Journal of Mines, Metals and Fuels, *71(11): 2056-2068; 2023. DOI: 10.18311/jmmf/2023/36095*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.com/index.php/jmmf*

A Review on Compression-Ignition Engine Performance and Emissions with Hydrogen-Diesel Mixtures: Effect of Operational Parameters

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Abstract

The combustion of conventional fuel in Compression-Ignition (CI) engines is generally understood as a primary cause of hydrocarbon exhaust emissions. Alternative fuels and hydrocarbon fuels can be mixed to lower pollution emissions while enhancing engine efficiency. Here, the various variables which impact emissions and engine efficiency are fully illustrated. Numerical work on the engine was done to examine the working and outflow patterns of a dual-fuel CI engine at various fuel combination ratios. In the test setup, diesel is used as main fuel and hydrogen and air as the controlling fuel. In order to formulate this special CI engine numerically, three-dimensional computer based analytical tools were used. For this method, n-heptane was chosen as reaction fuel and a reduced-reaction mechanism was taken into account. To investigate the soot formation rate inside the cylinder, the model by Hiroyasu-Nagel was developed. Here, a study looks into the performance effects on the variations of secondary fuel and its emissions. Presence of good amount of hydrogen during combustion results in better thermal efficiency and better performance. As the hydrogen rate increased, ignition timing was delayed as a result of a time lag in the OH component's evolution. Meanwhile, Exhaust Gas Recirculation (EGR) and timing of the diesel incorporation strategies are also taken as important performance parameter.

Keywords: *Compression-ignition, Hydrogen / Diesel Engine, Performance of Emission*

1.0 Introduction

Transportation, civil engineering, and the creation of electrical power are just a few of the industries that heavily rely on internal combustion engines, which are propelled by the combustion of carbon based natural fuels. As we know, fossil fuels are limited and create a lot of pollutants. The environment and public health continue to be harmed by unburned hydrocarbons, soot, which includes mixtures of carbon oxides and mixtures of nitrogen oxides. Clean, sustainable, and alternative fuels can be used in place of conventional internal combustion engines to reduce the harmful effects of emissions, in addition to hydrocarbon fuels.

By using of hydrogen in this engine, is expected to be able to bridge the future energy gap, lowering hydrocarbon emissions, and preserve effective engine performance. One of the most reliable, sustainable, and renewable fuels is hydrogen. In contrast, hydrocarbon fuels like natural gas, gasoline, and diesel, the usage of

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hydrogen as the working fluid in internal combustion engines can increase the thermal efficiency linked to depletion in carbon-based outflows. Utilizing hydrogen for transportation or power generation primarily benefits the environment by reducing our reliance on fossil fuels and increasing our reliance on renewable fuels[1].

In addition, hydrogen, a fuel free of carbon, has special qualities. Hydrogen can burn at a variety of equivalence ratios because, in comparison to all other fuels, it is a very flammable gas. Because it can operate on a lean mixture, hydrogen's low ignition energy ensures faster ignition with lower NOx and much better thermal efficiency[2-4]. Thanks to a decrease in exhaust losses brought on by the higher burning velocity of hydrogen (237 cm/s), engine thermal efficiency increases. Additionally, the combustion chamber's mixture is more homogeneous because of hydrogen's high diffusivity, which aids in complete fuel combustion[5].

Theoretically, for a higher auto-ignition temperature (857 K) Hydrogen is a better fuel for spark ignition engines compared to Continuous-Ignition (CI) engines. Although numerous studies have conclusively adapted SI engines to run exclusively on hydrogen, no commercial applications for these engines have yet been made[6,7]. However, no research[8,9] has been able to change the current CI engines so that hydrogen is the only fuel they use.

Recent studies[10,11] evaluated the possibility of using hydrogen in CI engines along with diesel. Even though these studies have proved a large amount of lowing in soot formation, higher hydrogen levels, hydro carbon emissions within the engine cylinder could increase the dangerous nitrogen-oxides emissions. The addition of hydrogen may lead to a significant improvement in thermal efficiency, according to studies on hydrogen-diesel dual-fuel engines[3,4,12,13].

It has been suggested that higher combustion temperatures and air oxygen concentrations result in higher NOx emissions from hydrogen than from pure diesel. Similar findings were reached by various analytical studies[11,12]. According to the recent numerical study, adding hydrogen to diesel fuel reduces pollutant emissions overall, with the exception of NOx emissions[13]. Two more consequences of substituting oxygen for hydrogen in diesel engines are that it slows down the onset of combustion and permits more fuel to enter the engine. When the proportion of hydrogen exceeded 50% of the total energy, the engine started to sputter[13].

The use of hydrogen in diesel engines may result in emissions that are both regulated and unregulated (CnHm). It was found that unrestricted emissions of hydro carbons like acetaldehyde, mixtures of pentane, hexane, heptane, octane etc. and olefins like ethene and propene decreased as hydrogen was incorporated to diesel in CI engines[14]. In addition to its effect on emissions, hydrogen should also be considered for its effect on engine performance because of the delayed ignition. The time lag between when the diesel injection into the cylinder begins and when combustion begins is known as the ignition delay. It can also be considered as the interval between the mixture's energy release and the first noticeable increase in cylinder pressure[4]. Gas oxidation during compression results in the production of certain chemical species that lengthen the ignition delay period because active OH radicals are lost along with the hydrogen molecules[15]. Experimental research was done on the impact of various fuels, such as hydrogen, Liquefied Petroleum Gas (LPG), and a blend of hydrogen and LPG, on the ignition time in dual-fuel diesel engines[16].

Various load scenarios and diesel substitutes were used during the experiments. It was discovered that the dualfuel engine ignites more quickly depending on the fuel type and its concentrations, the fuel mixture temperature, its pressure and relative density of oxygen. To improve engine performance and lower emissions, effective methods for today's conventional petrol, diesel, and hydrogen-fueled engines must be developed. This is in addition to finding alternative, efficient, and green energy producers. Diesel injection timing and Exhaust Gas Recirculation (EGR) are two regularly utilized methods that have been used to improve engine performance and reduce exhaust pollutants. The primary cause of the root issue of NOx formation is high temperature hydrogen-combustion. EGR was therefore considered to be a potentially efficient strategy for significantly reducing NOx emissions in CI engines[17–19]. In order to lower the temperature inside the cylinders, the EGR mechanism involves reintroducing some of the exhausted gases from a prior cycle. Although an EGR technique is less desirable for diesel engines as soot emissions rise, hydrogen/diesel dualfuel engines can still use it[20]. Numerous studies have considered using hydrogen combustion with an EGR technique to ensure the stability of the combustion and reduce NOx emissions[21–24].

Shin[24], who investigated the increase in carbon dioxide concentration with the EGR ratio under heavy EGR conditions, states that hydrogen has an impact on brake thermal efficiency and NOx emissions.

The EGR rate has a significant impact on the emissions of soot and Nitric Oxide (NO) from heavy-duty DI diesel engines. Conversely, an increase in EGR% leads to a decrease in soot emissions and a rapid increase in NO emissions. At low engine speeds, the power of this effect increases significantly[25]. High EGR levels are commonly used in CI and Homogeneous Charge Compression-Ignition (HCCI) engines.[26–28]. Although dual fuel engines with EGR typically emit more hydrocarbons than dualfuel engines without EGR, these emissions are still considerably less than those from pure diesel engines. In dualfuel engines with hydrogen induction, EGR techniques are crucial for governing the temperature of cylinder as well as NO_x emissions were regulated for enhancing the engine performance[17]. When compared to hydrogen combustion without them, EGR techniques help hydrogen engines emit less NOx. The increased specific heat capacity of the EGR causes a decrease in the in-cylinder temperature. Low NOx levels combined with an abundance of unburned fuel and CO produced when the combustion temperature is lowered can lower thermal efficiency. Because hydrogen is a highly flammable fuel, controlling the EGR level to a certain point can aid in engine load management[29-31].

Diesel engine NOx and soot emissions are frequently decreased by adjusting the commencement of injection timing. The timing of the diesel injection affects engine output and emissions. Early combustion caused by the advance timing of diesel injection raises the temperature and pressure inside the cylinder. For this, both power of the engine and evoked NOx increase[32,33]. Injection timing techniques and EGR are extremely helpful for boosting the NOx reduction method, by lowering the thermal effect in the cylinder, even though the power is significantly reduced. Despite the fact that sometimes, increasing power can also lead to an increase in NOx, engine designers strive to reduce harmful emissions as much as they can. Consequently, this problem exhibits the characteristics of a conflicting multi-objective optimisation problem.

The current study investigates the effect of operating factors on engine efficiency, soot content, and NOx emissions, including hydrogen levels, EGR, and injection time. There is little research on the operating conditions of dualfuel engines that run on hydrogen/diesel mixtures. Along with, there aren't many studies that examine the relationship between the hydrogen/diesel ratio and the duration of the ignition delay period as well as howthat impacts the efficiency of CI engines. The goal of this study is to numerically analyse how operating parameters, such as hydrogen variation, affect engine performance and output emissions[41]. The software also produces development that is significantly quicker and less expensive, as well as precise predictions with a smaller margin of error.

2.0 Methodology

2.1 Computational Methods

The obvious issues with hydrogen combustion are higher values of pressure increase, knocking during combustion, increase of temperature and NOx emissions. These problems require consideration, in depth investigation and management.

In the current computational work, the performance and emissions characteristics of diesel engines using a hydrogen/diesel combination were investigated. A reduced dual fuel reaction mechanism for both hydrogen and diesel was integrated with the AVL FIRE® 3D CFD program for numerical modeling. This study confirmed the hydrogen-diesel dual fuel engine developed with AVL Fire through investigative work using an engine model to project output power, efficiency, and emissions.[34, 35].

The exact mechanism[36] for the kinetics of the reactions of n-heptane consists of a large number of chemical elementary reactions and 76 species, including chemical reactions involving hydrogen but excluding reactions oxidizing nitrogen. Because N-Heptane's cetane number (56), which is nearly as high as diesel fuel's (50), it was taken into consideration for this work rather than diesel. To calculate the rate of NOx generation, Nitric oxide (NO) and nitrogen dioxide (NO_2)-related chemical reactions are added. The evolution of NO is depicted by the Zeldovich mechanism in the diagram below.

$$N_2 + O \leftrightarrow N + NO \quad (1)$$

$$N + O_2 \leftrightarrow NO + O \quad (2)$$

$$N + OH \leftrightarrow NO + H \quad (3)$$

357 simple reactions are thought to make up the final chemical kinetic mechanism. Numerical modeling may provide a better understanding of the complex processes of creation and combustion inside the cylinder, which are difficult to identify and quantify through experimental research. As hydrogen was injected into the engine's intake port, it is anticipated that after the intake valve is shut, hydrogen will be present in the combustion chamber alongside air. An injector used for direct diesel fuel injection is located in the top centre of the combustion chamber. Calculating the emissions of pollutants such CO_2, CO, and NO_x at the exhaust was done using the species in the chemical mechanism.

2.2 How Soot Forms

Because soot emissions are harmful to the environment and public health, the laws governing their emissions have become more stringent. To implement optimal operating conditions that will lower soot emissions, a thorough understanding of the formation of soot is essential. Carbonaceous particles (soot), which form with hydrocarbon fuels during the initial stages of combustion, have a strong propensity to do so. The ensuing oxidation process depletes some of the soot produced. Temperature, pressure, residence duration, and the air/fuel ratio (C/H and C/O ratio) are the most important variables affecting soot formation. This study took into account the Hiroyasu-Nagel model, which automatically integrates into AVL software and is used to model soot emissions.

2.3 Model Parameters

AVL Fire software was used to create the engine's shape (Figure 1). Table 1 contrasts the characteristics of hydrogen with those of diesel, while Table 2 provides

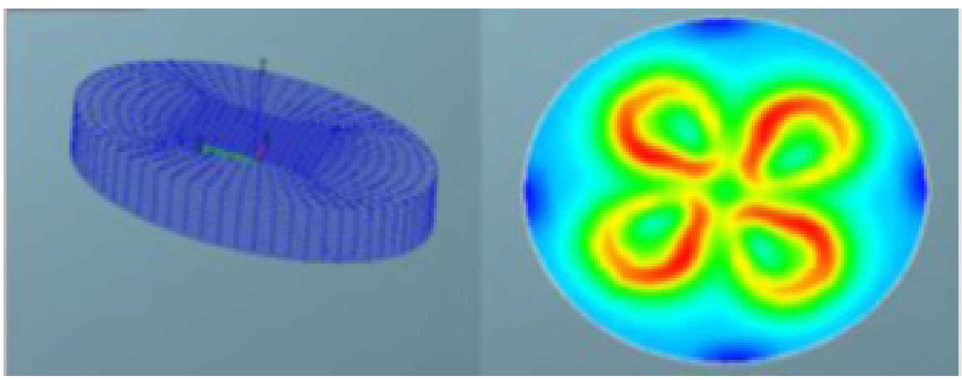

Figure 1. Engine geometry[41].

Table 1. Fuel Properties

Properties	Hydrogen	Diesel
Lowest ignition energy (mJ)	0.019	--
Air flammability limits (vol. %)	3.95 -74.5	--
fuel to air mass (Stoichiometric ratio)	0.03	0.07
Lower heating value (MJ/kg)	120.15	42.19
Flame speed (m/s) (Stoichiometric)	2.649 - 3.252	0.299
At STP density (kg/m^3)	0.084	823.9
Temperature (K) of auto ignition	857	530

the specs of the simulated single-cylinder engine and the operating circumstances.

3.0 Model Validaion

Utilizing AVL Fire software, the engine model used in this numerical analysis was produced. The model was run under different running cycles in accordance with the test and experiments. A portion of the soot produced is reduced by the subsequent oxidation process. The primary factors influencing soot formation are temperature, pressure, residence time, and the air/fuel ratio (C/H and C/O ratio). The identical hydrogen and diesel fuel mixtures were utilized in the experiments and simulations. Hydrogen was injected into the engine at flow rates of 7.5 l/min (12% by energy at full load) and 20 l/min (37.5% by energy at full load) using two different carburation and Timed Port Injection (TPI) techniques.

Table 2. Specifications of the Engine

No. of Cylinders	1
Bore (mm)	80
Stroke (mm)	110
Speed of engine (rpm)	1490
Compression ratio	16.6:1
Length of the connecting rod (mm)	234
Brake power (Max) (kW)	3.75
Piston type	Flat
Injector nozzle holes Number	4
Diameter of holes (m)	0.000169
Spray angle	161°
Fuel amounts (Vol. %)	7.145
Temperature (K) (Initial)	332
Initial pressure (bar)	1
Injection timing (CA)	23° BTDC
Duration of injection	30°

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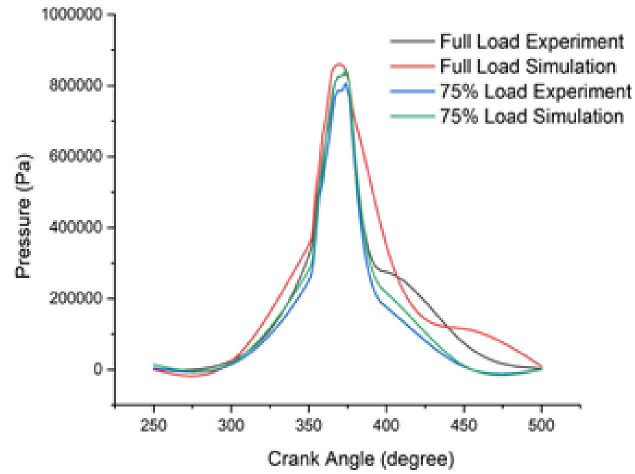

Figure 2. Pressure curve for the 7.45 l/min hydrogen/diesel mixture at 74% and full load.

While injecting diesel into the cylinder, the timing was 30o CA and 23o BTDC. With engine loads of 25%, 50%, 75%, and 100%, respectively, and brake powers of 1.05, 1.91, 2.8, and 3.73 kW, the engine was operated at a steady 1492 rpm. The hydrogen TPI case was taken into account in the current numerical study due to its notable escalation in fuel measuring over a carburetor. When diesel was injected, it was assumed that the cylinder had a hydrogen/air mixture inside of it. The results for the in-cylinder pressure and exhaust emissions (soot, NOx, CO, and CO_2) were verified against experimental results.

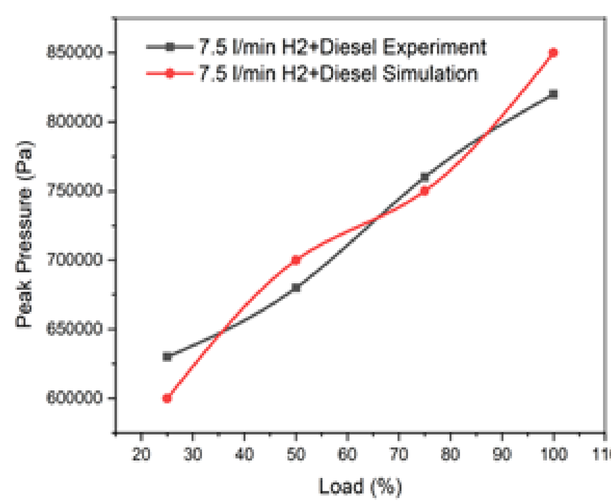

Figure 3. Peak pressure variation with loads at 7.45 l/min H_2 flow rate.

The performance of the model was evaluated during the test validation process using the correlation coefficient (R) and coefficient of determination (R2). The coefficient of determination is equal to the square of the correlation coefficient R. The correlation coefficient calculates the difference between the predicted and actual data. A perfect match between the simulation and experiment results would have a R value of 1.

The pressure curves for the 7.45 l/min hydrogen/diesel mixture at 74% and full load can be seen in Figure 2 and show a reasonable level of agreement between simulation and experiments. The model's accuracy was assessed using the pressure data's correlation coefficient. The pressure data's R value is 0.968[38]. This quantity represents the model›s ideal fit and best validation performance.

Peak pressure was also taken into account at various engine loads. The pressure was seen to increase with engine load because of the increased temperature at higher engine loads.

There is little doubt that the predicted and experimental values are close as shown in Figure 3. Peak pressure data has a correlation coefficient of 0.9919.

For various brake powers, the values of experimental and anticipated emission parameters are shown in Figures 4 and 5. For the emissions output validation with obtained experimental data, 20.5 l/min hydrogen/diesel blends were used. Figure 4 depicts the variation in soot emission

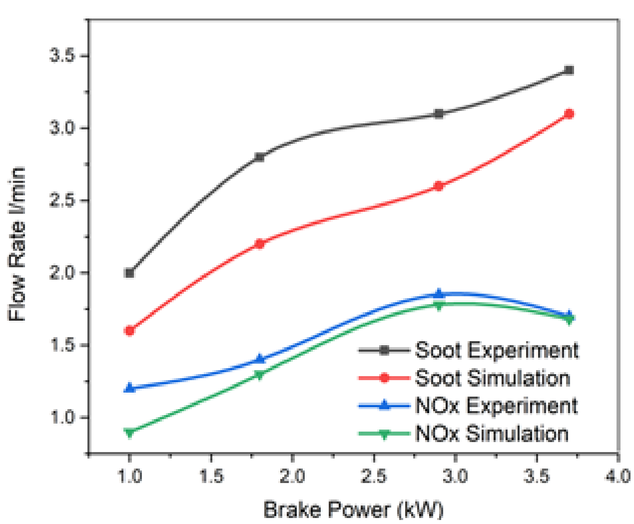

Figure 4. Soot and NOx emissions fluctuation at a 20.5 l/min H_2 flow rate with brake power.

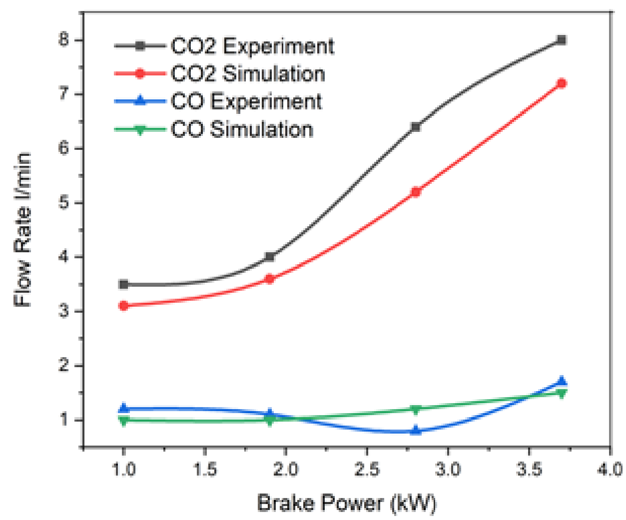

Figure 5. Variation in CO and CO_2 emissions for a 20 l/min H_2 flow rate with brake power.

as engine brake power is increased. It was discovered that as brake power increased, soot emissions somewhat increased. As a higher brake power requires a higher level of diesel flow inside the cylinder, soot formation rises as diesel flow does.

Figure 4 also shows the variation in NOx emissions with brake power. NOx emissions often occur at high levels of combustion temperature. Higher brake power was shown to result in higher NOx emissions.

Figure 5 illustrates variations in CO and CO_2 emissions for 20 l/min hydrogen/diesel blends at various braking powers. The data unequivocally shows an increase in CO and CO_2 with significant braking efforts. This is due to the fact that the engine's increased diesel flow emits CO and, with enough oxygen, CO_2 emission. CO and CO_2 emissions have validation performance correlation coefficient of 0.889 and 0.9958, respectively. Because CO emissions have low output values, compared to CO_2, the correlation coefficient for CO is marginally lower. The simulation model performed the best in terms of validation. Table 3 illustrates the close proximity and strong correlation between the anticipated and measured values.

The developed model was used to investigate the prospective effects of operational factors (injection time, EGR, and hydrogen levels) on engine outputs because it is obvious that it is capable of accurately forecasting emission parameters and engine performance.

Table 3. Comparison of experimental and numerical results [35]

20.5 l/min Hydrogen/Diesel[38]								
Brake Power (kW)	Soot (FSN) Sim.	Soot Exp.	NOx (ppm) Sim.	NOx Exp.	CO (%) Sim	CO Exp.	CO_2 (%) Sim.	CO_2 Exp.
1	1.597117	2.01	1517.47	1051	0.021	0.024	3.31	3.51
1.88	2.260628	2.79	1869.52	1802	0.019	0.024	4.01	4.21
2.89	2.591241	3.01	2504.13	2502	0.022	0.019	5.51	6.51
3.75	3.325151	3.45	2631.46	2601	0.034	0.039	7.01	8.01
R-Value	0.984415804		0.985931791		0.889265907		0.995820731	
R^2-Value	0.96906		0.97205		0.79088		0.99265	

Table 4. Operating conditions and goals.

Parameters	Value	Objectives
Injection Time (BTDC)	10.5, 15.5, 20.5, and 30	Min [Soot Emission]
H2 energy ratio (%)	5.5, 10.5, 20.5, 37.5, and 50.5	Min [Indicated Thermal Efficiency (%)]
EGR Level (%)	0.5,5. 5, 10.5, and 15.5	Min [NOx Emission (ppm)]

4.0 Problem Description

The AVL Fire software was used to conduct a numerical analysis of a heavy diesel engine running at various hydrogen levels (%), diesel injection timings, and EGR levels percentage. Numerical findings and outlines produced by software were used to analyze the impact of each parameter's modification. This study's main goal was to determine whether certain operational factors may have an impact on a diesel engine that had been upgraded with hydrogen fuel in terms of output and emission attributes. The intended results of this study are maximum indicated thermal efficiency and minimal soot and NOx emissions.

5.0 Results and Discussion

5.1 The Effects of Hydrogen Variation on Soot, No_x, and Efficiency

The measured hydrogen, lower heating values for diesel, and mass flow rates of the fuels were used to compute the hydrogen energy ratio. The result is shown in the following equation[41].

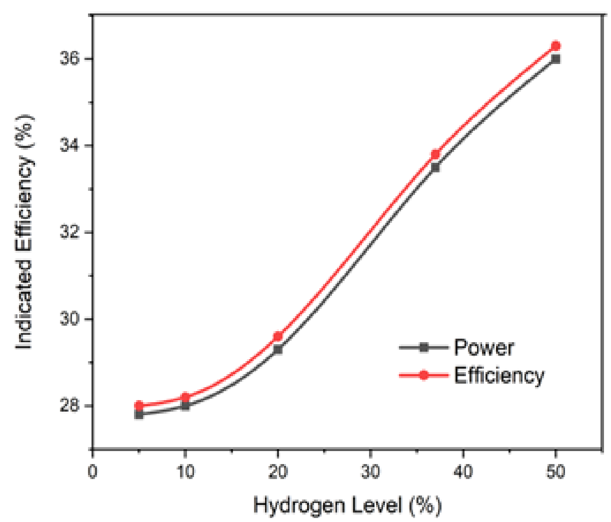

Figure 6. Engine power and efficiency with 0% EGR and 10 CABTDC injection timing as a function of hydrogen level.

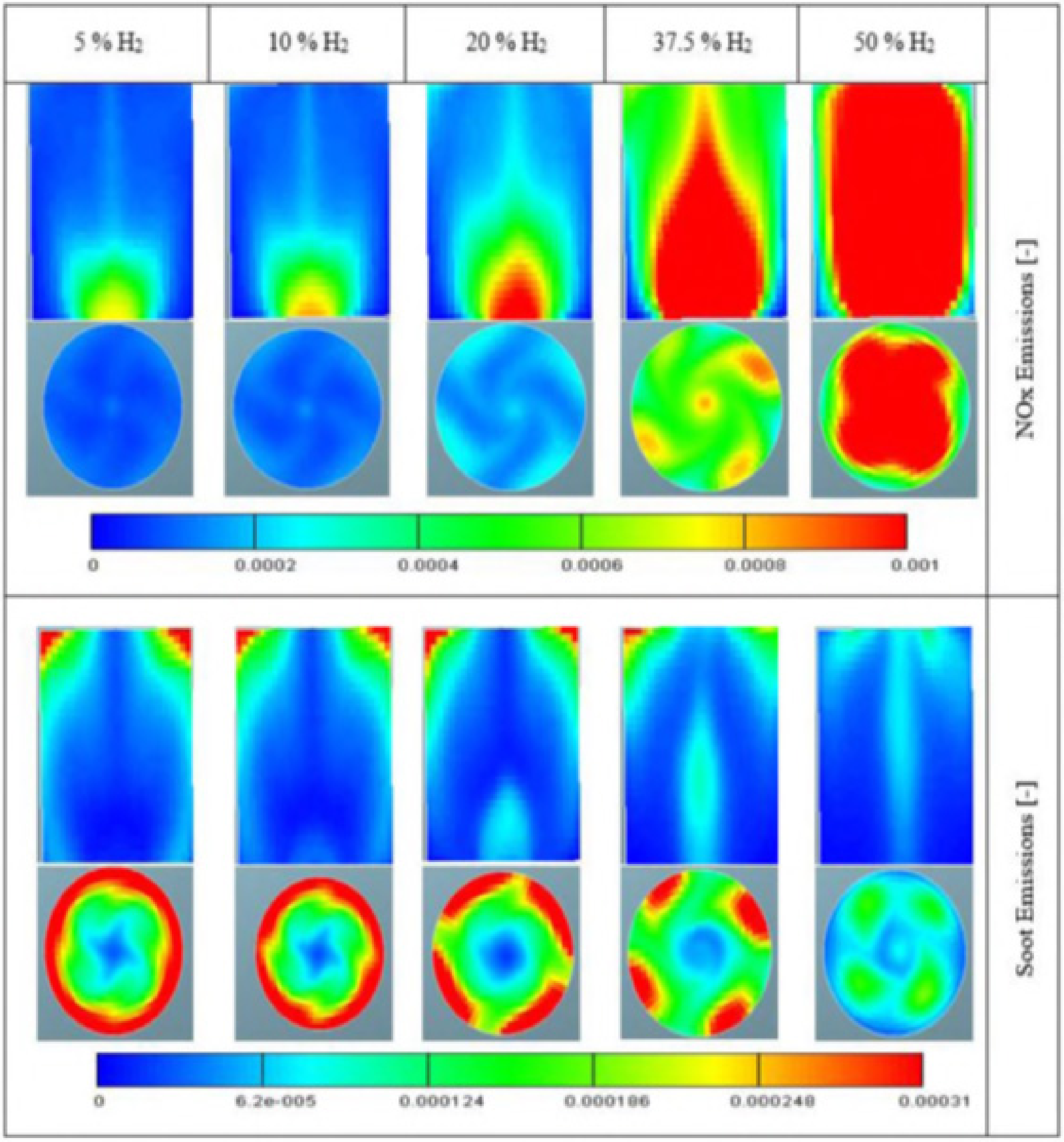

Figure 7. Effect of hydrogen concentration on soot and NOx emissions inside the engine cylinder at 0% EGR and 10 CA BTDC injection timing.

$$100\,X(H2) = \frac{\dot{m}(H2) * LHV(H2)}{\dot{m}(D) * LHV(D) + \dot{m}(H2) * LHV(H2)}$$

Where, X(H2) **:** is the hydrogen energy ratio [%]
M(H2) : is the mass flow rate of hydrogen [kg/s]
LHV(H2) : is the lower heating value of hydrogen [kJ/kg]
M(D) : is the mass flow rate of diesel [kg/s]
LHV(D) : is the lower heating value of diesel [kJ/kg]

Figures 6 and 7 illustrate the relationship between hydrogen and NOx emissions, soot emissions, and efficiency, respectively. EGR level and diesel injection timing were both maintained at 10 CA BTDC and 0%, respectively. Figure 6 illustrates how hydrogen rates affect the levels of NOx and soot in the cylinder. It was discovered that NOx formation increased by about 33.1% when the hydrogen ratio was raised to 50 from a 5% hydrogen ratio.

The primary mechanism of NO formation, high incylinder temperature, is to blame for this. When more hydrogen is injected into the engine cylinder, as opposed to a minimum hydrogen ratio, the soot concentration falls by 58% at 51% hydrogen.

Figure 7 shows how hydrogen levels affect a CI engine's power and efficiency. The pressure inside the cylinder increased along with the amount of hydrogen, improving engine efficiency and performance.

5.2 Hydrogen Variation's Impact on Ignition

The interval of time between injecting fuel into the cylinder and the beginning of combustion is known as the ignition delay4. During the ignition delay phase, physical and chemical delays occur simultaneously. The fuel's properties and chemical makeup are what cause the physical time delays. The reactions of petrol in the cylinder cause the chemical delay period, but these reactions are also influenced by the fuel's properties, cylinder pressure, and temperature[39].

The time between the start of compression and the breakdown of the H_2O_2 molecules connected to the increased concentration of active radical OH that raises pressure is known as the chemical delay period[40]. The active radical OH is shown to form as the H_2O_2 species start to dissociate, increasing pressure inside the cylinder in Figure 8a.

Figure 8a shows how the mass fraction of H_2O_2 changes with altered ratios of hydrogen. Figure 8b shows how boosting the diesel engine's hydrogen content stopped H_2O_2 from forming or breaking down too soon. This delayed the timing of ignition by lengthening the time it took for the active radical OH to form.

5.3 The Effect of Exhaust Gas Recycling on Engine Outputs

This section examines the relationship between engine efficiency and EGR and emissions of NOx and soot. The impact of EGR modifications on engine emissions is shown in Figure 9. Both the diesel Injection Timing (IT) and the hydrogen level were set to 50% and 10 CA BTDC, respectively. The graph shows how effectively EGR reduces NOx emissions. NOx emissions were reduced by approximately 44%, 74%, and 88% when 5%, 10%, and 15% EGR were used, respectively, when compared to no EGR. A lower combustion temperature is the primary cause of the decrease in NOx emissions, which is one of the most important NOx formation pathways.

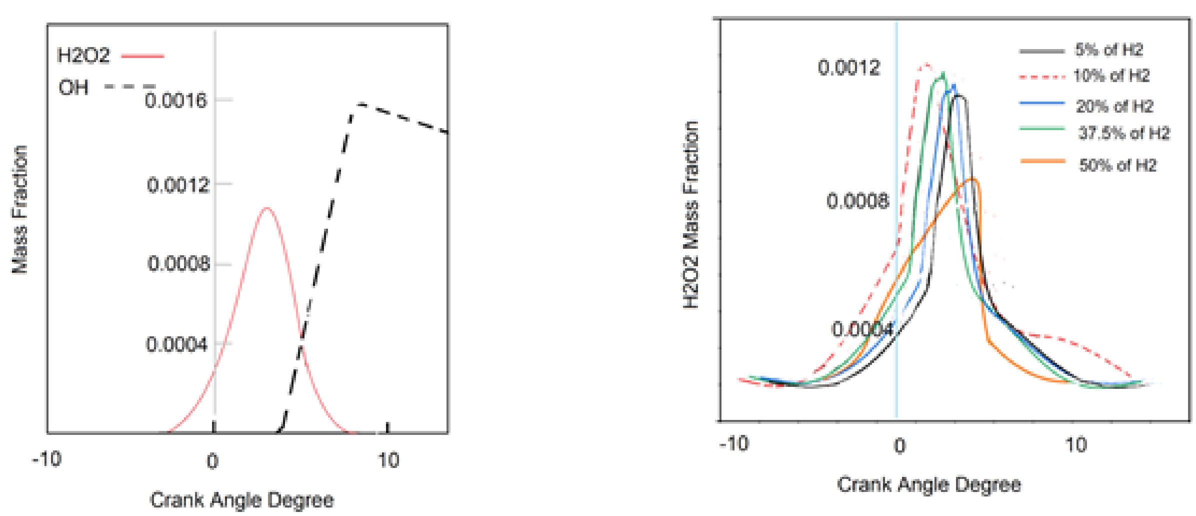

Figure 8. Variation in species mass fraction as a function of crank angle.

Additionally, it was discovered that as EGR increased, less fuel and air were present in the engine cylinder, which slowed soot oxidation and boosted soot formation. Increased EGR level was found to slightly reduce efficiency, as shown in Figure 10[37]. Engine power and efficiency were reduced as a result of the increased EGR level's effect on the air/fuel volume and speed of the hydrogen flame inside the engine.

5.4 Timing of Diesel Injection with its Impact on Efficiency, Soot, and No_x

The efficiency and emissions of hydrogen/diesel engines are significantly impacted by the diesel injection timing parameter, as shown in Figures 11 and 12. For these calculations, the EGR level was set to 0% and the hydrogen level to 50%. Advanced diesel injection timing

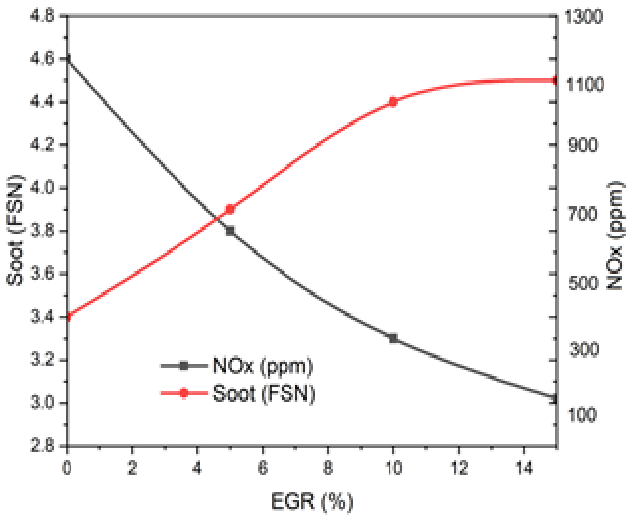

Figure 9. Soot and NOx emissions vary with EGR level of 50.5%hydrogen and 10 CA BTDC injection timing.

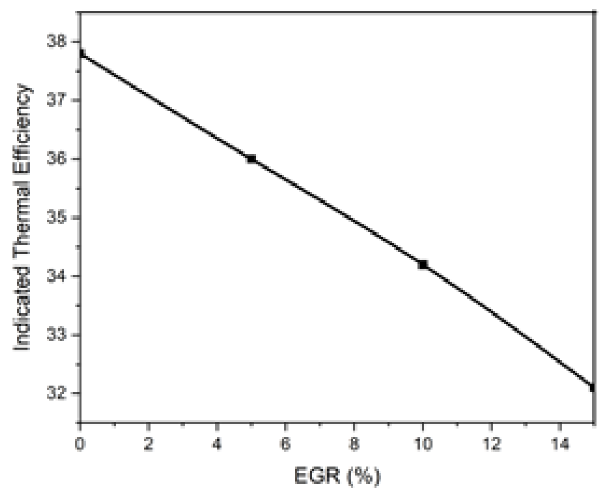

Figure 11. At 50.5% hydrogen and 0% EGR, the effect of injection timing on engine efficiency is studied.

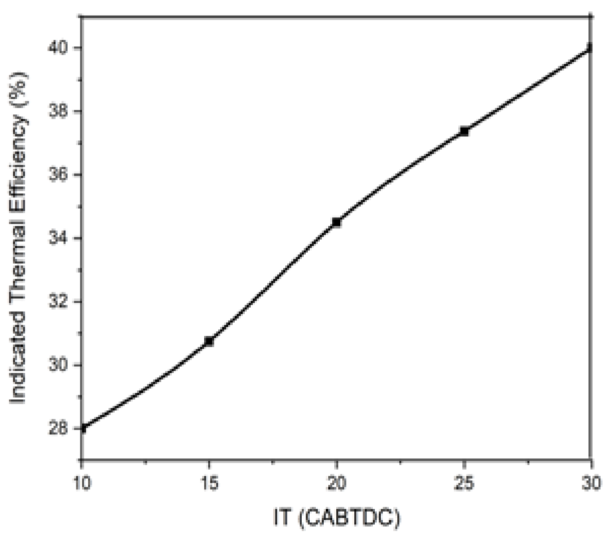

Figure 10. At 50.5% hydrogen and 10 CA BTDC injection timing, the effect of EGR on engine efficiency is examined.

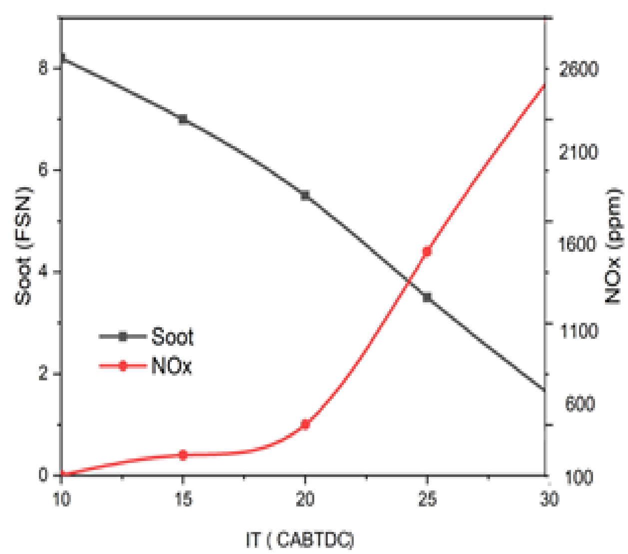

Figure 12. At 50.5% hydrogen and 0% EGR, the effect of injection timing on NOx and soot emissions was studied.

significantly increased engine efficiency, as shown in Figure 11. An increase in NOx emissions is shown in Figure 12. Due to the diesel injecting inside the cylinder earlier, the combustion occurs earlier, allowing for sufficient time for it to be completed. Consequently, the internal pressure and temperature of the cylinder increase, leading to a decrease in output power and efficiency. But there's also an increase in NOx emissions. Because most of the soot produced during the first stage of combustion is eventually exhausted by an oxidation when enough time passes, Figure 12 illustrates how the soot emissions decreased with advanced injection timing.

6.0 Summary and Conclusions

In the current study, the impact of operating parameters on the production and outflow of a CI dual-fuel engine using mixes was taken into account. The relationships between operating variables (hydrogen fluctuations, EGR, and injection timing) and efficiency, soot, NOx emissions, have been well studied. This study's findings, which were produced using sophisticated CFD software, were in strong agreement with the experimental data. The impact of theoperating circumstances under consideration on engine performance and emissions is summarized as:

- As hydrogen was injected into the chember, soot emissions were reduced by about 60% by using carbon/free hydrogen fuel instead of hydrocarbon diesel fuel. It was discovered that using hydrogen led to increases in NOx emissions and efficiency of 32.8% and 24.5%, respectively, owing to the high temperature of combustion and increase in cylinder pressure, respectively.
- Another notable factor in diesel engines, ignition timing, were examined for a range of hydrogen concentrations.
- It was found that the ignition timing shifted later as the hydrogen level increased because the active radical OH formed later.
- When compared to a scenario with no EGR, the drop in in/cylinder temperature reduced NOx emissions by 88% while increasing EGR level to 15%. However, as the EGR level rose, so did the soot emission.
- The amount of soot emitted was reduced with advanced injection timing because the majority of the soot created during the first stage of combustion was oxidised in time.

The timing of the diesel injection was advanced, which accelerated reactions and raised in-cylinder temperature, increase-ng NOx emission.

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