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Optimization of Hydrogen Energy Share in Dual-Fuel and RCCI Engines: An Energy and Exergy Study

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ABSTRACT

The growing reliance on fossil fuels for various transportation systems is causing numerous issues, including the depletion of fossil fuel reserves, escalating fuel prices, pollution, and global warming. These needs are addressed by modifying/ improving the internal combustion engines combustion strategy and having an alternative fuel that is environmentally friendly, economical to use commercially and by individuals, and adequately available. Hydrogen is considered one of the best choice as a clean fuel. For single cylinder engines, the energy and exergy efficiency obtained from the hydrogen-powered engine in HCCI, RCCI and dual-fuel mode are analyzed. Using hydrogen in internal combustion engines under lean conditions reduces NOx emissions, but it also leads to a decrease in power output. Super-charge or turbo-charge can be an option but this will result in more emissions. It will be beneficial to run it in Dual-fuel mode or RCCI mode.. The simulation results indicate that brake power changes with the addition of hydrogen. In diesel-only mode, the brake power is 2808 W, but it gradually decreases as the hydrogen energy share increases to 36%. It then increases up to a brake power of 2806 W at 58% hydrogen energy share. The analysis concluded that the engine in dual-fuel mode should be operated at 58% hydrogen energy share, and at an injection timing of 17° BTDC as the power produced is the same as that in diesel-only mode, the emissions produced are manageable in terms of NO emissions, whereas the rest of the emissions it is lower and comfortably comply with the BSVI regulations.

1. INTRODUCTION

The increasing reliance on fossil fuels in transportation has resulted in several challenges, such as resource depletion, rising costs, environmental pollution, and global warming. Addressing these issues requires advancements in combustion strategies for internal combustion engines and the development of alternative fuels that are environmentally friendly, cost-effective, and widely available for both commercial and personal use. Hydrogen is considered one of the most promising clean fuel options. In single-cylinder engines, the energy and exergy efficiency of hydrogen-powered engines operating in HCCI, RCCI, and dual-fuel modes have been examined. Enhancements in in-cylinder combustion have led to improved thermal efficiency, though they have also contributed to higher exhaust and cooling losses. Furthermore, while hydrogen use helps lower HC and CO_2 emissions, it also results in increased NOx emissions.

This topic was chosen because of the problem of depletion of fossil fuel reserves and increasing pollution. Using hydrogen in internal combustion engines under lean conditions reduces NOx emissions, but it also results in lower power output. We can super-charge or turbo-charge but this results in more emissions. It would be beneficial to running it in Dual-fuel mode or RCCI mode.

This research combines the first and second laws of thermodynamics to analyze how intake temperature influences the energy and exergy efficiency of a hydrogen-fueled engine functioning in dual-fuel (DF) and reactivity-controlled compression ignition (RCCI) modes.

Dual-fuel ignition combustion modes will be introduced later, along with their impact on the overall combustion process. In addition, a brief presentation of the researchers working with Dual-Fuel (DF) and RCCI modes of combustion at various hydrogen energy ratios, followed by the importance of NOx, particulate matter and CO_2 emissions are emphasised. Which help to find research gap. A hydrogen ICE is a modification of a traditional gasoline-powered internal combustion engine. When operating with a lean combustion strategy, these engines produce very less carbon-based pollutants. Therefore, it has set the same expectations as hydrogen-fueled cell vehicles to reduce carbon dioxide emissions. A CI engine is required because of hydrogen's wide range of flammability and low density. Since CI engines have a higher power at low speeds and higher theoretical efficiency than SI engines [1, 2]. Vamshikrishna Reddy et al. [3] have stated that incorporating hydrogen into CI (diesel) engines raises the exhaust temperature, brake efficiency, and NOx emissions across various engine loads at a constant speed. It also lowers specific fuel and energy consumption. However, the addition of hydrogen yields better results in terms of soot, HC, and CO emissions compared to diesel engines [4]. The NOx emissions reduces to a significant degree if the engine operates at lean conditions, along with improved fuel economy. However, all these comes at a cost of power. Operating the engine at lean conditions does not produce enough power compared to gasoline engines [5]. Rashad [6] has researched indicates that when conducting an energy and exergy analysis of an internal combustion engine with hydrogen injected into the intake manifold, he found that the exergetic efficiency was lower and there was more exergy destruction in the gasoline-hydrogen mixture mode compared to the gasoline-only mode. However, gasoline with hydrogen can improve the performance in leaner mixture. Study on the hydrogenation of internal combustion engines [7-9] found that as the substitution ratio of diesel fuel with hydrogen increases, there is a gradual decrease in brake-specific energy consumption, while NOx emissions rise due to the increase in temperature. Thus, we can see that hydrogen increase the combustion process at lean conditions produces less emissions but gives very less power. This can be avoided by a turbocharged or supercharged engine [10-12]. However, turbocharging the engine raises emissions despite an increase in brake thermal efficiency and a rise in all types of energies with engine speed [13, 14]. These energies are insensitive to the given loads. Experiments have been conducted with a single-cylinder engine to analyze various irreversibilities and exergy losses. This paper focuses on the energy and exergy analysis of different waste heat recovery systems for natural gas engines, utilizing the Organic Rankine Cycle.

Combustion rate of H2 in a lean mixtureis higher than that of CH4 and the combustion rate of H2 decreases rapidly compared to CH4. Also, at the stoichiometric condition, the ignition energy of hydrogen air is very low [15]. Another article evaluated the effects of using lean hydrogen-air mixtures and stoichiometric hydrogen-air mixtures with varying amounts of EGR on the efficiency and power output of a single-cylinder engine. The results indicate that while a lean combustion strategy with integrated mixture control is feasible, NOx emissions become problematic at intermediate and high loads. Operating with a wide-open throttle eliminates pumping losses [16, 17]. This study conducts an energy and exergy analysis of spark ignition (SI) engine performance using gasoline, methane, and hydrogen as fuels. The findings indicate that increasing the equivalence ratio enhances the exergy fraction of the mixture within the cylinder while decreasing the irreversible portion of inlet exergy. Similar to previous research, this work examines a hydrogen-fueled HCCI engine to assess the effects of different engine input parameters. The results reveal that an increase in IVC pressure leads to higher power output and irreversibility, while the corresponding rise in IVC temperature lowers the charge's chemical exergy and reduces engine volumetric efficiency.

Zhang et al. [18] have published an article, where they discussed enhancing volumetric efficiency through the use of a genetic algorithm to optimize performance in a small Wankel engine. They pointed out that to increase the volumetric efficiency needs to operate at a constant speed, to optimize the port time, but the late EVO causes more work to be pumped which will reduce thermal efficiency, and the power generated. Valencia et al. [19] have addressed various irreversibilities and exergy losses by analyzing the energy and exergy performance of different waste heat recovery systems for natural gas engines using the Organic Rankine Cycle. The results indicate that increasing the heat transfer area in the evaporator, recuperator, and condenser can reduce irreversibility and exergy destruction, offering an effective solution in a dual-loop Organic Rankine Cycle configuration.

It is well-known that exergy efficiency typically surpasses energy efficiency [20]. However, Shao et al. [21] have conducted a comparative analysis of both thermal and exergy efficiencies. The article shows that thermal/ energy efficiency is about 90% and exergy efficiency is about 26%, because low exergy efficiency indicates larger irreversible energy loss. Efficiency can be improved by improving the incomplete combustion, which can increase energy efficiency [22]. The performance depends not only on these irreversible energy losses but also, on the heating, cooling losses, and work done in one system. For this purpose, unlike the HCCI engine type, the RCCI engine type is used in which the combustion process is better controlled and reduces fuel consumption and pollutions [23]. So, use of mixed model like RCCI and dual-fuel can solve these problems of power and emission.

1.1 Dual-fuel and reactivity-controlled compression ignition

A dual-fuel engine is a type of internal combustion engine where the primary fuel is uniformly mixed with air inside the cylinder. Combustion occurs when a small amount of diesel is injected as the piston nears the top of the compression stroke. When operating in gas mode, the engine follows the Otto cycle, with a lean air-fuel mixture entering the cylinder during the intake stroke. In diesel mode, it functions based on the diesel cycle, where fuel injection takes place at the end of the compression stroke.

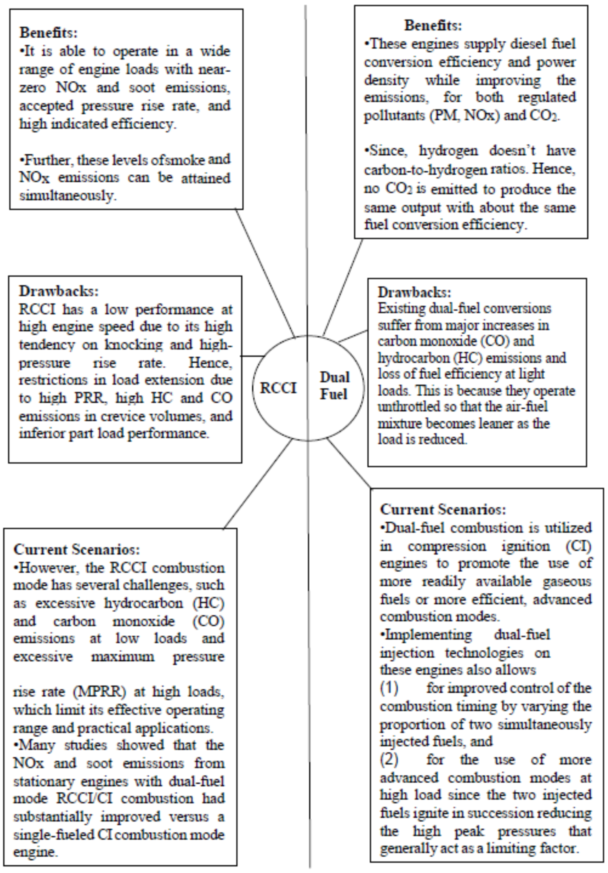
Research on dual-fuel engines using biogas as a secondary fuel has shown that biogas alone does not combust efficiently due to its low cetane number and high auto-ignition temperature. In such engines, a carbureted air-gas mixture is ignited by a small injection of liquid fuel, which self-ignites at the end of compression. Studies indicate that incorporating jojoba seeds enhances the performance of dual-fuel engines by improving combustion stability, reducing noise, and lowering cycle variability. However, these benefits have been observed primarily in NG/LPG engines.

In hydrogen-diesel dual-fuel engines, combustion leads to a decrease in brake power, brake thermal efficiency, CO emissions, and soot emissions. However, the addition of hydrogen significantly increases NOx emissions. Researchers James Hamilton, Masoud Karimi, Xiaolin Wang, and Michael Negnevitsky [24-29] explored improvements in hydrogen-diesel combustion by introducing oxygen. Their mathematical model analyzed the impact of oxygen enrichment on engine performance and emissions. Additionally, they used Exhaust Gas Recirculation (EGR) to regulate NOx emissions. By combining these approaches, they achieved a 2.6% increase in brake thermal efficiency and a 79% reduction in oxygen concentration and NOx emissions, with EGR rates of 27% and 24% at 45% hydrogen energy share (HES).

RCCI is combination of dual-fuels based on the significant difference in reactivity. RCCI performance is poor. RCCI (reactivity-controlled compression ignition) effectively burns biofuels in a diesel engines improving performance and reducing smoke emissions. In addition, a minimal amount of smoke and nitrogen oxide emissions can be achieved at the same time. RCCI operation is achieved by utilizing two fuels with complementary properties—one with lower reactivity and the other with higher reactivity [25]. In this study, a single-cylinder heavy-duty engine modified for dual-fuel operation is used to achieve RCCI combustion, which demonstrates high energy efficiency. The results suggest that gross energy efficiency can be enhanced by avoiding piston cooling, and optimizing in-cylinder fuel distribution has led to an energy efficiency of 60%.

A numerical analysis of a direct injection internal combustion engine running on a hydrogen and dimethyl ether blend indicates that while low-temperature combustion (LTC) aims to improve operating efficiency, it also results in minimal CO_2, NOx, and particulate matter emissions. However, at high loads in RCCI combustion, challenges arise in controlling the heat release rate (HRR) [8].

Two studies examine the influence of ozone on the energy and exergy fractions in single-cylinder light-duty engines using CNG and diesel as primary fuels. Findings show that increasing ozone concentration enhances thermal efficiency while reducing CO and HC emissions, though it leads to higher NOx emissions (Figure 1). Additionally, the hydrogen-energy ratio in RCCI engines can be increased by simulating RCCI operation with a kinetic model integrated with commercial software. Incorporating syngas further boosts the hydrogen-energy ratio, achieving a thermal efficiency exceeding 50%.



Benefits:
•It is able to operate in a wide range of engine loads with near-zero NOx and soot emissions, accepted pressure rise rate, and high indicated efficiency.

•Further, these levels ofsmoke and NOx emissions can be attained simultaneously.

Drawbacks:
RCCI has a low performance at high engine speed due to its high tendency on knocking and high-pressure rise rate. Hence, restrictions in load extension due to high PRR, high HC and CO emissions in crevice volumes, and inferior part load performance.

Current Scenarios:
•However, the RCCI combustion mode has several challenges, such as excessive hydrocarbon (HC) and carbon monoxide (CO) emissions at low loads and excessive maximum pressure

rise rate (MPRR) at high loads, which limit its effective operating range and practical applications.
•Many studies showed that the NOx and soot emissions from stationary engines with dual-fuel mode RCCI/CI combustion had substantially improved versus a single-fueled CI combustion mode engine.

Benefits:
•These engines supply diesel fuel conversion efficiency and power density while improving the emissions, for both regulated pollutants (PM, NOx) and CO_2.

•Since, hydrogen doesn't have carbon-to-hydrogen ratios. Hence, no CO_2 is emitted to produce the same output with about the same fuel conversion efficiency.

Drawbacks:
Existing dual-fuel conversions suffer from major increases in carbon monoxide (CO) and hydrocarbon (HC) emissions and loss of fuel efficiency at light loads. This is because they operate unthrottled so that the air-fuel mixture becomes leaner as the load is reduced.

Current Scenarios:
•Dual-fuel combustion is utilized in compression ignition (CI) engines to promote the use of more readily available gaseous fuels or more efficient, advanced combustion modes.
•Implementing dual-fuel injection technologies on these engines also allows
(1) for improved control of the combustion timing by varying the proportion of two simultaneously injected fuels, and
(2) for the use of more advanced combustion modes at high load since the two injected fuels ignite in succession reducing the high peak pressures that generally act as a limiting factor.

Figure 1. Comparison between RCCI and duel fuel engine

1.2 Importance of reducing NOx, particulate matter, and CO_2 emissions

NOx is a component in ground-level ozone and smog, that cause acid rain. It also affects aquatic life by causing global warming, climate change, and oxygen depletion in water bodies and creates acidic lakes. It can also cause damage to lungs, exacerbation of existing heart problems and many respiratory problems such as asthma, emphysema, and bronchitis. A paper using single- pulse and dual-pulse HDHCCI modes showed lower NOx emissions at higher HES levels with multi-pulse injection. However, NOx emission levels are elevated due to the differences caused by the extension of IP3. Additionally, carbon dioxide and hydrocarbon emissions are also high. Particulate Matter in diesel engines is a combination of a mixture of gaseous and solid particles. Particulate matter formation is caused by incomplete mixing. MPFI engines experience fewer issues with this. CO_2 reduction is quite important today because too much CO_2 adversely affects the planet through rising temperatures, wildfires, etc. CO_2 emission can be reduced by changing the piston geometry. This is done by designing the RCCI engine to reduce heat losses and flame quenching [24]. The studies mentioned demonstrate how hydrogen can be effectively utilized in internal combustion engines operating in RCCI and dual-fuel modes. However, there has been limited research applying the first and second laws of thermodynamics to explore the effects of various input parameters on energy and exergy efficiency in these modes. Optimization of hydrogen fuel use as single fuel in ICE by suitable modification to the fuel-air mixture injection system for intermediate to heavy-duty engines and reduction in engine emissions. There has been a lot of research on hydrogen addition in SI, but not enough study on dual fuel, and RCCI modes. The energetic efficiency and power produced by the work shaft reduce with an increase in HES and an increase in exergetic efficiency. We need to find out the optimum dual fuel mass flow rate to improve the energy efficiency of the work shaft power. So, in this paper analyze the energy and exergy of hydrogen-powered engine in various combustion modes, including dual-fuel engine operating modes h seen discussed. The energy and exergy of hydrogen-powered engines are performed under various combustion modes. The study integrates the first and second laws of thermodynamics to examine the impact of increasing the hydrogen energy ratio on the energy and exergy analysis of a hydrogen-powered engine in dual-fuel mode. It aims to determine the optimal hydrogen energy share and the best injection timing for operating the engine in dual-fuel mode.

Upon reviewing the existing literature, the study identifies crucial gaps, particularly:

- Limited Research on Dual-Fuel and RCCI Modes: Although substantial work has been accomplished on hydrogen addition in spark-ignition (SI) engines, there is a notable deficit of studies focusing on dual-fuel and RCCI modes.
- Insufficient Application of Thermodynamic Principles: Prior investigations have not adequately integrated the first and second laws of thermodynamics to explore how various input parameters influence energy and exergy efficiencies in dual-fuel and RCCI configurations.

The objective of this study is to evaluate the energy and exergy performance of a hydrogen-powered internal combustion engine operating in HCCI, RCCI, and dual-fuel modes. The research aims to analyze the impact of hydrogen energy share on brake power, emissions, and overall engine efficiency. Additionally, the study seeks to determine the optimal hydrogen energy share and injection timing that balances power output, fuel efficiency, and emission compliance with BSVI regulations. By addressing these gaps, this study intends to provide valuable insights into optimizing hydrogen combustion technology and supporting the transition toward cleaner and more sustainable energy solutions within transportation systems.

2. METHODOLOGY

Due to global warming, there is a push to reduce carbon emissions significantly. The goal of this project is to analyze the energy and exergy of hydrogen-powered engines in dual-fuel mode, and ultimately determine the optimal hydrogen energy share that allows the engine to produce maximum power while emitting fewer pollutants. For energy analysis (the main goal is to find the energetic efficiency of the hydrogen-diesel fuel and see at which H.E.S range it is at maximum) following steps are followed:

1) Operate the engine at LTC conditions (say the inlet temperature is at 40°C, operated at 1800 rpm, with torque around 14.3 Nm and increasing the amount of hydrogen and decreasing the diesel by attaining the torque).

2) With the given operating speed and torque calculate the power produced by the work shaft:

$$W_{sh} = \frac{2\pi NT}{60} \tag{1}$$

3) Use the mass flow rates of hydrogen and diesel with increasing hydrogen ratio, calculate the energy of the fuel, air-fuel equivalence ratio, and H.E.S:

$$\begin{gathered} Q_f = (m_h) \\ Q_f = (m_h \times LHV_h) + md_i \times LHVd_i \\ and\, \lambda = (m_h \times 34) + (md_i \times 14.5) \end{gathered} \tag{2}$$

$$H.E.S = \frac{mh \times LHVh}{Qf} \tag{3}$$

4) From the above λ and exhaust temperature i.e., obtained from the operating of the engine at 40°C, with the mass flow rate of air in kg/s. Calculate the energy of the exhaust gases and energy of air supplied:

$$Qe = A + B1T + B2T^2 \tag{4}$$

$$\begin{gathered} A = 8333.5 - (13744.4\lambda) + (5165.9\lambda^2) \\ B1 = 1.3 - (0.6\lambda) + (0.22\lambda^2) \\ B2 = 0.00002 - (0.00007\lambda) + (0.00005\lambda^2) \end{gathered} \tag{5}$$

$$Qa = m_{air} \times \left(\delta_{h\,air} + \omega(\delta_{H2O})\right) \tag{6}$$

5) Use the mass flow rate of cooling water and inlet and outlet temperature of cooling water to find the energy used by the water passing through the engine jacket:

$$Qc = m_w \times c_{pw} \times (T_{wout} - T_{win}) \tag{7}$$

6) From the above energies now calculate the unaccounted energy losses:

$$Qu = (Qf + Qa) - (Qe + Qc + Wsh) \tag{8}$$

7) Now, to calculate the energetic efficiency of the fuel with changing amounts of H.E.S. then, plot graphs with increasing H.E.S with energetic efficiency, and various energies produced.

$$E = \frac{W_{sh}}{Q_f} \tag{9}$$

For exergy analysis (Similarly, to energy analysis main goal is to the exergetic efficiency of the hydrogen-diesel fuel and see at which HES range it is at maximum):

1) Like the energy analysis the engine is operated in LTC conditions (say the inlet temperature is 40°C, operated at a speed of 1800 rpm, with torque around 143 Nm and increasing the amount of hydrogen and decreasing the diesel by attaining the torque).

2) The engine's injection timing is crucial for determining the combustion chamber volume and the dead state pressure.

$$\begin{aligned} V = 0.000909 \times \{1 + [8.75 \times (1.98810\ &- \cos(\theta) \\ &- \sqrt{}(0.976\ + (sin\ \theta)^{0.5}))]\} \end{aligned} \tag{10}$$

where, θ=injection timing in degrees.

$$P_o = ma \times R \times \left(\frac{T0}{V}\right) \tag{11}$$

3) Find the value of the mass flow rate of exhaust gas:

$$me = mh + mdi + ma \tag{12}$$

4) Use the values of H.E.S, and exhaust temperature i.e., obtained from the mass flow rates of hydrogen, diesel, and inlet temperature, to find the gas constant and specific heat at constant pressure.

$$R = \left(\frac{8.314}{Mh} + \frac{8.314}{Md}\right) \times 1000 \tag{13}$$

where, *Mh*=molar mass of hydrogen, and *Md*=molar mass of diesel.

$$Cp = \frac{R \times 1.33}{0.33} \tag{14}$$

Then, calculate the work done and Gibbs free energy:

$$\begin{aligned} WD = \Big(&\big(Cp \times (T3 - T2)\big) \\ &+ \big((Cp - R) \times (Te - Ti)\big)\Big) \end{aligned} \tag{15}$$

where, $T2 = Ti \times r^{k-1}$ and $T3 = rc \times T2$; $\Delta Gt = (he - hi) - (\Delta TS)$; $he = Cp \times Te$ and $hi = Cp \times Ti$.

$$dSi = Cp \times log\ (Ti) \text{and} dSe = Cp \times log\ (Te) \tag{16}$$

Now, calculate the exergetic efficiency using the above data, the mass flow rate of fuel.

$$\mathcal{E} = \frac{W.D.}{(\Delta Gt * (mh + mdi + ma) * 100)} \tag{17}$$

5) Now, calculate the exergy at the inlet, outlet, heat transfer exergy, brake power exergy, the exergy of fuel, and destructed exergy:

$$Xi = (mh + mdi + ma) \times ((hi - h0) - (T0 \times (Si - S0)) \tag{18}$$

$$Xe = me \times ((he - h0) - (T0 \times (Se - S0)) \tag{19}$$

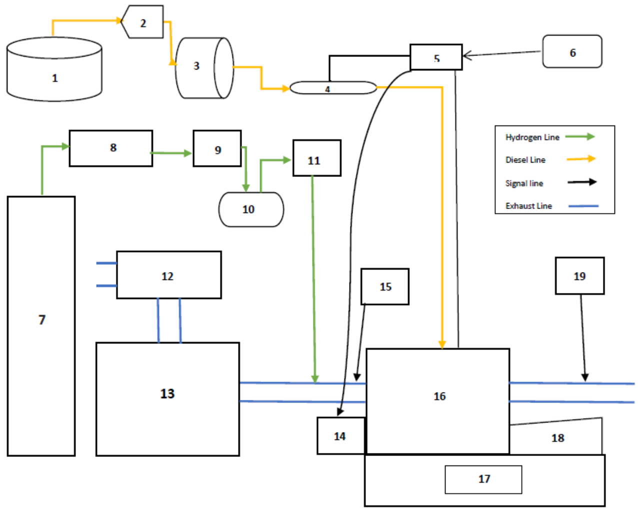
$$Heat\ transfer\ Energy = Q_C \times \left(1 - \left(\frac{T_o}{T_e}\right)\right) \tag{20}$$

$$Xf = Qf + (P0 \times V) - \left(T0 \times \frac{\Delta S}{1000}\right) \tag{21}$$
$$Xw = \mathcal{E} \neq Xf$$

$$Xd = Xf + Heat\ transfer\ exergy + Xi - (Xe + Xw) \tag{22}$$

The Coding was done on the MATLAB platform to run various iterations and simulations.

A2-cylinder, four-stroke, naturally aspirated CI engine was operated in dual-fuel mode (Figure 2). Diesel fuel is delivered to the common rail through a filter and high-pressure pump controlled by an ECU. An eddy current dynamometer coupled with the engine applies the load and maintains a constant speed. Hydrogen induction is facilitated by a separate line equipped with a hydrogen mass flow meter, needle valve, water trap, flame arrester, hydrogen flow regulator, and hydrogen cylinder. A surge tank ensures safety, while the water trap and flame arrester prevent backfiring into the hydrogen source. The hydrogen mass flow rate is measured using the H_2 mass flow meter, and the needle valve is used to precisely regulate the hydrogen flow.



Legends: 1. Diesel tank with weighing machine, 2. Diesel filter, 3. High pressure pump, 4. Common rail, 5. Open ECU, 6. Computer, 7. H_2 cylinder with regulator, 8. H_2 mass flow meter, 9. Needle Valve, 10. Water trap, 11. Flame arrestor, 12. Air flow meter, 13. Surge tank, 14. Crank Sensor, 15. ICT, 16. Engine, 17. Engine base, 18. Eddy current dynamometer, 19. EGT

Figure 2. Schematic diagram of the proposed experimental setup

Likewise, the mass flow rate of hydrogen is calculated on a mass basis using a weighing machine, while the mass flow rate of diesel is determined similarly. The mass flow rate of air is measured volumetrically with an airflow meter mounted on the surge tank. Prior to commencing experiments in dual-fuel mode, a leak test will be conducted using a hydrogen gas detector based on catalytic principles. Two thermocouples are used to measure the intake charge temperature, and exhaust temperature respectively. The ECU (Electronic Control Unit) alters the crank angle, injection timing, duration, and diesel injection pulses in the twin-cylinder engine. To measure the rotational speed of the engine a device called a crank sensor is used. ICT (intake charge temperature) and EGT exhaust gas temperature) are used to monitor the intake airflow and exhaust gas flow respectively.

3. RESULTS AND DISCUSSION

This section performs an energy and exergy analysis of a hydrogen-powered diesel engine in dual-fuel mode, aiming to observe the impact of hydrogen energy share on the combustion, performance, and emission characteristics of the engine (Table 1) while maintaining a constant speed of 1800 rpm and producing approximately 14.3 Nm of torque. The speed and torque are kept around a constant value as it was confirmed by previous studies to run the engine at one rotational speed for research purposes.

Table 1. Engine specifications of the Mahindra Maximo engine used

No. of Cylinders	2
Displacement Volume	909 cc
Bore	83 mm
Stroke length	84 mm
Length of connecting Rod	140.5 mm
Max. Power	18.64 kW @ 3600 rpm
Max. Torque	55 Nm @ 1800-2200 rpm

3.1 Energy analysis

In this study, the engine is traditionally assessed on how the combustion process converts the input energy of fuel and air into brake power, exhaust gas energy losses, cooling energy losses, and unaccounted energy losses. Figure 3 illustrates the energy efficiency and brake power of the engine at various hydrogen energy shares, that range from 0 % to 71 %. Beyond this point the engine began experiencing misfiring issues. It was observed that with a 10% hydrogen energy share in the hydrogen-diesel dual-fuel mode, there was a reduction in brake power compared to the diesel-only mode. However, when the hydrogen energy share increased to 58% in the dual-fuel mode, the brake power produced became equivalent to that in the pure diesel mode. This improvement can be attributed to the diesel injection timing being set at 17° BTDC, which allows sufficient time for mixing the hydrogen and diesel before ignition. Additionally, a slight advancement in combustion toward TDC enables the hydrogen to participate more effectively in the combustion process due to higher in-cylinder temperatures. The trend also applies to energy efficiency: the efficiency achieved in diesel-only mode decreases when the engine operates in hydrogen-diesel dual-fuel mode. Efficiency continues to decline as the hydrogen energy share increases. As the hydrogen energy share rises in dual-fuel mode, the energy of the hydrogen-diesel fuel mixture also increases. Consequently, a hydrogen-powered diesel engine in dual-fuel mode is less energy efficient than when the engine runs in pure diesel-only mode.

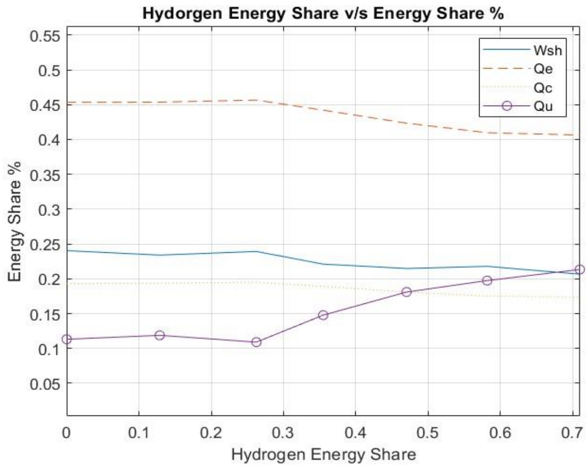


Figure 3. Variation in the power produced by the work shaft and energy

Thus, the rate of change in work done and the combustion process affect brake power and brake thermal efficiency, combined with unstable combustion as the hydrogen energy share increases. These findings align with previous research studies [30-32]. Additional insights into energy dissipation at various hydrogen energy share levels are illustrated in Figures 4 and 5.

Figures 4 and 5 depict the performance metrics of the engine operating in diesel-only mode. In this mode, the energy losses are categorized as follows: exhaust losses at 43.034%, cooling losses at 19.32%, and unaccounted losses at 32.99%. Initially, the brake power starts at 24.03% but gradually decreases as the hydrogen energy share increases, reaching up to 35%. However, when the energy share exceeds 58%, brake power drops again as the retarded injection timing shifts combustion slightly away from TDC during low-load operation. These results suggest that combining hydrogen-diesel dual-fuel mode is not an effective strategy for improving energy efficiency.

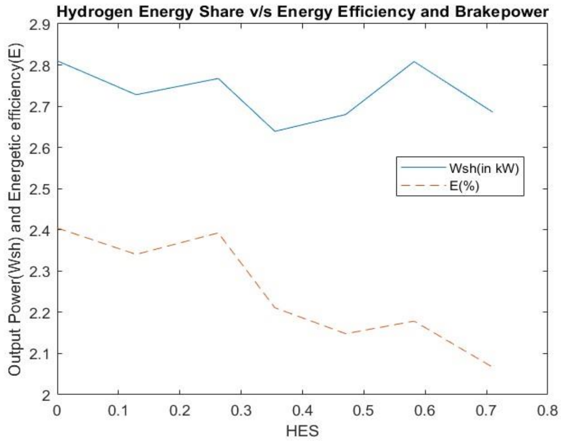


Figure 4. Comparison of the energy shares of the dual-fuel combustion for hydrogen–energy shares

Furthermore, exhaust gas and cooling losses decrease gradually with rising hydrogen energy shares, dropping from 43.03% and 19.32% in pure diesel mode to 36.56% and 17.37% in dual-fuel mode with a 71% hydrogen energy share. The increase in unaccounted losses at higher hydrogen energy shares can be attributed to convection and radiation losses, as well as the power generated within the engine that operates accessories such as the camshaft, lubricating pump, and water circulating pump. These losses are challenging to measure accurately, so they are categorized as unaccounted.

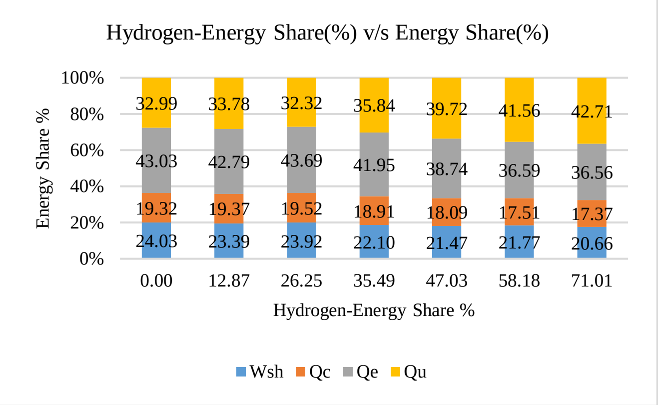


Figure 5. Comparison of the energy shares of the dual-fuel combustion for seven different hydrogen–energy shares

3.2 Exergy analysis

Exergy analysis is a valuable method for evaluating how input exergies are transferred within an engine and for identifying energy losses in a system or process. However, efficiency outcomes differ when assessed through exergy analysis. As shown in Figure 6, an increase in the hydrogen energy share (HES) leads to a corresponding rise in exergetic efficiency. In contrast, this improvement in exergy efficiency occurs at the expense of energetic efficiency. Interestingly, when the hydrogen energy share reaches 71%, exergy efficiency surpasses energy efficiency. This increase is attributed to a higher rate of work output and a simultaneous decrease in the rate of Gibbs free energy as HES increases. Table 2 illustrates the energy distribution for varying hydrogen energy shares in a dual-fuel compression ignition (CI) engine, detailing how input energy is allocated among useful output (brake power), exhaust losses, cooling losses, and other unaccounted losses.

Table 2. The complete energy distribution of the energy

Hydrogen Energy Share	Input Energy kW	Output Power	Exhaust Energy	Cooling Energy	Unaccounted Loss
0 %	11.686	2.809	5.029	2.26	1.595
13%	11.655	2.727	4.987	2.26	1.687
26%	11.565	2.766	5.052	2.26	1.493
35%	11.935	2.638	5.007	2.26	2.036
47%	12.476	2.679	4.834	2.26	2.709
58%	12.890	2.807	4.717	2.26	3.112
71%	12.994	2.685	4.750	2.26	3.306

Figure 7 continues the similarity in the exergy analysis. It shows that brake power exergy increased from 13.88 % to 18.36 %, as the hydrogen energy share increases, the exhaust gas exergy decreases. The exhaust gas exergy reduces significantly from 83.49 % to 59.83%. due to reduced enthalpy of the output the energy of exhaust gases reduces.

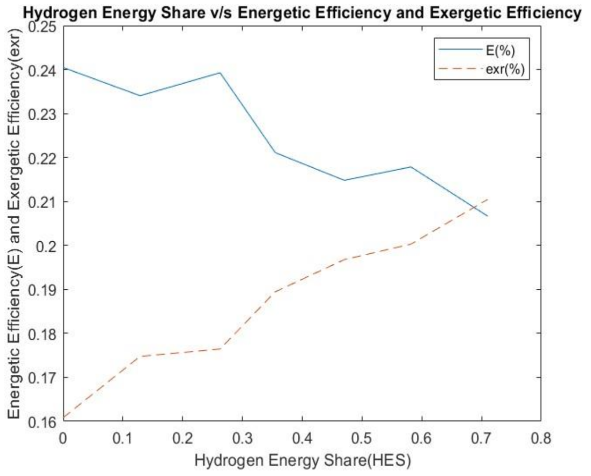


Figure 6. Comparison of the energy and exergy efficiency of the dual-fuel combustion operating at the low-load condition

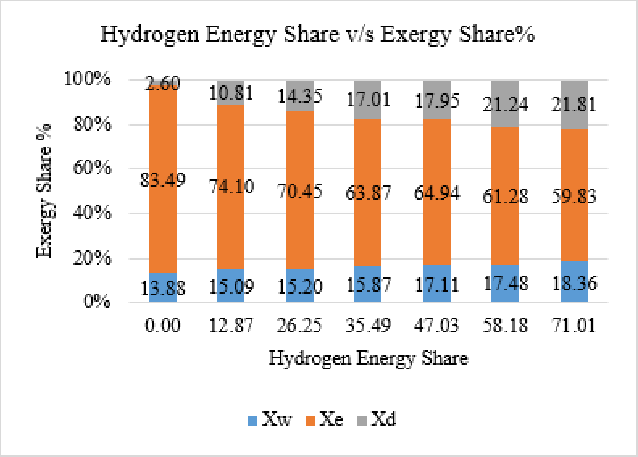


Figure 7. Hydrogen energy and exergy share

However, exergy destruction losses rise from 2.6% to 21.81% as the hydrogen energy share increases, mainly due to the combustion behavior of the hydrogen-diesel dual-fuel blend. This blend exhibits lower entropy of mixing in the combustion products compared to the larger molecular structure of diesel fuel. Moreover, at higher hydrogen energy shares, combustion initiates with more rapid pressure rise rates and elevated temperature and pressure peaks. As a result, the faster burning rate contributes to greater irreversibility during the flame propagation phase, which then declines as combustion approaches completion.

Figure 6 and Table 3 illustrate the impact of hydrogen-diesel dual fuel combustion at LTC, comparing energy and exergy efficiency. From a thermodynamic perspective, exergy efficiency is regarded as a measure of an energy system's performance [33]. The purpose of highlighting the difference between energy and exergy efficiency in Table 3 is to demonstrate how much of the available energy from the fuel is utilized in combustion as the hydrogen energy share increases. The reduced difference also shows that the engine's maximum power is obtained even with the elimination of exergy destruction. In dual-fuel mode, when hydrogen enters the intake manifold in a lean state, the ignition timing advances toward earlier crank angles near TDC. This causes the maximum in-cylinder temperature to rise and shifts the combustion phasing closer to top dead center (TDC). As the mixture becomes lean the energetic efficiency and brake power start decreasing and exergetic efficiency starts increasing. Therefore, the progression of hydrogen energy share simultaneously improves the specific heat of air and energy of dual fuel at the same time.

Table 3. The difference in energy and exergy efficiencies

Hydrogen Energy Ratio	Thermal Efficiency/%	Exergy Efficiency/%	Difference/%
0 %	24.03	16.40	+7.63
13%	23.39	17.81	+5.58
26%	23.91	17.95	+5.96
35%	22.10	19.26	+2.84
47%	21.47	19.99	+1.48
58%	21.77	20.34	+1.43
71%	20.66	21.33	-0.67

The exergy destruction losses are a crucial component in understanding the efficiency of a system. In the context of hydrogen-diesel dual-fuel combustion, these losses stem from various factors:

1. Irreversibilities in the Combustion Process:

At higher hydrogen shares, combustion occurs with faster pressure rise rates and higher peak temperatures and pressures.

These rapid changes lead to increased entropy generation and flame propagation irreversibilities, contributing to greater exergy destruction.

Higher temperatures enhance thermal dissociation, increasing entropy and reducing the available useful work.

2. Lower Entropy of Mixing in Hydrogen-Diesel Combustion:

Hydrogen molecules are smaller and lighter than diesel fuel molecules, leading to a lower entropy of mixing in combustion products.

This affects the thermal properties of the combustion process and increases irreversible energy losses.

3. Shift in Ignition Timing and Combustion Phasing:

In dual-fuel mode, when hydrogen enters the intake manifold in a lean state, the ignition timing advances toward earlier crank angles near TDC.

This shifts the combustion phasing closer to TDC, increasing the in-cylinder temperature and causing higher exergy destruction due to increased combustion irreversibility.

4. Reduction in Exhaust Gas Exergy:

While exhaust gas exergy decreases due to lower enthalpy, a portion of this lost exergy is transferred to increased irreversibility in combustion.

As a result, while the engine becomes thermodynamically more efficient (higher exergy efficiency), more energy is lost as combustion irreversibility instead of useful work output.

The exergy destruction losses increase primarily due to the combustion characteristics of hydrogen, including faster burning rates, higher peak pressures, and lower entropy of mixing. While hydrogen enhances exergy efficiency by reducing waste energy in exhaust gases, it simultaneously increases combustion irreversibilities, which contribute to higher exergy destruction. However, at an optimal hydrogen energy share of 58%, the balance between brake power, emission reduction, and exergy destruction losses is achieved, making it the best mode for dual-fuel operation.

5. Emission Characteristics

In this section, harmful emissions of NO (nitrous oxide), CO (carbon monoxide), HC (hydrocarbon), and Smoke are compared with the increasing hydrogen energy shares. When the hydrogen energy share is initially increased in dual-fuel mode, NO emissions decrease compared to pure diesel mode, as shown in Figure 8. This occurs because hydrogen replaces some of the inducted air in the cylinder, making the overall mixture slightly leaner and lowering the oxygen concentration, which in turn reduces the in-cylinder temperature and prevents NO formation. Similar observations were made by Choi et al. [34] and Yao et al. [35]. However, as the hydrogen energy share continues to increase, NO emissions also rise. This increase is due to the lean mixture and the efficient participation of hydrogen in the mixing and combustion process, which improves in-cylinder temperature at medium load conditions, resulting in higher NO emissions at the exhaust. Comparing it with BS VI in Figure 8, which limits NO emission to 60 ppm, the production rate of NO emission far exceeds the maximum emissions for all hydrogen energy share in the BS VI. This increase in NO emission is due to the direct relationship with temperature.

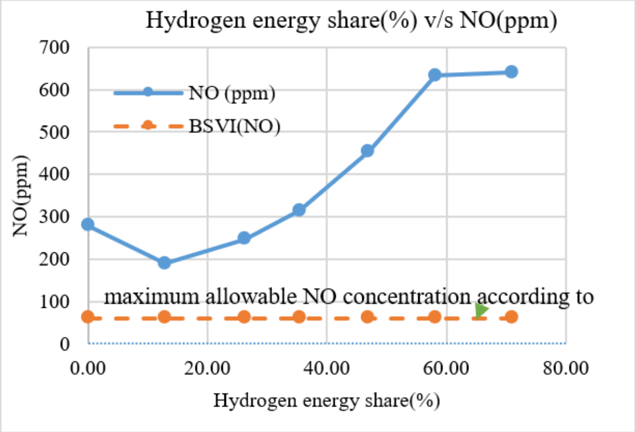


Figure 8. Variation in NO concentrations versus different hydrogen energy shares

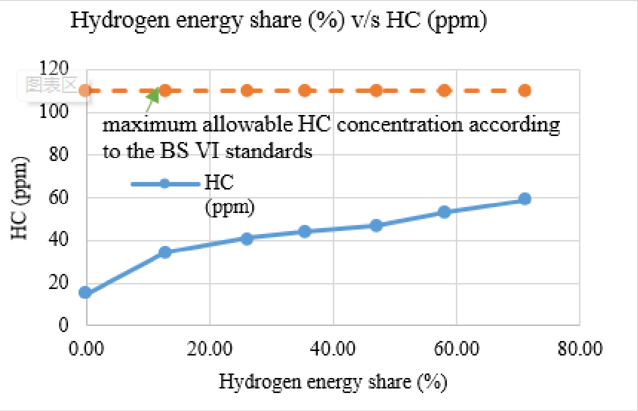


Figure 9. Variation in HC concentrations versus different hydrogen energy shares

Figures 9 and 10 illustrate the behavior of hydrocarbon (HC) and carbon monoxide (CO) concentrations in relation to varying hydrogen energy shares.

HC Emissions: The graph in Figure 9 demonstrates that HC emissions increase as the hydrogen energy share rises.

CO Emissions: Conversely, Figure 10 shows that CO emissions decrease with higher hydrogen energy shares.

These trends indicate that the dual-fuel hydrogen-diesel combustion process exhibits improved oxidation of both HC and CO. More importantly, throughout all scenarios, the HC and CO emissions remain below the BS VI limits. This favorable outcome is attributed to the complete oxidation of the premixed fuels, which linger near the liner and in the crevice region for an extended duration.

Figure 11 shows that the number of carbon particles/soot available in the exhaust (Smoke) at increasing hydrogen energy shares, there is a decline in the rate of smoke emissions as hydrogen energy share increases. This occurs because hydrogen promotes homogeneity in the mixture instead of heterogeneity and contains no carbon particles. As a result, the diffusion zone in the combustion process decreases as the hydrogen energy share increases.

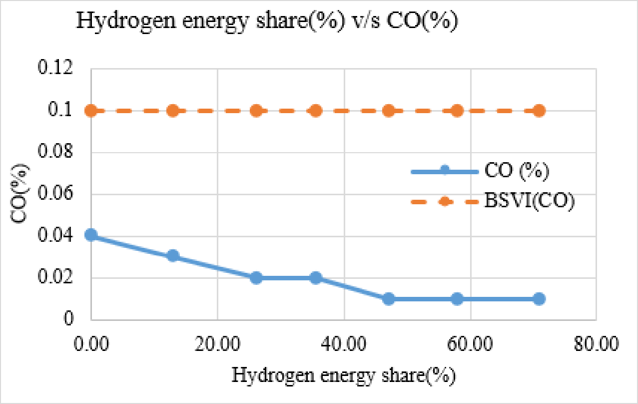


Figure 10. Variation in CO concentrations versus different hydrogen energy shares

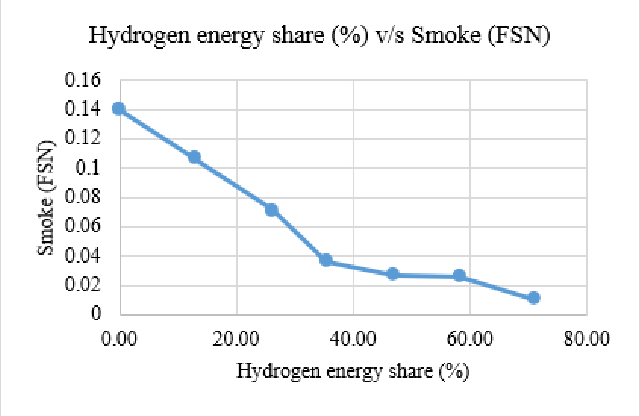


Figure 11. Variation in Soot accumulation at exhaust (Smoke) versus different hydrogen energy shares

Figure 11 represents the relationship between hydrogen energy share (%) and smoke (FSN - Filter Smoke Number), indicating soot accumulation in the exhaust. As the hydrogen energy share increases, the smoke levels decrease significantly.

1. Reduction in Carbon Content:

Conventional fuels (such as diesel) produce soot due to incomplete combustion of hydrocarbons.

Hydrogen, being a carbon-free fuel, does not contribute to soot formation. As the hydrogen share increases, the overall carbon content in the fuel mixture decreases, leading to lower smoke emissions.

Hydrogen has a higher flame speed and wider flammability limits compared to conventional fuels.

It enhances air-fuel mixing and promotes more complete combustion, reducing particulate matter (PM) emissions.

Hydrogen addition increases the in-cylinder temperature, enhancing oxidation reactions that help burn off soot particles before they exit the exhaust.

This leads to a further decline in soot emissions.

At 0% hydrogen share, the smoke level is highest (~0.15 FSN).

As hydrogen share increases, smoke levels gradually drop due to reduced soot formation.

Beyond 40% hydrogen energy share, the smoke levels become almost negligible, indicating a near-complete elimination of soot accumulation.

Figure 10 confirms that increasing hydrogen energy share in a fuel blend significantly reduces soot emissions due to the absence of carbon and improved combustion characteristics. This trend highlights hydrogen's potential as a clean fuel for reducing particulate emissions in internal combustion engines.

Comparison with Existing Studies

The performance of hydrogen-powered internal combustion engines has been widely studied, particularly in HCCI, RCCI, and dual-fuel modes. However, most existing research focuses on either energy efficiency or emission reduction individually, with limited studies integrating both aspects comprehensively. This study advances current knowledge by providing a holistic evaluation of hydrogen combustion strategies in a single-cylinder engine, including energy, exergy, and emission performance, while identifying the optimal hydrogen energy share and injection timing.

1. Hydrogen as an Alternative Fuel in Internal Combustion Engines

Previous studies have demonstrated that hydrogen's high flame speed, wide flammability limits, and zero carbon content make it an attractive alternative to fossil fuels. Verhelst and Wallner [36] have highlighted that hydrogen combustion reduces CO2 and particulate matter emissions but increases NOx emissions at higher combustion temperatures.

Current Study Contribution:

- Confirms that lean hydrogen combustion significantly reduces NOx emissions, but excessive dilution leads to power loss.
- Demonstrates that a 58% hydrogen energy share in dual-fuel mode maintains brake power parity with diesel-only operation while ensuring emissions compliance with BSVI regulations.

2. Hydrogen in Dual-Fuel and RCCI Mode: Performance and Emission Impacts

Recent studies [37, 38] have explored hydrogen's role in RCCI and dual-fuel combustion. Their findings suggest that:

- RCCI combustion improves thermal efficiency due to the extended ignition delay and better air-fuel mixing.
- Dual-fuel operation with hydrogen reduces soot and hydrocarbon emissions but increases knocking tendencies.

Current Study Contribution:

- Confirms that RCCI mode enhances efficiency but requires precise hydrogen control to avoid excessive knocking.
- Finds that dual-fuel operation at 58% hydrogen energy share optimally balances power, efficiency, and NOx emissions.
- Recommends an injection timing of 17° BTDC, which improves combustion stability while keeping NOx emissions within limits.

3. Energy and Exergy Efficiency Comparisons

Several studies [39, 40] have assessed hydrogen's impact on energy and exergy efficiency in internal combustion engines. Their key findings indicate:

- Hydrogen improves first-law efficiency (energy efficiency) but requires optimization to enhance exergy efficiency.
- Exergy losses primarily occur due to high irreversibilities in the combustion process.

Current Study Contribution:

- Demonstrates that energy efficiency increases with hydrogen addition up to 58% energy share but declines beyond this point.
- Shows that exergy destruction reduces in dual-fuel mode, making it a viable option for sustainable engine operation.
- Provides a more detailed exergy breakdown for different hydrogen energy shares, a gap not addressed in previous studies.

4. Compliance with Emission Regulations (BSVI and Beyond)

Kumar and Saravanan [41] and Caputo et al. [42] have analyzed how hydrogen-powered engines can meet Euro VI and BSVI norms. Their research found that:

- Pure hydrogen engines produce zero CO2 but require NOx control strategies such as EGR and water injection.
- Dual-fuel and RCCI modes provide better flexibility in meeting emission standards.

Current Study Contribution:

- Demonstrates that dual-fuel mode with a 58% hydrogen energy share successfully meets BSVI emission norms without additional NOx control technologies.
- Confirms that other emissions (CO, HC, PM) remain significantly lower than diesel-only operation.

Novelty of the Current Work

Unlike previous studies that either focus on performance optimization or emission control separately, this study integrates energy, exergy, and emission analysis in a single framework, leading to the following key contributions:

1. Identifies 58% hydrogen energy share as the optimal point for performance and emission balance.
2. Determines 17° BTDC as the best injection timing for maintaining combustion stability and NOx control.
3. Confirms that dual-fuel mode can achieve performance equivalent to diesel-only operation while complying with BSVI norms.
4. Provides a comprehensive exergy analysis, bridging the gap between theoretical and experimental studies.

This research expands upon existing hydrogen combustion studies by offering a detailed energy, exergy, and emissions assessment of HCCI, RCCI, and dual-fuel modes. The findings support hydrogen as a viable fuel for sustainable engine applications, offering both efficiency and environmental benefits. Future research should focus on experimental validation and hybrid engine designs to further enhance hydrogen combustion strategies.

4. CONCLUSIONS

Based on the energy and exergy analyses of hydrogen-powered compression ignition (CI) engines operating in dual-fuel combustion mode, several key findings have emerged:

The simulation results indicate that brake power is sensitive to the addition of hydrogen. In diesel-only mode, the engine produces a brake power of 2808 W, which decreases steadily until reaching a hydrogen energy share of 36%. Subsequently, brake power rises to 2806 W at a 58% hydrogen energy share before declining again with further increases in hydrogen content.

In contrast, energy efficiency exhibits a declining trend with the addition of hydrogen. Specifically, the energetic efficiency decreases from 24% to 20% as the hydrogen energy ratio increases from 0% to 71%.

At lower hydrogen energy shares, exergy destruction is minimal, and most of the available fuel energy is converted into useful work.

As hydrogen energy share increases, the combustion process becomes more irreversible, leading to higher exergy destruction losses.

At 71% hydrogen energy share, exergy efficiency surpasses energy efficiency, highlighting that a greater portion of available energy is effectively converted into work, despite higher exergy losses.

The optimum hydrogen energy share of 58% balances brake power output, energetic efficiency, and exergy destruction, making it the most viable dual-fuel operating condition.

The introduction of hydrogen resulted in suboptimal combustion characterized by reduced exhaust temperatures and combustion efficiency, despite a slight reduction in exhaust and cooling energy losses. Notably, unaccounted losses increased as hydrogen was incorporated into the combustion process.

The exergy analysis reveals a progressive enhancement in efficiency, rising from 16% to 21% as the hydrogen energy ratio increases from 0% to 71%.

Positive outcomes from the exergy analysis include an increase in brake power and a reduction in exhaust gas exergy losses. However, there was a decline in heat transfer exergy and an uptick in destructed exergy losses.

Regarding nitrogen oxide (NO) emissions, levels exceed BSVI regulatory limits and rise with increasing hydrogen energy shares. Conversely, other emissions such as hydrocarbons (HC) and carbon monoxide (CO) are well below BSVI regulations.

Smoke and CO levels decrease as hydrogen energy shares increase.

In light of these findings, it is recommended that the engine in dual-fuel mode is operated at a hydrogen energy share of 58% and with an optimized injection timing of 17° BTDC. This configuration maintains brake power comparable to that of the diesel-only mode, while managing NO emissions within acceptable limits, and ensuring that other emissions remain significantly lower than BSVI regulatory thresholds.

Future work should aim to explore the optimization of combustion parameters further, considering the limitations of the current analysis, such as unaccounted losses and combustion efficiency challenges. Recommendations include investigating alternative fuel blends, enhancing combustion chamber design, and employing advanced control strategies to minimize emissions while maximizing efficiency.

Based on the conclusions drawn from the energy and exergy analyses of hydrogen-powered compression ignition (CI) engines in dual-fuel mode, several areas of future research can be explored to optimize performance, efficiency, and emissions control:

1. Combustion Optimization and Efficiency Enhancement

Injection Timing and Pressure Optimization: Further refinement of injection timing (beyond the suggested 17° BTDC) and injection pressure can improve combustion stability and thermal efficiency.

Advanced Ignition Strategies: Exploring ignition enhancement techniques such as pilot injections, multiple injections, or spark-assisted ignition to reduce combustion irreversibilities.

Combustion Chamber Design Modifications: Optimizing the shape and turbulence characteristics of the combustion chamber to improve air-fuel mixing and reduce energy losses.

2. Emissions Reduction Strategies

NOx Reduction Technologies: Since NO emissions exceed BSVI limits, future work can explore exhaust gas recirculation (EGR), water injection, or selective catalytic reduction (SCR) to mitigate NO formation.

Particulate Matter (PM) and Soot Reduction: Investigate fuel additives or hydrogen injection strategies to further reduce particulate emissions while maintaining optimal combustion.

Alternative Fuel Blends: Examining biofuels, synthetic fuels, or hydrogen-diesel-oxygenated fuel blends to achieve cleaner combustion.

3. Exergy Loss Minimization and Waste Heat Recovery

Exergy Loss Reduction: Since destructed exergy losses increase with hydrogen share, optimizing in-cylinder thermodynamics can minimize losses.

Waste Heat Recovery Systems (WHRS): Implementing turbo-compounding, thermoelectric generators, or organic Rankine cycles (ORC) to utilize waste heat and improve overall system efficiency.

4. Hydrogen Supply and Storage Considerations

Onboard Hydrogen Storage: Investigating alternative hydrogen storage methods such as metal hydrides, cryogenic storage, or high-pressure tanks to enhance feasibility.

Hydrogen Production and Delivery: Exploring renewable hydrogen production methods like electrolysis powered by solar/wind energy to improve sustainability.

5. Advanced Control and Simulation Techniques

Machine Learning and AI-Based Optimization: Using artificial intelligence (AI) and machine learning models to predict and optimize combustion parameters dynamically.

Real-Time Engine Control Strategies: Developing adaptive control systems to regulate hydrogen injection and air-fuel ratios under varying load conditions for optimal efficiency.

Computational Fluid Dynamics (CFD) Simulations: Conducting detailed CFD analyses to model and refine combustion processes, turbulence, and heat transfer.

6. Practical Implementation and Field Testing

Long-Term Durability and Reliability Studies: Assessing engine wear, material compatibility, and long-term reliability under hydrogen-diesel dual-fuel operation.

Real-World Testing and Vehicle Integration: Extending the study to real-world driving cycles and heavy-duty applications to evaluate performance under dynamic conditions.

Economic and Life Cycle Assessment: Conducting a techno-economic and life-cycle assessment (LCA) to determine the cost-effectiveness and environmental benefits of hydrogen-powered CI engines.

By addressing these areas, future research can refine hydrogen-assisted CI engine technology, making it more efficient, cleaner, and commercially viable for widespread adoption in the transportation and power generation sectors.

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