance and reducing the emissions of CI engines. Through a comprehensive analysis of engine parameters and emission characteristics, this study contributes to ongoing efforts to develop sustainable and efficient transportation technologies in the face of global energy and environmental challenges.

2. Materials and Methodology

2.1 Experimental setup

The experimental setup is shown in Figure 1. Experiments were conducted in a single-cylinder, 4-stroke engine. The engine specifications are listed in Table 1. It has a maximum power rating of 3.5 kW, a 17.5 compression

ratio, and a 1500 rpm maximum speed. An eddy-current dynamometer was used for loading. A valve controls fuel delivery. Thermocouples and sensors were attached to detect temperatures, loads, and speeds, including exhaust temperatures at outlets and hot water out. To assess each testing fuel, the engine incorporated a data acquisition (DAQ) system. Table 2 shows the measuring range and uncertainty of parameters and fig 2 shows the construction of gas analyser.

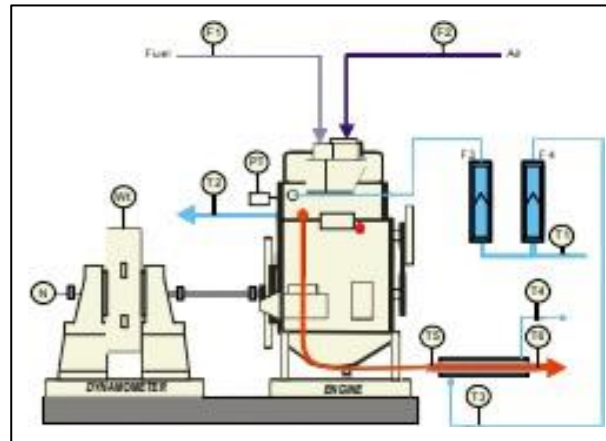


Figure 1 Experimental setup

Table 1 Engine Specifications

Product Code	234
Rated Power	3.5 kW
Number of cylinders	Single cylinder
Number of Stroke	4 Stroke,
Dynamometer	Eddy current, water cooled, with loading unit
Calorimeter	Pipe in pipe
ECU	Open ECU



Figure 2 Gas Analyser

Table 2 specifications of gas analyser

Parameters	Measuring Range	Resolution
CO	0 to 10% Volume	0 .01%
CO2	0 to 20% Volume	0 .1%
HC	0 to 15000 PPM Vol	0 .01%
O2	0 to 25% Volume	0 .01%
NOx	0 to 5000PPM	1 PPM

3. Result and Discussion

3.1 CO Emission

Fig 3,4,5 shows the variation of CO emission. Hydrogen is a carbon-free fuel that does not contribute to the formation of carbon monoxide (CO). Increasing the hydrogen blend enhances combustion efficiency, resulting in more complete oxidation of carbon in the biogas, which consequently reduces CO emissions. At higher loads, the elevated combustion temperatures facilitate improved oxidation of CO. Conversely, at lower loads, incomplete combustion occurs due to lower temperatures, resulting in higher CO emissions. An increased number of injector holes ensures superior fuel atomization and air-fuel mixing, thereby promoting more efficient combustion. This leads to reduced CO formation as more carbon is fully oxidized CO [7]. A 5-hole nozzle, 30% hydrogen fuel, and 100% load operation result in the lowest CO emissions.

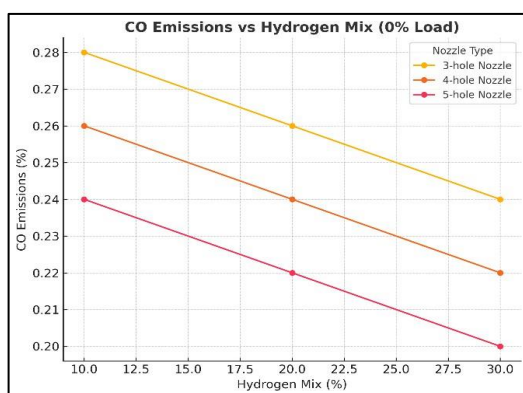


Figure 3 Variation in CO Emission at 0% load

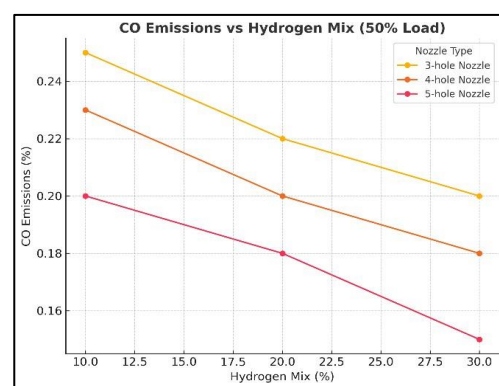


Figure 4 Variation in CO Emission at 5% load

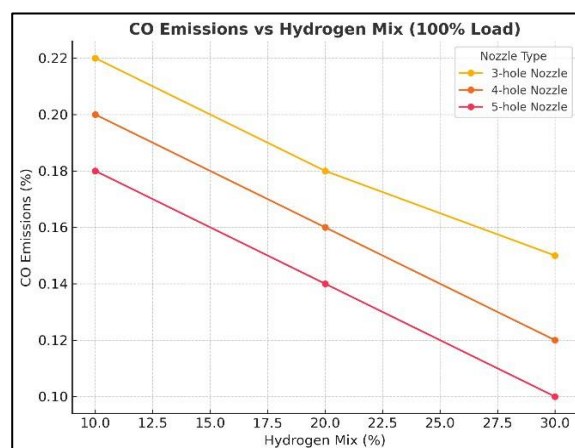


Figure 5 Variation in CO Emission at 100% load

3.2 HC Emission

Fig 6,7,8 shows the variation of HC emission. Hydrogen exhibits a higher flame speed and diffusivity, thereby facilitating more rapid and complete combustion. As the proportion of hydrogen increases, the quantity of unburned fuel in the exhaust diminishes, resulting in a reduction of hydrocarbon (HC) emissions.

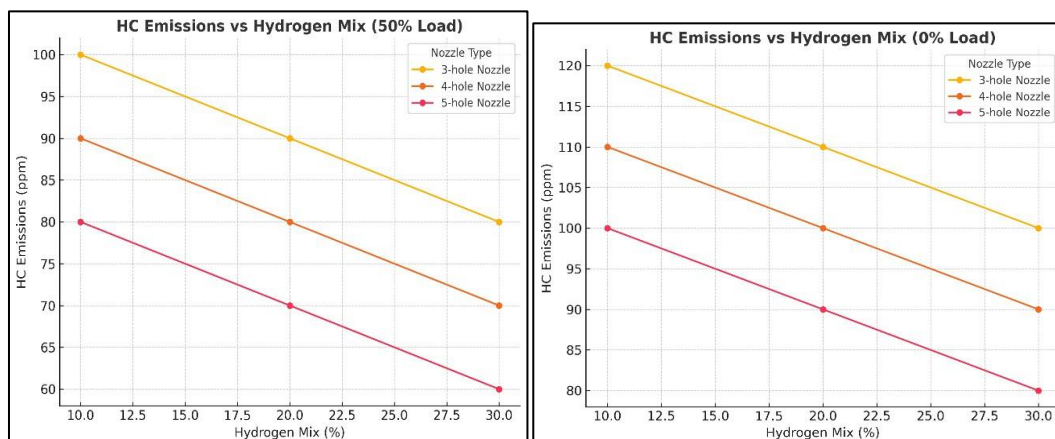


Figure 6 Variation in HC Emission at 0% load Figure 7 Variation in HC Emission at 50% load

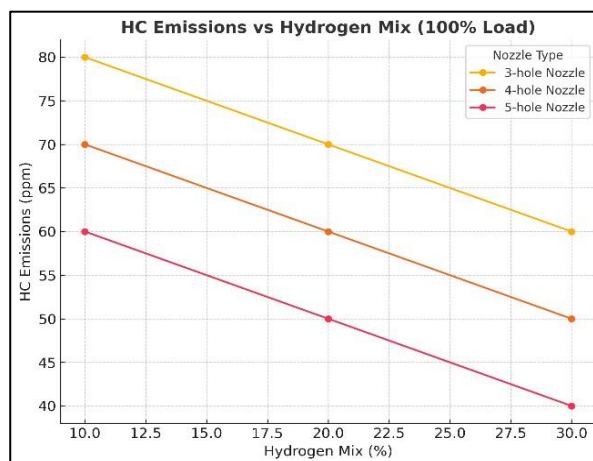


Figure 8 Variation in HC Emission at 100% load

At elevated engine loads, the combustion temperature increases, which enhances fuel oxidation and reduces the presence of unburned hydrocarbons. Conversely, lower loads may result in incomplete combustion and increased HC emissions. A greater number of injector holes contributes to improved fuel atomization and air-fuel mixing, thus ensuring more efficient and complete combustion of the fuel. This process consequently reduces the formation of unburned hydrocarbons in the exhaust gas [8]. A 5-hole nozzle, 30% hydrogen fuel, and 100% load operation result in the lowest HC emissions.

3.3 NO_x Emission

Fig 9,10,11 shows the variation of NO_x emission. Hydrogen exhibits a higher flame speed and combustion temperature compared to biogas. The addition of hydrogen results in an increase in peak in-cylinder temperature, consequently leading to enhanced thermal NO_x formation due to the Zeldovich mechanism (temperature-dependent NO_x production). Elevated engine loads result in higher combustion temperatures and pressures, thereby promoting NO_x formation. At high loads, increased fuel combustion further raises the flame temperature and oxygen availability, accelerating NO_x production.

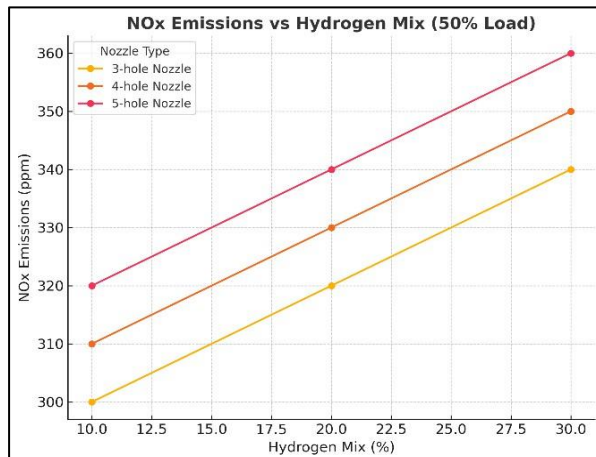


Figure 9 Variation in NOx Emission at 0% load

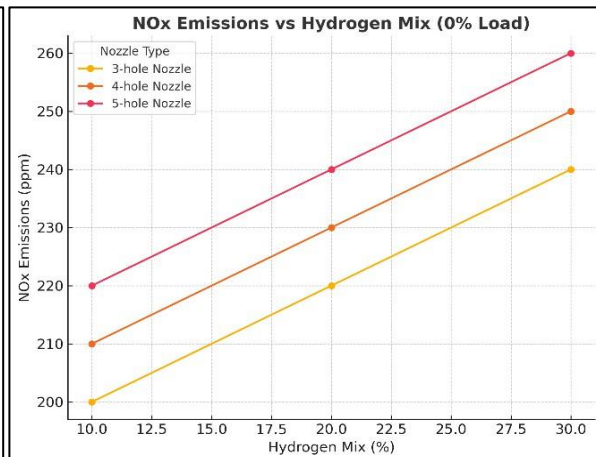


Figure 10 Variation in NOx Emission at 50% load

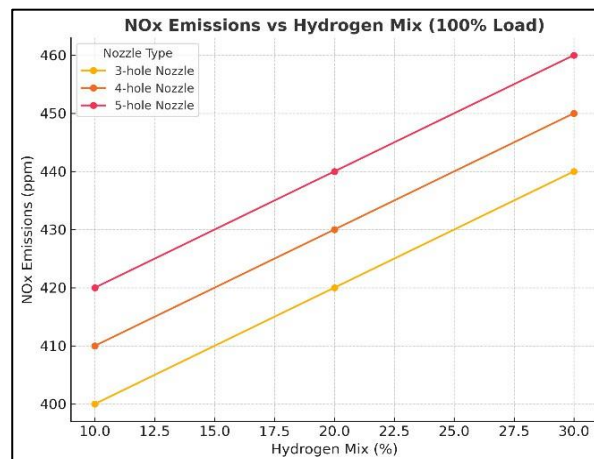


Figure 11 Variation in NOx Emission at 100% load

A greater number of injector holes facilitates improved fuel atomization and mixing, thus ensuring more efficient combustion. While this enhances fuel efficiency and reduces unburned emissions, it also elevates peak temperatures, contributing to increased NOx formation [9]. A 3-hole nozzle, 10% hydrogen fuel, and 0% load operation result in the lowest NOx emissions.

3.4 Smoke Opacity

Fig 12,13,14 shows the variation of Smoke Opacity. Hydrogen is a carbon-free fuel, which precludes its contribution to soot formation. An increase in the hydrogen blend resulted in more complete combustion, thereby reducing the quantity of unburned carbon and decreasing smoke emissions. At higher loads, a greater volume of fuel was injected, and the air-fuel ratio decreased. This phenomenon leads to incomplete combustion and elevated particulate matter (PM) formation, consequently increasing smoke opacity.

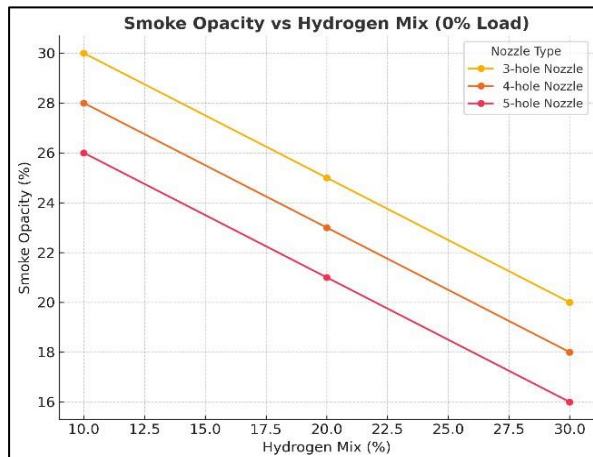


Figure 12 Variation in Smoke Opacity at 0% load

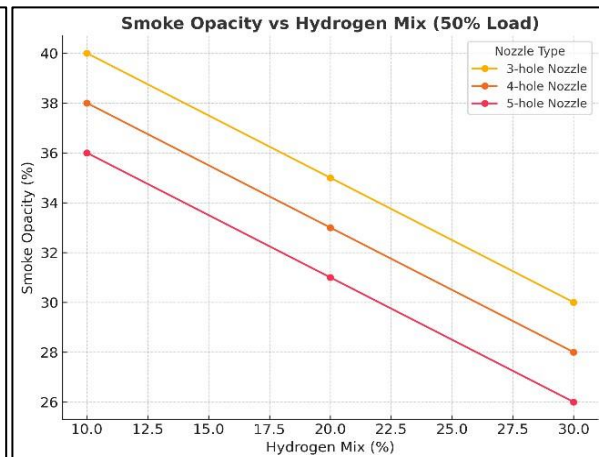


Figure 13 Variation in Smoke Opacity at 50% load

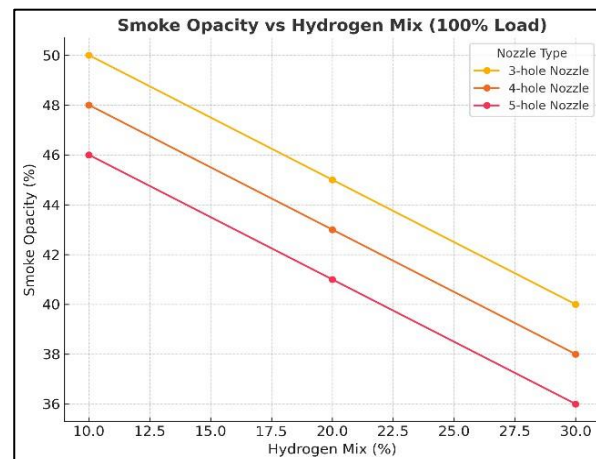


Figure 14 Variation in Smoke Opacity at 100% load

A higher number of nozzle holes enhanced fuel atomization and mixing, resulting in improved combustion efficiency. This enhancement reduced the formation of soot and unburned hydrocarbons, thus leading to lower smoke opacity [10]. A 5-hole nozzle, 30% hydrogen fuel, and 0% load operation result in the lowest smoke opacity.

3.5 Brake Thermal Efficiency (BTE)

Fig 15,16,17 shows the variation of BTE. Hydrogen exhibits a higher flame speed and calorific value compared to biogas, resulting in enhanced combustion efficiency and reduced combustion delay. This phenomenon leads to an improved Brake Thermal Efficiency (BTE). At elevated engine loads, the fuel-air mixture undergoes more complete combustion due to the higher in-cylinder temperatures and pressures, consequently improving energy conversion efficiency and minimizing unburned fuel losses.

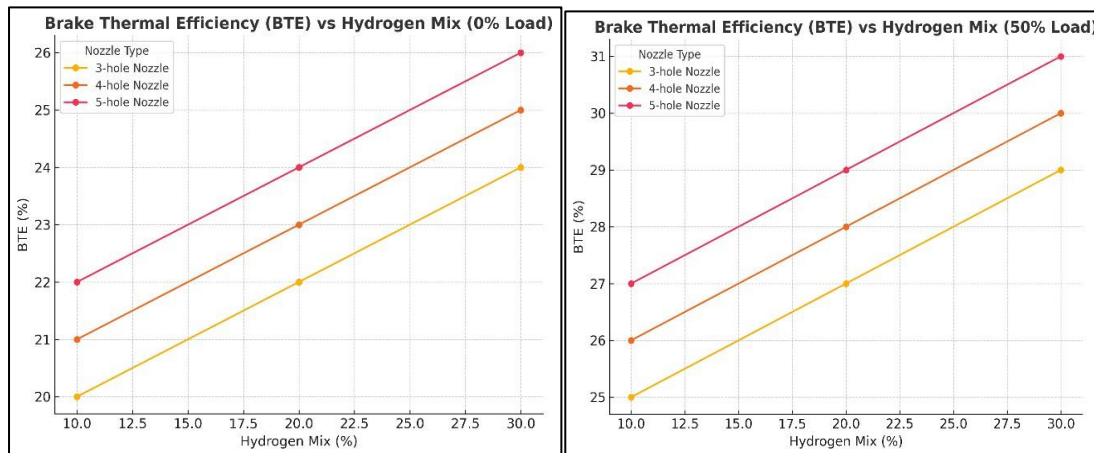


Figure 15 Variation in BTE at 0% load

Figure 16 Variation in BTE at 50% load

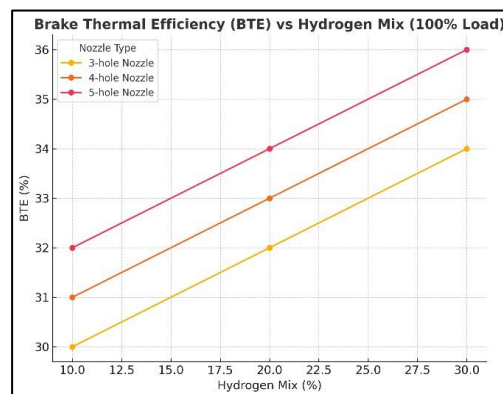


Figure 17 Variation in BTE at 100% load

An increased number of nozzle holes facilitates superior fuel atomization, thereby enhancing the fuel-air mixing process. This enhancement promotes more uniform combustion and increased efficiencies [11]. A 5-hole nozzle, 30% hydrogen fuel, and 100% load operation provide the best conditions for Brake Thermal Efficiency (BTE).

3.6 Brake Specific Fuel Consumption (BSFC)

Fig 18,19,20 shows the variation of BSFC

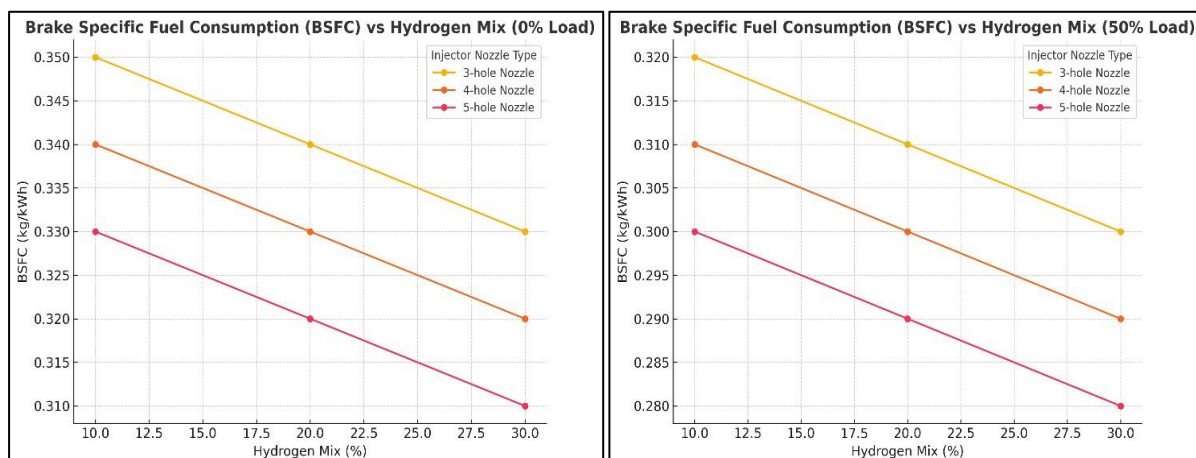


Figure 18 Variation in BSFC at 0% load

Figure 19 Variation in BSFC at 50% load

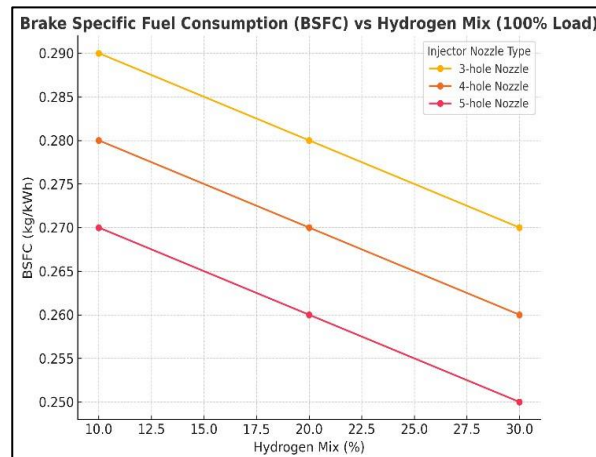


Figure 20 Variation in BSFC at 100% load

The graph illustrates the relationship between Brake Specific Fuel Consumption (BSFC) and Hydrogen Mix (%) at 100% engine load. Three distinct injector nozzle configurations (3-hole, 4-hole, and 5-hole) were evaluated. The BSFC demonstrated a decreasing trend for all nozzle types as the hydrogen blend increased. This phenomenon can be attributed to the higher calorific value of hydrogen compared to biogas, resulting in enhanced combustion efficiency and reduced fuel consumption per unit of power output. The 5-hole nozzle configuration exhibited the lowest BSFC values across all hydrogen mix levels. An increased number of holes in the injector facilitates improved atomization and air-fuel mixing, thereby enhancing combustion efficiency. At full engine load, the engine operates at a higher thermal efficiency, resulting in a lower BSFC compared to lower load conditions. This is due to the more efficient fuel combustion under high-load conditions, which reduces the required amount of fuel per unit of power. The enhanced mixing leads to more complete combustion and decreased fuel consumption. The addition of hydrogen promotes accelerated flame propagation and improved fuel-air mixing, facilitating leaner combustion. Leaner combustion contributes to a reduction in unburned hydrocarbons and incomplete combustion, thereby directly decreasing the BSFC [12]. The reduction in BSFC was more pronounced for the 5-hole nozzles due to their superior fuel distribution characteristics.

Conclusion:

This study investigated the impact of hydrogen enrichment in biogas on the performance and emission characteristics of a compression ignition (CI) engine. The results demonstrated that increasing the hydrogen blend up to 30% led to significant improvements in engine performance and emission reduction. Specifically, at full load, a 30% hydrogen mix resulted in an increased thermal efficiency, a reduction in HC, CO, and smoke opacity, albeit with a corresponding increase in NO_x emissions. The enhanced combustion characteristics of hydrogen, including its higher flame speed and calorific value, contributed to improved fuel oxidation and reduced unburned hydrocarbons. The study also highlighted the importance of injector nozzle design, with a 5-hole nozzle configuration demonstrating superior fuel atomization and air-fuel mixing, resulting in lower BSFC and improved combustion efficiency. While hydrogen enrichment offers a promising pathway for enhancing biogas utilization in CI engines, careful optimization of operating parameters, including hydrogen percentage, engine load, and nozzle design, is crucial to balance performance gains with emission control, particularly



regarding NO_x formation. Future research should focus on exploring advanced combustion strategies and emission control technologies to further optimize the performance and sustainability of hydrogen-enriched biogas in CI engines.

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