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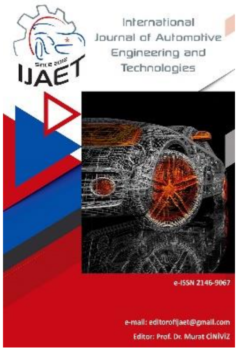

Original Research Article

The hydrogen injection strategy's influence on the performance and emissions (exhaust, vibration, and noise) of a dual-fuel engine

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ABSTRACT

The new trend in the search for alternative fuels for compression ignition engines is the hydrogen-diesel dual fuel (HDDF) mode. In order for dual fuel mode to provide maximum benefit in compression ignition engines, ECU-controlled fuel systems should be used, and their settings should be optimized. In this study, the effects of hydrogen energy ratio and hydrogen injection timing on engine performance, exhaust, noise, and mechanical vibration emissions in an ECU-controlled HDDF system compression ignition engine were investigated. The experiments were carried out at constant speed (1850 rpm), constant load (5 Nm), different hydrogen ratios (11, 14, 17, 20%), and different hydrogen injection timings (20, 30, 40, 50, and 60 °CA aTDC). The specific energy consumption decreased by 8.4%, NOx emissions decreased by 68.4%, and mechanical vibrations increased by 16.6% at a 14% hydrogen energy ratio and a 30°CA aTDC hydrogen injection timing. The main objective of the study is to determine the optimum hydrogen energy ratio and hydrogen injection timing in a compression ignition engine using HDDF.

Keywords: H_2-diesel dual fuel engine; H_2 ration; H_2 injection timing; Engine performance; Emission (exhaust, noise, and mechanical vibration)

1. Introduction

The transportation sector around the world is growing rapidly. This growth increases the demand for fuel and leads to rising fuel prices. Additionally, the emission standards implemented by countries have raised questions about the future of internal combustion (IC) engines. Consequently, several nations have implemented prohibitions on the commercialization of automobiles equipped with compression ignition (CI) engines that rely on diesel fuel. Manufacturers and researchers have turned to alternative energy sources to overcome these problems [1, 2]. Electric vehicles are at the forefront of vehicles using alternative energy. However, it will take some time for these vehicles to become widespread due to charging time, battery life, and infrastructure problems [3]. Because of these things, it is a given that IC motors, which have been used by people for the past 150 years, will continue to be the most common type for a long time [4-6]. Therefore, studies to develop IC motors continue at a great pace [7-9].

CI engines used in most of today's vehicles have many advantages over their equivalent spark ignition engines [10]. Almost all of the engines used, especially in freight road vehicles, railway vehicles, and ships, are CI engines. The primary reason for this is because these motors have excellent torque and thermal efficiency [11, 12]. However, the pressure on these engines due to emissions has increased in recent years. As a result of printing, some automobile companies stopped the production of vehicles using CI engines [13]. To solve this problem, it is possible to use different fuel mixtures in diesel engines. Biodiesel in particular has been around for a long time. At the same time, the use of bio-based alcohols is an ideal way to reduce emissions [12]. In recent years, along with the use of biofuel-diesel, studies on the combined use of liquid and gaseous fuels have accelerated [14]. Hydrogen fuel is an ideal fuel for this. The use of H_2 with diesel fuel will contribute to these engines meeting emission standards. Studies on the dual fuel mode for H_2-diesel indicate that due to H_2's lack of carbon atoms, it can reduce carbon dioxide, carbon monoxide, particulate matter, and hydrocarbon (CO_2, CO, PM, and HC) emissions [15-17]. At the same time, it is also possible to improve engine efficiency [18, 19]. Furthermore, it is anticipated that H_2 may be derived from sustainable energy sources such as wind, wave, solar, and biomass, hence diminishing reliance on conventional oil-based fuels [20-22]. Akçay et al. [23] conducted experiments on a common rail diesel injection (CRDI) engine. Researchers discovered a correlation between the increase in H_2 rate and engine load and the decrease in CO_2 emissions. Many studies have found that this is due to the fact that the fuel used in the burning chamber has less carbon in it. [24-26]. Koten [27], looked at the emissions in dual-fuel mode and how adding H_2 at different loads affected the emissions. According to the study's results, CO, HC, and PM pollution all went down by a lot, no matter how much the load there was.

Many researchers have examined how HDDF mode affects exhaust pollutants. However, today, studies on mechanical vibration and noise emissions, which have proven to have many negative effects on humans, nature, and engines, are limited [28, 29]. Nag, Dhar [30] discovered that adding H_2 to the HDDF mode decreased mechanical vibration and noise at low loads while increasing it at high loads. In a similar study, Nag, Sharma [31] conducted tests with H_2 energy ratios (HER) of 5%, 10%, and 20% utilizing the dual fuel method. They witnessed an increase in the HER at low loads reduced mechanical vibration and noise emissions, while it increased them at high loads. Barelli, Bidini [32], who examined the relationship of in-cylinder pressure with mechanical vibration and noise, determined that these emissions were related to in-cylinder pressure.

In the HDDF mode, the fuel energy ratio is critical. This is mostly due to the fact that the energy ratio is the critical factor impacting emissions and engine performance. The small molecular structure of H_2 causes its volume per unit mass to be higher [33, 34]. Because of this circumstance, the H_2 that is supplied to the cylinder takes up more space and blocks the entry of air. Akçay at al. [18] investigated the biodiesel-H_2 mixture in a CRDI engine. The study discovered that increasing the H_2 ratio increased the maximum cylinder pressure. However, in this study, the H_2 ratio was limited to a certain level. In another similar study, Yılmaz and Gümüş [35] looked at how adding H_2 to the intake air affected CI engine combustion performance. According to the study, the in-cylinder pressure increased as the volume of H_2 in the cylinder increased. In a similar study, Sharma and Dhar [36] altered the HER in dual fuel mode to 5, 10, and 20% and fed it into the intake manifold. At all engine conditions, the addition of H_2 was found to reduce the thermal efficiency (BTE) and increase the in-cylinder pressure. Whereas in another research variable H_2 ratios were studied experimentally; Qin et al. [37] found that raising the amount of H_2 energy to 20% raised the highest pressure in the cylinder by about 8%. The study also discovered that the rate of heat (HRR) increases and appears at earlier points. In another study where different HER were tested, Koten [27] revealed that augmenting the levels of H_2 and engine load led to a notable enhancement in thermal efficiency, while simultaneously causing a reduction in specific fuel consumption. The fact that the HER can't be raised to high levels is the most important problem with the dual fuel system. This causes a reduction in volumetric efficacy and a deterioration of combustion. In their research, Morais et al. and Geo et al. [25, 38], found that increasing the HER and engine load had a detrimental effect on volumetric efficiency. The H_2 that is packed in the cylinder stops air from being drawn into it, which is why volumetric efficiency has decreased, according to researchers [39].

As significant as the impact of fuel energy ratios on engine output and emissions is how the H_2 is supplied to the cylinder in the HDDF mode. Especially with the high diffusion rate of H_2, the injection timing time is important. In engines with port injection, the timing of H_2 injection should be adjusted, taking into consideration the timings at which the intake valves and the exhaust valves open. Otherwise, the H_2 will ignite with the exhaust gases and cause blowback. Studies on the H_2 injection strategy are limited. Focusing on this issue, Saravanan, Nagarajan [40], investigated the injection approach utilized by a single-cylinder CI engine when operating in HDDF mode. In addition, diethyl ether was utilized in this investigation as a source of ignition. The researchers determined the optimum timing for H_2 injection to be 5° CA bTDC of the gas exchange and 40° CA aTDC for diethyl ether injection. The same researchers, in another study, in their experimental study to optimize H_2 injection in HDDF mode, stated that the optimum timing of port injection is 30° CA aTDC and the injection should be during gas exchange [41].

When research is assessed in aggregate, it is shown that the HER in HDDF mode as well as the injection methods of H_2 fuel have an influence on the overall performance of the engine as well as the pollutants it produces [31, 42, 43]. As a result, the ratio of hydrogen to diesel fuel and the time of hydrogen injection were the primary focuses of this research. Another important point study's conclusion is that the H_2 and diesel fuel systems are ECU-controlled and programmable. In this respect, it has a different importance from other studies.

In the course of this investigation, using a CI engine with a single cylinder, constant speed (1850 rpm), constant load (5 Nm), different H_2 injection ration (11, 14, 17, 20%), and different H_2 injection timing (20, 30, 40, 50, and 60 °CA aTDC) were performed. Engine performance, exhaust, mechanical vibration, and noise emissions were investigated as a consequence of the studies, and the optimal HER and optimum H_2 injection timing was identified. The primary objective of the research is to develop a suitable replacement for CI engines, which are banned in many countries and whose production has been stopped by companies. With just a few tweaks (H_2 fuel system), these motors can run on both diesel and hydrogen. Thus, performance and emissions can be improved, and usage can be continued.

2. Instrumentation and Methodology

The system set up to the schematic view of the experimental engine test setup is shown in Fig. 1. In the system, there is an ANTOR AD320 model single-cylinder CI engine with an ECU-controlled dual fuel system. To load the engine, an ABB brand active dynamometer is used, and an AVL brand pressure measurement system is employed to measure in-cylinder pressure. For measuring emission values, Bosch BEA 60-70 emission devices are used. To measure mechanical vibrations, a PCE-VD 3 brand vibration device is utilized, and for noise measurements, a Geratech DT 8820 model noise measuring device is used. Additionally, there is a fuel measuring system available for precise fuel measurements. MOTEC ECUs are used in the control of diesel fuel systems, whilst Spark EMS ECU are put to use in the management of hydrogen fuel systems. Thanks to the interface of this system on the computer, the open time of the hydrogen injector and the injection timing can be changed. In this way, different amounts of hydrogen can be sent to the cylinder at any time.

Diesel fuel has been used with the CRDI fuel system. Thanks to the ECU and the interface loaded onto the computer in the system, various parameters such as fuel pressure, fuel timing, and pre-injection can be adjusted instantly. The H_2 injector is placed behind the intake port, enabling the implementation of a port injection system. In addition, the hydrogen consumption data was recorded using a flowmeter from Sierra Instruments that

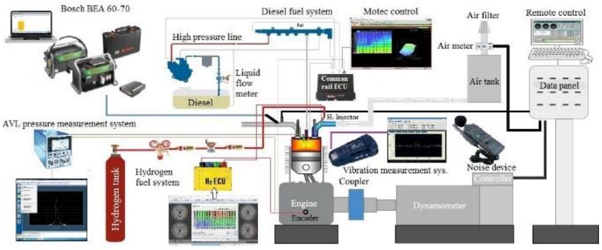


Fig. 1. Schematic view of experimental engine test setup.

was installed in the hydrogen fuel system. In the experiments, changes in cylinder pressure were measured to assess the combustion in the cylinder. In order to get the necessary data, a pressure sensor is used alongside an amplifier that effectively filters the voltage produced by the sensor, converting it into a discernible pressure signal. Additionally, an encoder is utilized to detect fluctuations in cylinder pressure resulting from changes in crank angle. Throughout the experimental procedure, data points were meticulously documented for every 0.1 °CA increment of the crankshaft's rotational position. The average of 180 cycles was utilized to generate in-cylinder pressure readings.

2.1. Test fuels and methodology

In Table 1 we can see the chemical and physical characteristics of the H_2 and diesel fuel that was used in the tests. Diesel fuel meets the requirements of TS EN 590:2013+A1:2017. At 200 bar pressure, H_2 fuel was kept in high purity tubes (99.9995%).

Table 1 - Diesel and H_2 fuel physical and chemical properties [44].

Property	**Unit**	**H_2**	**Diesel**
Formula		H_2	$C_nH_{1,8n}$ $C_8 - C_{20}$
Ignition temperature	K	858	530
Minimum Ignition Energy	MJ	0.02	–
Ignition limits (% by volume)		4 – 75	0.7 – 5
Stoichiometric H/Y ratio (Mass)		34.3	14.5
Ignition limits (equity ratio)		0.1 – 71	
Net Calorific Value	MJ/kg	119.93	42.5
Density (at 15°C and 1.01 bar)	kg/m³	0.0838	832
Flame speed	cm/s	269 – 325	30
Diffusion in Air	cm²/s	0.63	–
Octane Number		130	30
Cetane Number		–	53.9

First, experiments with standard diesel were conducted in the study, and data were collected. The HER is calculated using the fuel consumption data from these tests. The H_2 electronic control unit (ECU) was used to adjust the injection duration and timing, while a flow meter measured the amount of H_2 utilized. The observed values and equations (1)-(3) were utilized in the computation of HERs [26, 35].

$$ES_H = E_H/(E_H + E_D) \tag{1}$$

$$E_H = LHV_H.\dot{m}_H \tag{2}$$

$$E_D = LHV_D.\dot{m}_D \tag{3}$$

In the formulae, LHV_H represents H_2's lower calorific value, and LHV_D represents diesel fuel's lower calorific value (MJ/kg). $\dot{m}_H$ and $\dot{m}_D$ signify H_2 and diesel mass fluxes (kg/h). The total energy acquired from H_2 (E_H) and diesel (E_D) the initial measurement was adjusted to match the energy content of normal diesel fuel. The observed values and equations (1)-(3) were utilized in the computation of HERs formed by calculations are 11%, 14%, 17% and 20%.

Eq. (4) was used to calculate the motor's thermal efficiency. BP denotes braking power (kW) in the equation.

$$BTE = BP/(E_H + E_D) \tag{4}$$

2.2. Experimental procedure

Following the necessary changes and calibrations, the test engine was then linked to the engine test center, as seen in Fig. 2. Before commencing the trials, preparatory tests were undertaken to ensure that the engine was brought to suitable operating conditions. The trials were performed three times to limit the margin of error in the data, and the averages of the values were recorded. Table 2 exhibits the technical specifications of the modified engine and the test parameters.

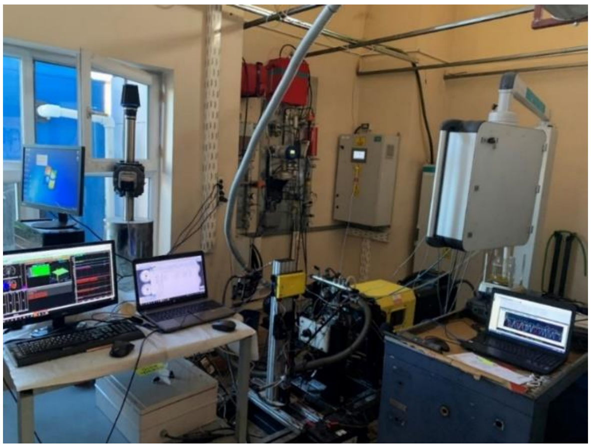
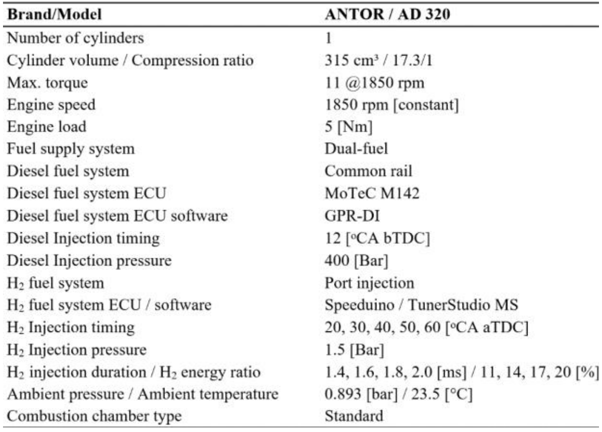


Fig. 2. The manner in which all systems attach to the engine test system.

Table 2- Characteristics of the engine and test

parameters.



Brand/Model	ANTOR / AD 320
Number of cylinders	1
Cylinder volume / Compression ratio	315 cm³ / 17.3/1
Max. torque	11 @1850 rpm
Engine speed	1850 rpm [constant]
Engine load	5 [Nm]
Fuel supply system	Dual-fuel
Diesel fuel system	Common rail
Diesel fuel system ECU	MoTeC M142
Diesel fuel system ECU software	GPR-DI
Diesel Injection timing	12 [°CA bTDC]
Diesel Injection pressure	400 [Bar]
H_2 fuel system	Port injection
H_2 fuel system ECU / software	Speeduino / TunerStudio MS
H_2 Injection timing	20, 30, 40, 50, 60 [°CA aTDC]
H_2 Injection pressure	1.5 [Bar]
H_2 injection duration / H_2 energy ratio	1.4, 1.6, 1.8, 2.0 [ms] / 11, 14, 17, 20 [%]
Ambient pressure / Ambient temperature	0.893 [bar] / 23.5 [°C]
Combustion chamber type	Standard

While selecting the test parameters, the operating conditions of the engine in the market, the results obtained from the preliminary tests, and the literature analysis were taken into consideration. 1850 rpm is the speed at which the maximum torque of the engine occurs. 5N load is the half-load condition where the engine is operated for a long time in operating conditions. The hydrogen energy ratio was determined as a result of the literature study. The hydrogen injection timing was determined according to the valve adjustment diagram of the engine.

3. Results and discussions

3.1. Volumetric efficiency

The decrease in volumetric efficiency in H_2-diesel dual-fuel engines is an important problem. Increasing the H_2 ratio reduces volumetric efficiency and has a negative impact on engine performance. The main reason for this problem is that H_2 occupies too much room in the cylinder [45-48]. The impact of the observed values and equations (1)-(3) were utilized in the computation of HER and timing of the H_2 injection on volumetric efficiency is shown in Fig. 3.

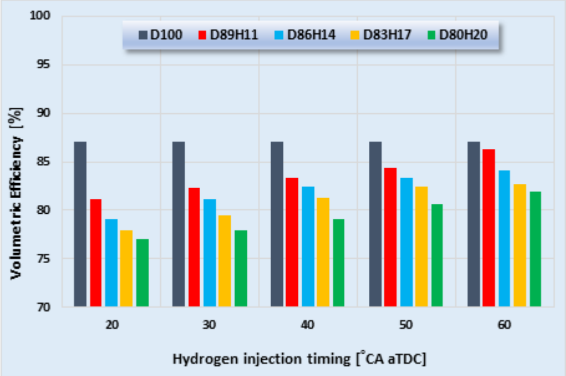


Fig. 3. Volumetric efficiency resulting from H_2 energy rate and injection timing.

A drop in volumetric efficiency was the result, as can be shown in Fig. 3, of a rise in the HER. The drop in volumetric efficiency, on the other hand, was mitigated by postponing the beginning of the H_2 injection. The main reason for this situation is that H_2 injection occurs close to the closing of the intake valve. Delaying the hydrogen injection ensures that there is enough time for most of the air to be taken into the cylinder [6, 49, 50].

3.2. Break thermal efficiency (BTE)

The thermal efficiency of a system is a significant measure of how effectively fuel is utilized, therefore it is desirable to have greater thermal efficiency. Fig. 4 shows how HER and injection timing affect thermal efficiency.

As can be clearly seen in Fig 4, a rise in the energy of H_2 ratio up to 14% caused an increase in BTE. In 17% and 20%, the rate of increase in BTE decreased. However, in experiments where the H_2 injection initiation was at 30 °CA aTDC, it was determined that the maximum rate of increase in BTE was achieved. At the same time, increasing the hydrogen energy rate prevents air from entering the cylinder by occupying too much space in the cylinder. This worsens combustion and causes the BTE to decrease.

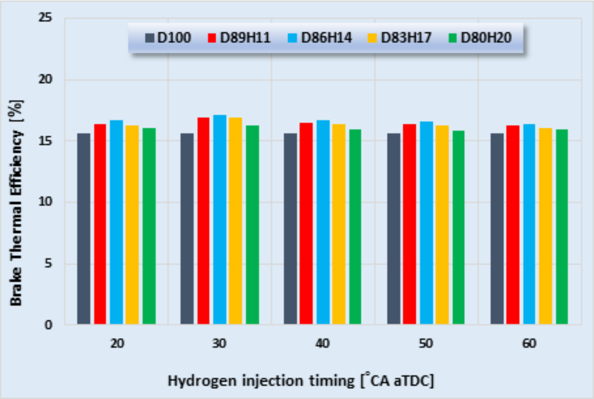


Fig. 4. BTE resulting from H_2 energy rate and injection timing.

3.3. Brake specific energy consumption (BSEC)

BSEC refers to the quantity of energy consumed per unit of output by an internal combustion engine. The aforementioned data source holds significant importance in the realm of fuel efficiency [51]. Fig. 5 shows the HER and the effect of H_2 injection initiation on BSEC.

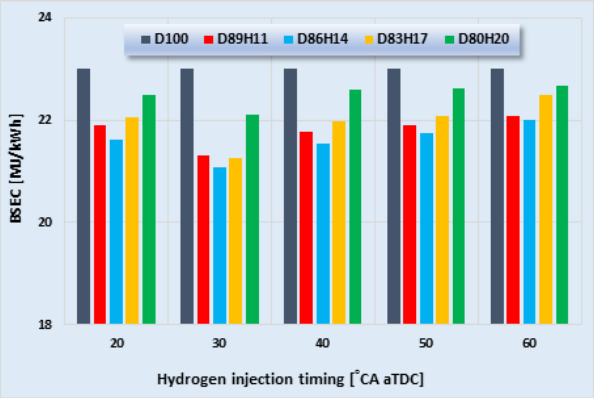


Fig. 5. BSEC resulting from H_2 energy rate and injection timing.

When Fig. 5 is evaluated, an increase in HER up to 14% has led to a decrease in BSEC. At 17% and 20% HER, the effect of H_2 on BSEC decreased. Additionally, in experiments where the H_2 injection initiation was at 30 °CA aTDC, it was determined that the BSEC decreased at the maximum rate. Elevating the HER to elevated levels has a detrimental impact on the BSEC. Volumetric efficiency is declining, and combustion is getting poorer, which is the major cause of this problem [25, 38, 52-54].

3.4. Peak cylinder pressure and heat release rate (HRR)

Fig. 6 shows how the amount of H_2 energy and the timing of H_2 injection affect the pressure inside the cylinder and the rate at which heat is released.

The rise in HER to as high as 14% has resulted in an increase in both the maximum pressure and the HRR of the cylinder. The maximum pressure within the cylinder rose by 9% in the experiment when the HER was 14% and the H_2 injection timing was 30 °CA aTDC. However, raising the H_2 ratio over 17% resulted in a slower rise in HRR and cylinder pressure. These results can be attributed to the insufficient air supply caused by injecting more H_2 into the cylinder. Inadequate air causes a drop in in-cylinder pressure and HRR. These findings are congruent with those of previous research published in the literature [4, 38, 45, 48, 55]. By advancing the timing of the H_2 injection, the maximum cylinder pressure as well as the maximum HRR were moved closer to the top dead center position. As a result, the maximum pressure created increased as well. The primary cause of this condition is that H_2 injection is made during air intake and a more homogeneous mixture is provided.

3.5. Exhaust emissions

Reducing the carbon atom in the fuel is an ideal method to decrease carbon-based emissions. However, increasing the H_2 concentration to high levels reduces the amount of oxygen entering the cylinder and worsens combustion. Fig. 7 demonstrates the impact of HER and H_2 injection timing on CO emissions.

The increase in the HER has reduced CO emissions. Adjusting the start of H_2 injection to 30 °CA aTDC and the HER to 17% resulted in a 53% reduction in CO emissions. The reduction in the fuel's carbon content is the primary cause of the drop in CO emissions.

By joining the combustion process, the HC emissions that come out of the exhaust without being burned tell us about the quality of the combustion. The increase in these emissions worsens the fuel economy as well as environmental pollution [56, 57]. Fig. 8 shows what happens to HC emissions when the ratio of H_2 energy and the start of H_2 input is changed.

Fig. 8 shows that increasing the HER resulted in a considerable drop in HC emissions. When the hydrogen injection timing was evaluated, increasing the time prevented the increase in HC emissions to some extent.

The NO emissions induced by high cylinder temperatures rise in tandem with the improvement in combustion quality [58-60]. The influence of HER and H_2 injection commencement on NO emissions is seen in Fig. 9. As can be seen in Fig. 9, the addition of H_2 resulted in an increase in the amount of NO emissions. Nevertheless, bringing the HER up to 20% mitigated the impact of the rise in NO emissions. The primary cause of this condition is that the high H_2 ratio decreases volumetric efficiency and worsens combustion. The maximum rate of increase in NO emissions was determined when the H_2 injection was set at 30 °CA aTDC.

Petroleum-derived fuels consist of H_2 and carbon.

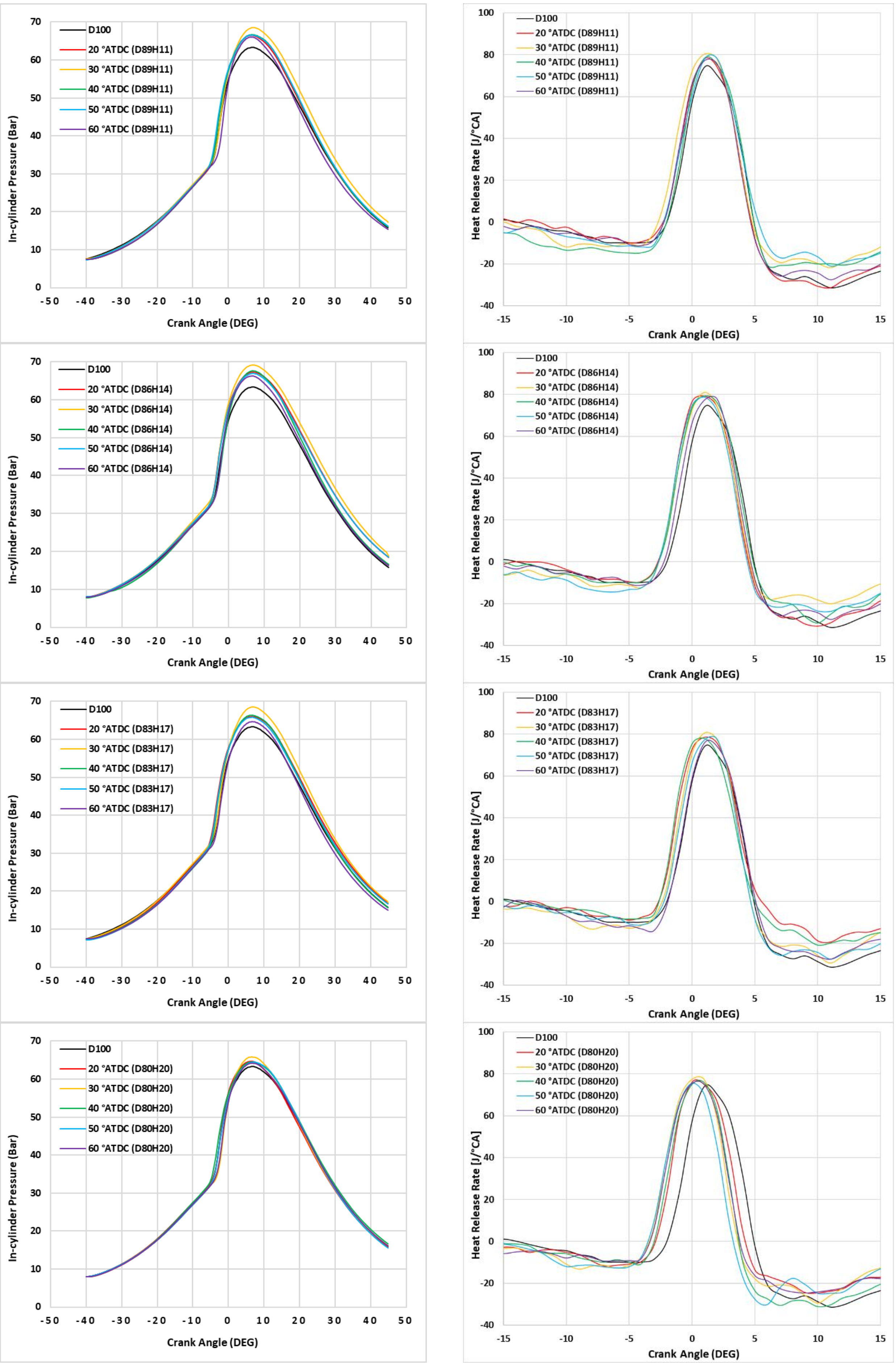


Fig. 6. Cylinder pressure and HRR resulting from H_2 energy rate and injection timing.

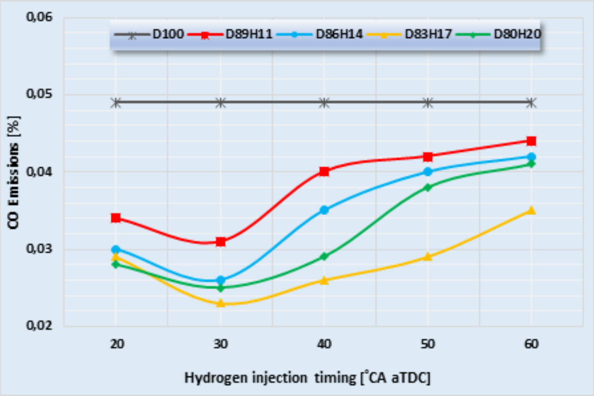


Fig. 7. CO emissions resulting from H_2 energy rate and injection timing.

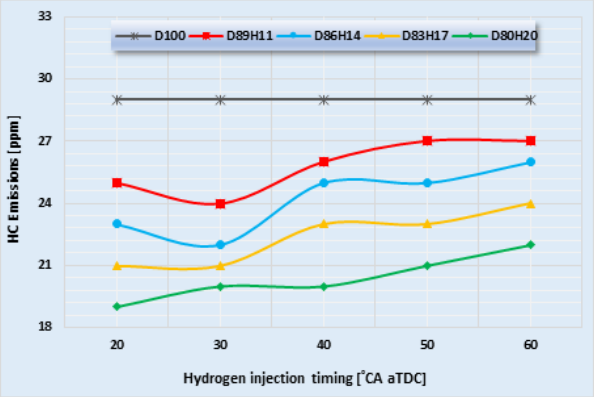


Fig. 8. HC emissions resulting from H_2 energy rate and injection timing.

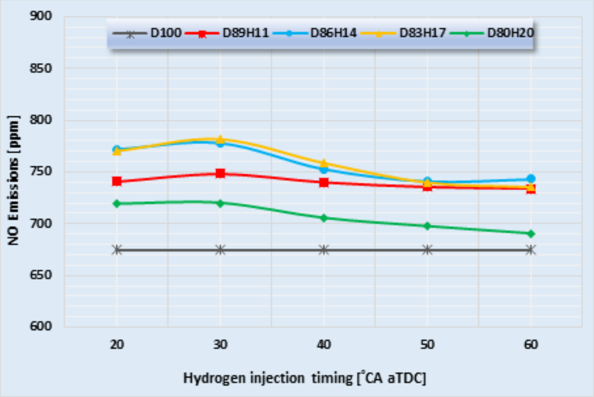


Fig. 9. NO emissions resulting from H_2 energy rate and injection timing.

The rapid combustion of H_2 with a high burning rate causes the carbon atoms to be deprived of oxygen, resulting in smoke [26, 61, 62]. Fig. 10 demonstrates how the ratio of H_2 energy and the timing of the start of H_2 injection impact smoke output.

The effectiveness of the HDDF mode in lowering smoke emissions may be noticed when Fig. 10 is reviewed. It was discovered that when the HER increased, the smoke emissions dropped. It was found that when H_2 injection was set at 30 °CA aTDC, the maximum reduction rate in smoke emissions was achieved.

Noise is undesirable in CI engines. The noise levels of these engines are quite high due to their high compression ratio [63]. Fig. 11 illustrates the impact of the HER and the timing of H_2 injection on noise emissions.

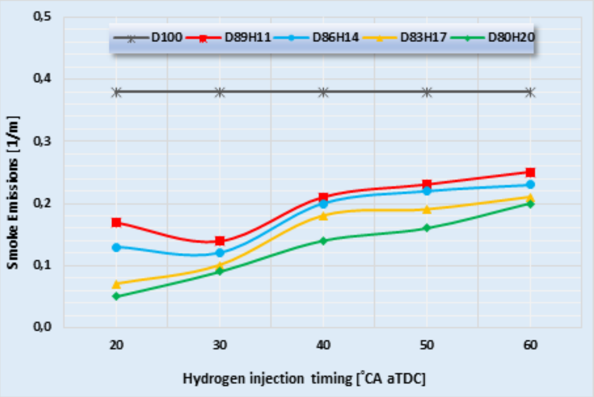


Fig. 10. Smoke emissions resulting from H_2 energy rate and injection timing.

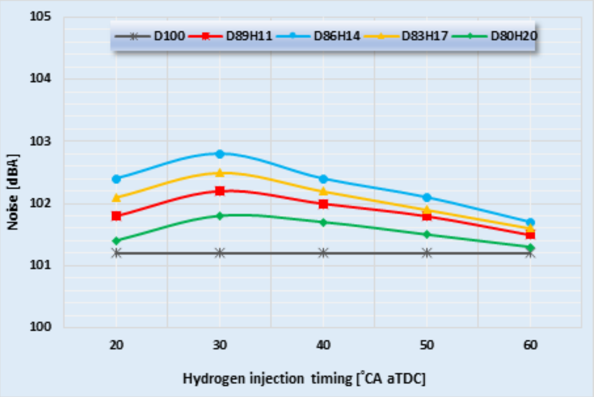


Fig. 11. Noise emissions resulting from H_2 energy rate and injection timing.

The introduction of H_2 resulted in an increase in the engine's noise levels. The reason for this situation can be shown by the increase in cylinder pressure [64]. The increments in the table are given in dBA. The highest increase was observed at 14% H_2 ratio and 30 °CA aTDC H_2 injection. In these test parameters, a 1.6 dBA increase in noise emissions was detected compared to D100 fuel.

The pressure created by the combustion in the engine causes vibration. The presence of a single-cylinder configuration in the test engine results in elevated levels of mechanical vibrations. Fig. 12 illustrates the impact of the HER and the timing of H_2 injection on mechanical vibrations.

With the addition of H_2, an increase in mechanical vibrations in the engine was seen. The most significant increase rate was obtained when the H_2 ratio was set at 14% and the hydrogen injection timing at 30 °CA aTDC. In these test parameters, a 16.6% increase in mechanical vibrations was detected compared to D100 fuel. The in-cylinder pressure levels are the primary cause of these outcomes.

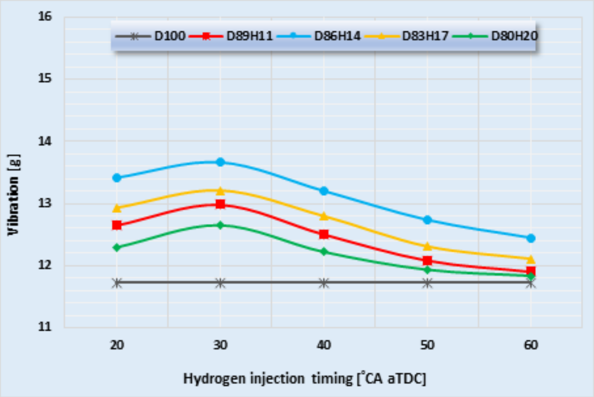


Fig. 12- Mechanical vibrations resulting from H_2 energy rate and injection timing.

4. Conclusions and recommendations

The following basic conclusions may be drawn from this study's investigation of the effects of HER and H_2 injection time on engine performance, exhaust, noise, and mechanical vibration emissions in an ECU-controlled HDDF system CI engine:

- HDDF mode reduces volumetric efficiency. Delaying the start of H_2 injection prevents this decrease to a certain extent.
- The thermal efficiency rose to 9.6% when the HER was adjusted to 14%. The amount of gain in thermal efficiency was reduced when the energy ratio was raised. Maximum thermal efficiencies were determined in experiments where the injection timing was 30 °CA aTDC.
- The dual fuel mode has positively affected BSEC. A decrease of 8.4% in BSEC was observed at a 14% H_2 ratio and an injection timing of 30 °CA aTDC.
- HRR and in-cylinder pressure have risen due to the usage of H_2. This increase is observed to be more effective up to a H_2 ratio of 14%. Because of the rise in H_2 ratio and the advancement of injection timing, in-cylinder pressure has increased and the maximum cylinder pressure point has approached TDC.
- It has been discovered that using H_2 may significantly lower emissions made up of carbon, such as CO, HC, and smoke. It has, however, increased noise, mechanical vibration, and NO emissions.
- It has been determined that the optimum H_2 injection timing for carbon-based emissions is 30 °CA aTDC.
- In the experiments, it was determined that bringing the H_2 injection timing to the open time of the exhaust valve causes kickback and jeopardizes combustion safety.
- The fact that the dual fuel system is ECU-controlled and can be programmed instantly contributed to obtaining high-quality test data and ensuring operational safety.
- In future studies, studies on engine modifications in HDDF mode will be beneficial.
- It is known that liquid and gas fuel pressures affect engine performance and emissions in the hydrogen-diesel dual fuel mode. Studies in this direction will contribute to the more efficient operation of dual fuel mode.

The operation of the gas fuel system with direct injection will help reduce the negative effect of hydrogen usage on volumetric efficiency.

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