

The analysis of hydrogen gas addition in biodiesel dual-fuel system of the efficiency and operational characteristics of pro quip u.s.a qdx-400 diesel engine

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Abstract

The increasing demand for energy and the need for more efficient fuel utilization have encouraged the development of technologies aimed at improving diesel engine performance. One promising approach is the utilization of hydrogen gas produced through water electrolysis as a supplementary fuel in a biodiesel–hydrogen dual-fuel system. This study aimed to analyze the effect of hydrogen gas addition on the performance of a Pro Quip U.S.A QDX 400E diesel engine fueled with biodiesel under a dual-fuel operating system. The research was conducted experimentally by varying the Pulse Width Modulation (PWM) voltage from 6.0 to 6.4 V to regulate hydrogen production. The parameters evaluated included fuel consumption, engine speed (RPM), vibration, noise level, and hydrogen concentration (PPMv). The results showed that the addition of hydrogen improved the combustion process, resulting in reduced fuel consumption and increased engine speed. The optimum operating condition was achieved at a PWM voltage of 6.3 V, which produced the lowest fuel consumption of 15.5 mL/min, an RPM increase of 2.44%, and the highest efficiency improvement of 14.84% compared to the baseline condition. However, at a voltage of 6.4 V, indications of hydrogen over-supply were observed, leading to increased engine vibration and noise levels. Based on the scoring method, the best operating condition was obtained at a hydrogen concentration of approximately 12,450 PPMv.

Keywords: biodiesel; hydrogen; dual fuel; electrolysis; fuel efficiency; diesel engine

INTRODUCTION

The increasing global demand for energy and the depletion of fossil fuel reserves have encouraged the development of alternative and renewable energy sources. Diesel engines remain one of the most widely used power generation systems in transportation, marine, industrial, and military applications due to their high thermal efficiency, reliability, and durability. However, their dependence on petroleum-based fuels presents significant economic and environmental challenges. Rising fuel consumption and greenhouse gas emissions have intensified the need for cleaner and more efficient energy technologies.

In Indonesia, biodiesel has been promoted as a strategic renewable fuel to reduce dependence on imported fossil fuels and enhance national energy security. Biodiesel possesses several advantages, including biodegradability, lower sulfur content, and reduced emissions of carbon monoxide and particulate matter. Nevertheless, biodiesel generally exhibits a lower heating value than conventional diesel fuel, resulting in increased fuel consumption and reduced engine performance under certain operating conditions. Hydrogen has emerged as a promising supplementary fuel because of its high lower heating value, wide flammability range, low ignition energy, and high flame propagation speed. The addition of hydrogen to diesel engines through a dual-fuel system has attracted considerable attention due to its potential to improve combustion quality, enhance thermal efficiency, and reduce fuel consumption. When introduced into the intake manifold, hydrogen can promote more complete combustion by accelerating flame propagation and improving air-fuel mixture homogeneity.

Several studies have demonstrated the benefits of hydrogen supplementation in diesel engines. Tosun and Özcanlı (2021) reported that hydrogen enrichment improved engine performance and reduced carbon monoxide emissions in soybean biodiesel-fueled diesel engines. Scignoli et al. (2024) showed that moderate hydrogen substitution increased brake thermal efficiency in diesel-hydrogen dual-fuel combustion systems. Felayati et al. (2025) also observed improvements in torque, power output, and fuel economy through the application of hydrogen-oxygen gas generated by water electrolysis. Despite these advances, most previous studies have primarily focused on engine performance and exhaust emissions.

Limited research has been conducted on the influence of hydrogen concentration on operational characteristics such as engine speed (RPM), vibration, noise level, and overall fuel efficiency, particularly for small stationary diesel engines. Furthermore, information regarding the optimum hydrogen concentration that maximizes efficiency while maintaining stable engine operation remains scarce. Therefore, this study investigates the effect of hydrogen gas generated through water electrolysis on the performance and operational characteristics of a Pro Quip U.S.A QDX-400E diesel engine operating on a biodiesel-hydrogen dual-fuel system. The study evaluates fuel consumption, engine speed, vibration, noise level, and efficiency under various hydrogen concentrations. In addition, a scoring method is employed to determine the optimum operating condition that provides the best balance between performance improvement and operational stability. The novelty of this research lies in the

comprehensive evaluation of hydrogen concentration effects on multiple operational parameters simultaneously, including fuel consumption, RPM, vibration, noise, and efficiency, thereby providing practical recommendations for implementing biodiesel-hydrogen dual-fuel technology in stationary diesel engines.

Theoretical Background

Hydrogen has attracted significant attention as a supplementary fuel for diesel engines due to its superior combustion characteristics compared to conventional hydrocarbon fuels. Hydrogen possesses a high lower heating value (approximately 120 MJ/kg), a wide flammability range, low ignition energy, and a high flame propagation speed, which collectively contribute to faster and more complete combustion. In biodiesel–hydrogen dual-fuel systems, biodiesel serves as the pilot fuel that initiates combustion through compression ignition, while hydrogen is introduced through the intake manifold to enhance the combustion process. The addition of hydrogen improves air–fuel mixture homogeneity, accelerates flame propagation, and increases the rate of heat release inside the combustion chamber, resulting in improved thermal efficiency and reduced fuel consumption.

Furthermore, the absence of carbon atoms in hydrogen contributes to cleaner combustion and lower carbon-related emissions. However, excessive hydrogen concentration may lead to abnormal combustion phenomena such as knocking, increased cylinder pressure, higher vibration levels, and elevated engine noise. Therefore, the performance of a dual-fuel biodiesel–hydrogen engine is strongly influenced by the hydrogen concentration supplied to the combustion system. Understanding the relationships among hydrogen combustion characteristics, lower heating value, flame speed, auto-ignition behavior, and engine operational parameters is essential for determining the optimum operating condition that maximizes efficiency while maintaining stable engine performance.

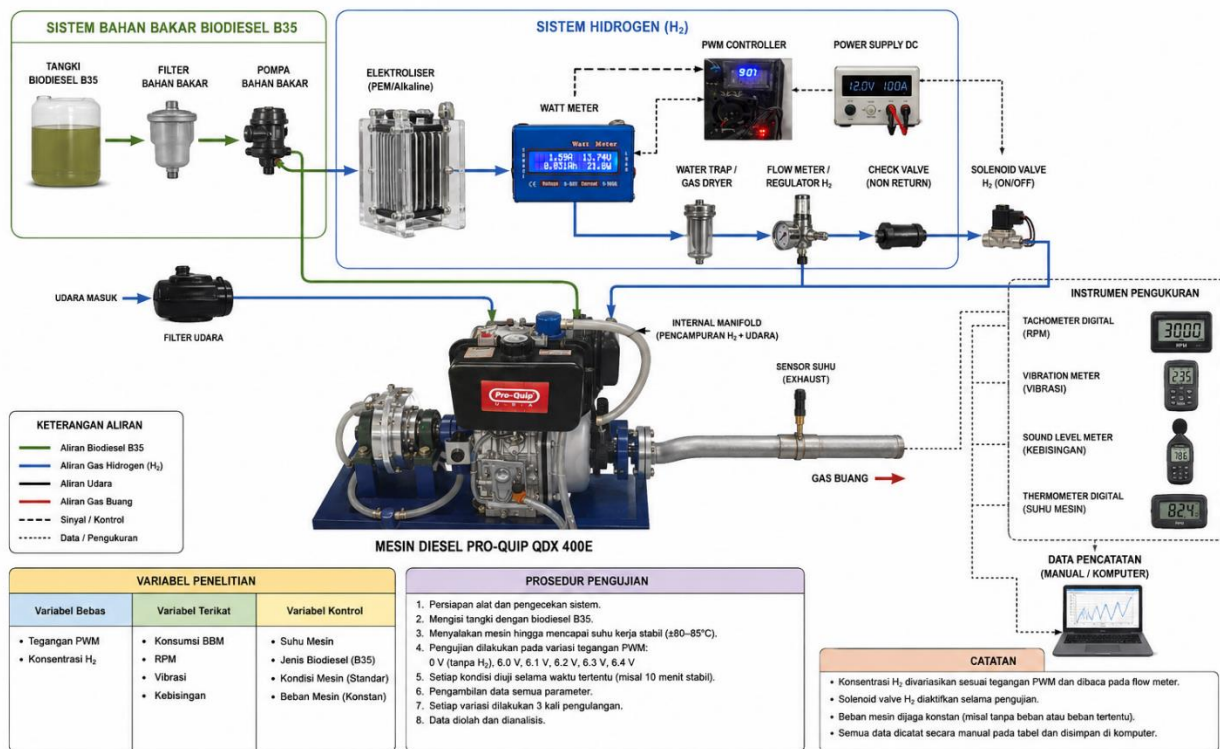


Figure 1. Schematic of hydrogen gas addition

MATERIALS AND METHODS

Simulation Methods, Conditions and Parameters The experimental study was conducted using a Pro Quip U.S.A QDX-400E stationary diesel engine fueled with B35 biodiesel. Hydrogen gas was produced through water electrolysis using a hydrogen generator supplied by a DC power source and controlled by a Pulse Width Modulation (PWM) controller. The generated hydrogen was introduced into the engine intake manifold to form a biodiesel–hydrogen dual-fuel system. The equipment used in this study included a digital tachometer (Ono Sokki) for engine speed measurement, a VibXpert II vibration

analyzer for vibration monitoring, a Sound Level Meter Type 2250 for noise measurement, a gas analyzer for determining hydrogen concentration, and volumetric measuring equipment for fuel consumption analysis.

The experimental setup consisted of a hydrogen production system, a hydrogen delivery system, and a diesel engine test rig. Water electrolysis was employed to generate hydrogen gas, which was then passed through a flowmeter before entering the intake manifold. Biodiesel B35 was supplied to the diesel engine through the standard fuel injection system, while hydrogen acted as a supplementary fuel. The hydrogen production rate was regulated by varying the PWM voltage supplied to the electrolysis unit. The experiment was performed under stationary operating conditions using five PWM voltage variations: 6.0 V, 6.1 V, 6.2 V, 6.3 V, and 6.4 V. A baseline condition without hydrogen addition (0 V) was also evaluated for comparison purposes. For each test condition, hydrogen concentration, engine speed (RPM), vibration level, noise level, and fuel consumption were measured. Each experiment was repeated three times to ensure data reliability and repeatability. The average value of the three measurements was used for subsequent analysis.

The hydrogen concentrations obtained during the experiments were 8,450 PPMv, 10,250 PPMv, 11,800 PPMv, 12,450 PPMv, and 13,850 PPMv for PWM voltages of 6.0 V, 6.1 V, 6.2 V, 6.3 V, and 6.4 V, respectively. Fuel consumption was determined using a volumetric method and expressed in mL/min. Engine speed was recorded in revolutions per minute (RPM), while vibration and noise measurements were expressed in mm/s and dB, respectively. The experimental data were analyzed using descriptive statistical methods and linear regression analysis to determine the relationship between hydrogen concentration and engine operating parameters. Fuel efficiency improvement was calculated by comparing the fuel consumption of each hydrogen concentration with the baseline condition. In addition, a scoring method was applied to identify the optimum operating condition. The scoring criteria considered four parameters: fuel consumption, engine speed, vibration, and noise. Higher scores were assigned to conditions with lower fuel consumption, lower vibration, lower noise, and higher RPM. The operating condition with the highest total score was identified as the optimum hydrogen concentration for the biodiesel–hydrogen dual-fuel system.

The research began with the preparation and calibration of all testing instruments, followed by the operation of the hydrogen generation system and diesel engine under predetermined test conditions. Data collection was conducted for each PWM voltage variation, and the resulting measurements were analyzed to evaluate the effects of hydrogen addition on engine performance and operational characteristics. Finally, the optimum operating condition was determined based on the scoring analysis, considering both efficiency improvement and operational stability.

The stages of the flowchart in this study displays in **Figure 2**.

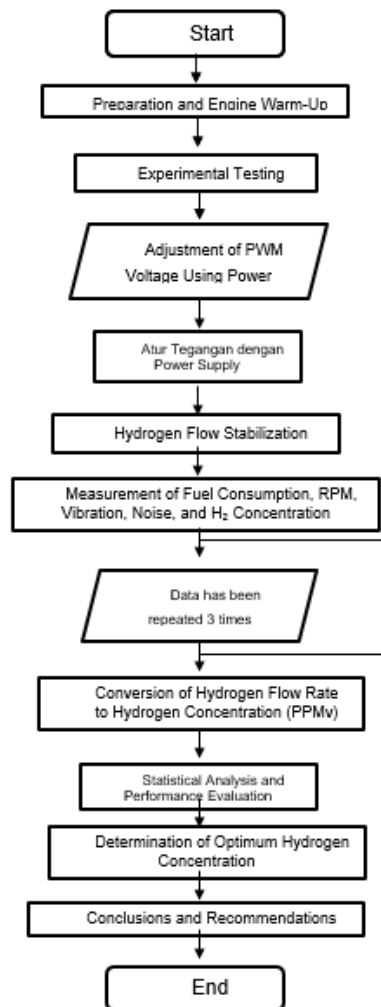


Figure 2. Flowchat

RESULTS AND DISCUSSION

The results indicate that hydrogen supplementation significantly influenced fuel consumption in the biodiesel-fueled diesel engine. As shown in Table I, fuel consumption decreased with increasing hydrogen concentration up to a certain level. Under baseline conditions without hydrogen addition, the average fuel consumption was recorded at 18.20 mL/min. The introduction of hydrogen reduced fuel consumption to 17.50 mL/min, 16.80 mL/min, 16.20 mL/min, and 15.50 mL/min at hydrogen concentrations of 8,450 PPMv, 10,250 PPMv, 11,800 PPMv, and 12,450 PPMv, respectively. However, a slight increase to 15.80 mL/min was observed at the highest concentration of 13,850 PPMv.

Table I. Hydrogen Concentration and Fuel Consumption

Hydrogen Concentration (PPMv)	Fuel Consumption (mL/min)
0	18.20
8,450	17.50
10,250	16.80
11,800	16.20
12,450	15.50
13,850	15.80

The reduction in fuel consumption can be attributed to the superior combustion characteristics of hydrogen. Hydrogen possesses a higher flame speed and wider flammability range than biodiesel, promoting more complete combustion and improving thermal efficiency. Consequently, less biodiesel was required to maintain engine operation. The slight increase observed at the highest hydrogen concentration suggests that excessive hydrogen supply may reduce combustion stability and diminish the efficiency gains obtained at moderate concentrations.

Effect of Hydrogen Addition on Engine Speed

Engine speed (RPM) increased with increasing hydrogen concentration, indicating improved combustion quality and energy conversion efficiency. Hydrogen accelerated flame propagation inside the combustion chamber, resulting in a more effective pressure rise and greater mechanical output. The highest RPM was achieved at a hydrogen concentration of approximately 12,450 PPMv, demonstrating the beneficial effect of hydrogen enrichment on engine performance.

The increase in RPM confirms that hydrogen addition enhances the combustion process by shortening ignition delay and improving fuel-air mixture homogeneity. Similar findings have been reported by Tosun and Özcanlı (2021), who observed performance improvements in biodiesel-fueled diesel engines through hydrogen supplementation.

Effect of Hydrogen Addition on Engine Vibration

Vibration measurements were conducted to evaluate engine operational stability. The results showed that vibration levels generally decreased as hydrogen concentration increased from 0 to 12,450 PPMv. This trend indicates a smoother and more stable combustion process due to improved fuel oxidation and more uniform pressure development inside the cylinder.

However, vibration increased noticeably at the highest hydrogen concentration of 13,850 PPMv. This phenomenon may be attributed to excessive combustion intensity, resulting in rapid pressure rise and the onset of abnormal combustion behavior. Although hydrogen improves combustion efficiency, excessive concentrations can negatively affect engine stability and mechanical integrity.

Effect of Hydrogen Addition on Noise Level

Noise measurements exhibited a trend similar to that observed for vibration. Moderate hydrogen concentrations contributed to reduced engine noise due to smoother combustion and more efficient energy release. The lowest noise level was observed near the optimum hydrogen concentration.

At the highest hydrogen concentration, noise levels increased significantly. This increase is likely associated with rapid combustion and higher in-cylinder pressure fluctuations. Elevated noise levels may indicate the occurrence of combustion instability and potential knocking phenomena. Therefore, noise analysis supports the conclusion that excessive hydrogen addition may adversely affect engine operation despite improving combustion performance.

Effect of Hydrogen Addition on Engine Efficiency

The improvement in fuel consumption and engine performance directly contributed to enhanced engine efficiency. The highest efficiency improvement of 14.84% was obtained at a hydrogen concentration of approximately 12,450 PPMv. This result demonstrates the capability of hydrogen to increase the utilization of chemical energy during combustion.

Hydrogen contributes additional energy to the combustion process while simultaneously improving the combustion characteristics of biodiesel. The combined effect results in reduced fuel consumption and improved engine output. These findings are consistent with previous studies reporting enhanced thermal efficiency in hydrogen-assisted diesel combustion systems.

Determination of Optimum Operating Condition

A scoring method was employed to determine the optimum operating condition by considering fuel consumption, engine speed, vibration, and noise simultaneously. Higher scores were assigned to lower fuel consumption, lower vibration, lower noise, and higher RPM.

Table 2. Scoring Analysis for Optimum Condition Determination

PWM Voltage (V)	H ₂ Concentration (PPMv)	Total Score
6.0	8,450	15
6.1	10,250	15
6.2	11,800	16
6.3	12,450	18
6.4	13,850	13

The highest score was achieved at a PWM voltage of 6.3 V corresponding to a hydrogen concentration of approximately 12,450 PPMv. At this condition, the engine exhibited the lowest fuel consumption, improved RPM, and acceptable vibration and noise levels. Therefore, 12,450 PPMv was identified as the optimum hydrogen concentration for the biodiesel–hydrogen dual-fuel system.

Overall, the results demonstrate that hydrogen supplementation can effectively improve the performance and efficiency of biodiesel-fueled diesel engines. Nevertheless, hydrogen concentration must be carefully controlled because excessive hydrogen supply may lead to increased vibration, noise, and combustion instability. The findings indicate that moderate hydrogen enrichment provides the best balance between efficiency enhancement and operational stability.

CONCLUSIONS

This study investigated the effect of hydrogen gas generated through water electrolysis on the performance and operational characteristics of a Pro Quip U.S.A QDX-400E diesel engine operating under a biodiesel–hydrogen dual-fuel system. The results demonstrated that hydrogen supplementation positively influenced engine performance by improving combustion quality, reducing fuel consumption, and increasing engine speed. As the hydrogen concentration increased, fuel consumption decreased from 18.20 mL/min under baseline conditions to 15.50 mL/min at a hydrogen concentration of approximately 12,450 PPMv, corresponding to an efficiency improvement of 14.84%. In addition, hydrogen enrichment contributed to improved engine speed due to faster flame propagation and more complete combustion. The study also revealed that hydrogen concentration significantly affected engine vibration and noise characteristics. Moderate hydrogen concentrations improved combustion stability and maintained acceptable vibration and noise levels. However, excessive hydrogen addition at 13,850 PPMv resulted in increased vibration and noise, indicating the onset of abnormal combustion behavior and reduced operational stability. These findings suggest that hydrogen concentration must be carefully controlled to maximize performance benefits while avoiding undesirable combustion effects. Based on the scoring analysis, the optimum operating condition was achieved at a PWM voltage of 6.3 V, corresponding to a hydrogen concentration of approximately 12,450 PPMv. Under this condition, the engine exhibited the best combination of fuel economy, engine speed, vibration, and noise performance. Therefore, the application of hydrogen as a supplementary fuel in biodiesel-fueled diesel engines has considerable potential for improving energy efficiency and supporting the development of cleaner and more sustainable engine technologies.

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REFERENCES

1. Abdullah, N. R., Rahman, M. M., Kalam, M. A., & Masjuki, H. H. (2021). Hydrogen enrichment in biodiesel-fueled diesel engines: A review of performance and emission characteristics. *Renewable and Sustainable Energy Reviews*, 147, 111242.
2. Akal, D., Öztuna, S., & Büyükkakın, M. K. (2020). A review of hydrogen usage in internal combustion engines from combustion performance aspects. *International Journal of Hydrogen Energy*, 45(60), 35257–35268.
3. Felayati, F. M., Prasutiyon, H., Janah, S., Wijaya, D. H., Saputra, M. B., & Semin, S. (2024). Performance and carbon emissions of a diesel/oxy-hydrogen dual-fuel engine with oxy-hydrogen injection variation under low and medium load conditions. *International Journal of Renewable Energy Development*, 13(2), 235–244.
4. Huynh, D. N. L., Nguyen, V. T., & Le, T. H. (2024). Hydrogen-assisted combustion in biodiesel-fueled compression ignition engines: Experimental investigation and performance analysis. *Energy Conversion and Management*, 315, 118920.
5. Jamrozik, A. (2025). An overview of development and challenges in the use of hydrogen in compression ignition dual-fuel engines. *Energies*, 18(21), 5793.
6. Kadhim, N. S., Adhas, S. M., Al-Mahdawi, E., & Milton, T. (2025). Advances in hydrogen-diesel dual fuel engine technology: A systematic review of emissions and performance characteristics. *International Journal of Mechanical Engineering*, 12(3), 61–70.
7. Karthikeyan, S., Elango, A., & Prathima, A. (2020). Hydrogen as a supplementary fuel in compression ignition engines: A review. *Renewable Energy*, 145, 2265–2283.
8. Kumar, S., Verma, R., & Singh, P. (2021). Experimental investigation of hydrogen enrichment in diesel engines operating on biodiesel blends. *Fuel*, 302, 121142.
9. Nguyen, H. T., Pham, D. T., & Tran, M. D. (2023). Evaluation of hydrogen supplementation on diesel engine efficiency and emissions. *Journal of Cleaner Production*, 385, 135664.
10. Periyathambi, V., et al. (2025). Balancing efficiency and emissions: A study on biodiesel-hydrogen dual-fuel compression ignition engines. *Engineering Reports*.
11. Rahman, M. M., Kalam, M. A., & Masjuki, H. H. (2021). Potential of hydrogen as a supplementary fuel for diesel engines: A review. *Energy Reports*, 7, 1458–1472.
12. Scignoli, F., Ferrari, G., & Bianchi, M. (2024). Hydrogen-enriched combustion systems for sustainable diesel engine applications. *International Journal of Engine Research*, 25(4), 1342–1358. [13] J. Xiao, L. Roiban, G. Foray, and K. Masenelli-Varlot, “Characterization of Liquid Suspensions in 3D using Environmental Scanning Electron Microscopy in

- Transmission,” *Microscopy and Microanalysis*, vol. 24, no. SI, pp. 350–351, 2018, doi: 10.1017/s1431927618002246.
13. Tosun, E., & Özcanlı, M. (2021). Investigation of hydrogen enrichment effects on soybean biodiesel fueled diesel engine performance and emissions. *International Journal of Hydrogen Energy*, 46(62), 31750–31762.
 14. Winangun, K., Aditya, R., & Nugraha, P. (2023). Performance enhancement of biodiesel-powered diesel engine using hydrogen induction system. *International Journal of Renewable Energy Development*, 12(5), 1025–1034.
 15. Wright, M. L., Lewis, A. C., & Carslaw, D. C. (2022). Decarbonisation of heavy-duty diesel engines using hydrogen fuel: A review of the potential impact on NOx emissions. *Environmental Science: Advances*, 1(5), 425–442.
 16. Yilmaz, E., Atmanli, A., & Vigil, F. M. (2020). Hydrogen addition effects on diesel engine combustion and performance characteristics. *Fuel*, 276, 118083.
 17. Zhang, Y., Li, H., & Wang, X. (2022). Experimental study on hydrogen-assisted combustion in compression ignition engines. *Energy Reports*, 8, 1178–1188.