Thermal efficiency and emission characteristics of a diesel-hydrogen dual fuel CI engine at various loads condition

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Abstract

Efforts to find alternative fuels and reduce emissions of CI engines have been conducted, one of which is the use of diesel-hydrogen dual fuel. One of the goals of using hydrogen in dual-fuel combustion systems is to reduce particulate emissions and increase engine power. This study investigates the thermal efficiency and emission characteristics of a diesel-hydrogen dual fuel CI engine at various loads condition. The hydrogen was used as a secondary fuel in a single cylinder 667 cm^3 diesel engine. The hydrogen was supplied to intake manifold by fumigation method, and diesel was injected directly into the combustion chamber. The results show that the performance test yielding an increase around 10% in the value of thermal efficiency of diesel engines with the addition of hydrogen either at 2000 or 2500 rpm. Meanwhile, emission analyses show that the addition of hydrogen at 2000 and 2500 rpm lead to the decrease of NO_x value up to 43%. Furthermore, the smokeless emissions around 0% per kWh were occurred by hydrogen addition at 2000 and 2500 rpm of engine speeds with load operation under 20 Nm.

Keywords: dual-fuel hydrogen; hydrogen engines; diesel-hydrogen; diesel-hydrogen efficiency; diesel-hydrogen emissions.

I. Introduction

The use of alternative fuels in internal combustion engine [1][2][3] can reduce dependence on petroleum-based fuels, where this is a step forward to maintain the security and availability of energy sources. In this study, hydrogen was used as additional fuel in a conventional diesel engine to replace partially diesel fuel that was burned in the engine. The engine efficiency and exhaust emissions product when hydrogen replaces some amount of diesel fuel is the most exciting topic to be studied. Previous studies on diesel-hydrogen show that the addition of hydrogen is a promising method for reducing unwanted exhaust emissions while maintaining the engine performance [4][5]. The engine ~~operated~~ with the addition of hydrogen may reduce NO_x over 90% [6], and simultaneously decreases soot emission by increasing the hydrogen addition [7][8][9]. However, NO_x emission increased at higher loads of compression ignition engine with hydrogen [10][11]. Furthermore, the engine with 17% hydrogen content, the hydrogen–diesel–air mixture was stoichiometric and provided favorable conditions for generating combustion knock [12]. The other study by Calik [13] and Syed *et al*. [14] showed that the addition of hydrogen gas further managed the engine vibration both with a conventional diesel engine and biodiesel blend.

The autoignition temperature of hydrogen gas is at 585°C; thus, it requires another autoignition source or trigger to burn it in an internal combustion engine. Diesel fuel which has autoignition temperature 280°C, much lower than hydrogen, can be used as a trigger for burning hydrogen inside the cylinder of diesel engines [15]. This combustion system is also called the "diesel-hydrogen dual fuel." Diesel with the addition of

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hydrogen provides many advantages both concerning performance and emission reduction. This application is possible because some of the diesel fuel is replaced by hydrogen which has a higher combustion efficiency and low hydrocarbon content.

Many works and studies on diesel-hydrogen have been widely reported. The research and development of hydrogen engines by Das concluded that hydrogen could be used on both gasoline and diesel engines without any modification to its systems [16]. In CI engines the hydrogen can be used with diesel-hydrogen dual fuel model. Therefore, NO_x emissions can be significantly reduced by monitoring engine conditions during operation, for example with a lean combustion model or by exhaust gas recirculation (EGR) application.

Adnan *et al.*, have conducted an investigation on a single cylinder 406 cm^3 direct injection stationary diesel engine with the hydrogen addition [17]. In their study, the engines were operated at a fixed speed of 1500 rpm, and hydrogen was injected through the intake manifold, while diesel fuel was injected directly into the combustion chamber. The engine testing results showed an increase in performance up to 16%. However, the value of NO_x and CO emissions tends to increase from 48 to 197 ppm, and 423 to 758 ppm respectively.

Another study on 4-cylinder diesel engines with the addition of hydrogen has been carried out by Bari *et al.* [18]. The engine was operated at a constant speed of 1500 rpm with the addition of hydrogen varying from 1 to 6%. Meanwhile, an electric generator was connected to the engine shaft to manage three variations of load at 19 kW, 22 kW, and 28 kW. The test results showed an increase in brake thermal efficiency up to 36.3%, fuel savings up to 15.16%, and a decrease in HC, CO_2, and CO. However, the value of NO_x emissions continue to rise.

Miyamoto *et al*. conducted a study of hydrogen addition on a single cylinder diesel engine equipped with an EGR system [19]. Diesel fuel was injected into the combustion chamber with a common rail fuel injection device. The EGR ratio was regulated through a valve mechanism, while hydrogen was injected non-continuously (intermittent) into the inlet air manifold using a gas injector.

The machine was operated at a constant speed of 1500 rpm. Test results showed that a combination of hydrogen addition with slow diesel fuel injection contributes to low combustion temperature, resulting in a decrease in NO_x without raising the remaining unburnt fuel. The reduction of smoke due to the addition of hydrogen is more significant than without hydrogen for the high EGR ratio and slow diesel fuel injection time.

Previous references have discussed the application of hydrogen on diesel engine comprehensively. However, the engine efficiency and emissions in CI engine are very dependent on many factors such as energy input, fuel management strategy, combustion mode, initial conditions, and variation of loads. Furthermore, the effects of various loads including the high and low load on the thermal efficiency and emissions of CI engine fueled with diesel-hydrogen dual fuel have not been explored and discussed in depth and complete. Therefore, this paper aims to discuss the characterization of diesel-hydrogen dual fuel performance and exhaust emissions at 2000 and 2500 rpm against loading variations, as a new solution to overcome the lack information on the effect of various loads on diesel-hydrogen dual fuel. The thermal engine efficiency, NO_x and smoke emissions are the main topics presented in this paper. The information presented in this paper will be beneficial for researchers, academics and practitioners who will utilize hydrogen for dual-fuel applications on conventional diesel engines with minimum modification.

II. Materials and methods

A. Engine testing preparation

The experiment was conducted by using an engine test bed composed of a single cylinder diesel engine coupled with an eddy-current dynamometer, the fuel balance measurement, NO_x meter, smoke meter, and pressure and temperature sensors. The eddy current dynamometer was used to adjust and measure engine speed and loads. Meanwhile, fuel consumption was measured by using the fuel balance measurement system, and the intake air flow was measured with a hotwire anemometer. The combination of a pressure transducer, crank-angle sensor, and a data acquisition system was used to obtain the data inside of engine cylinder during the experiment. The engine specifications are shown in Table 1, and the engine testing arrangement can be seen in Figure 1.

B. Testing procedure

The engine tests were carried out with two engine speeds, namely 2000 and 2500 rpm fueled with pure diesel and compared with diesel mixed with hydrogen addition. Engine loading was varied from 0, 5, 10, 20, and 25 Nm. The characteristics of pure diesel and hydrogen refer to Bari and Mohammad [18] is shown in Table 2.

Hydrogen was inserted into the combustion chamber by the fumigation method using a small tube directly into the inlet manifold with a distance of 50 cm from the base of the intake manifold. The hydrogen was set at a constant flow around 10 litres/minute with a pressure of 0.5 bar. Furthermore, some parameters in each condition including Indicated mean effective

Table 1.
Engine specifications

Parameters	Units
Engine type	Naturally aspirated, DI-CI, 4 stroke, 2 valves
Number of cylinder / configuration	1 / Vertical
Displacement volume	667 cm^3
Bore x stroke	100 mm × 85 mm
Compression ratio	20 : 1
Maximum torque	28 Nm at 2000 rpm
Maximum power	11 kW at 3000 rpm

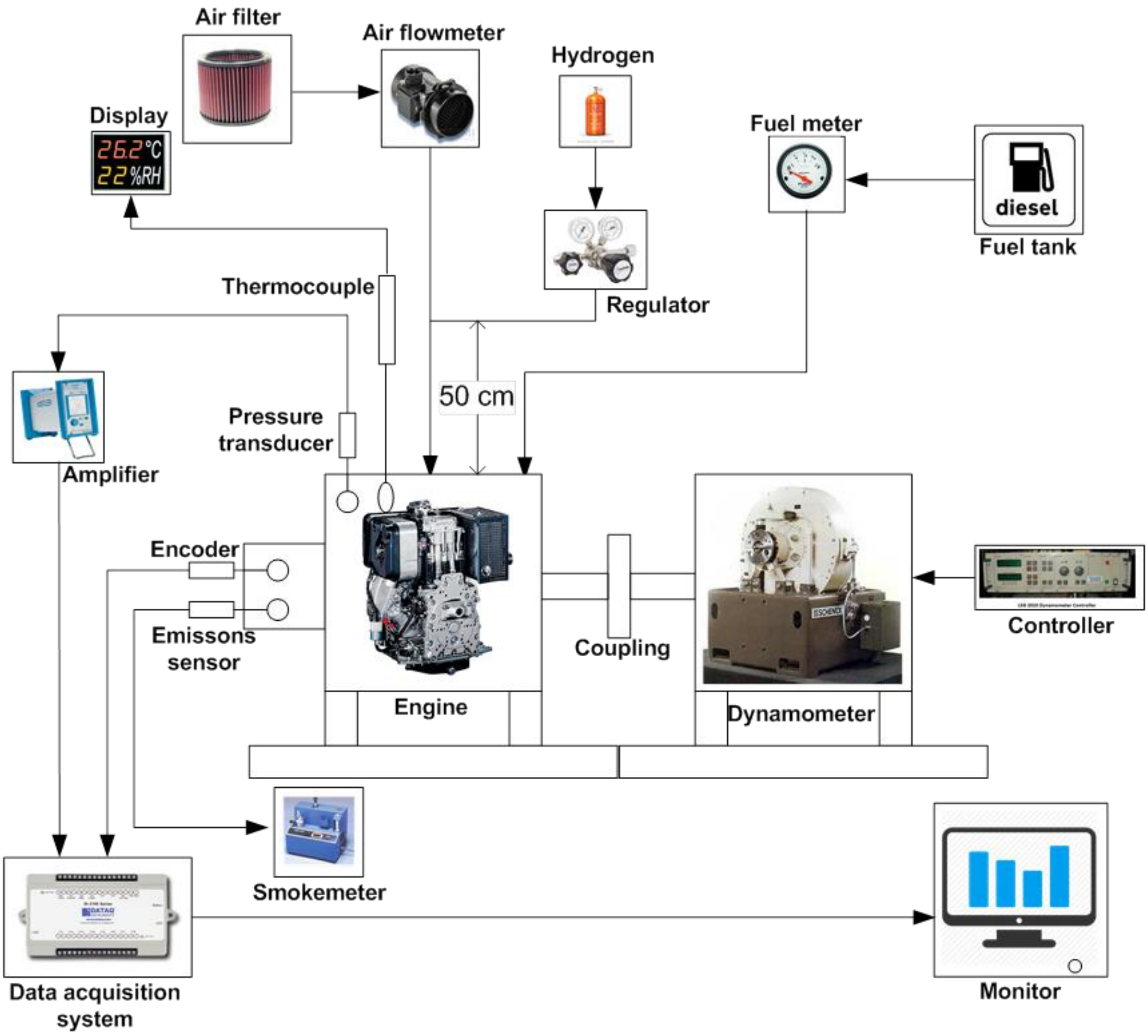

Figure 1. Engine testing diagram

Table 2.
Characteristics of diesel and hydrogen

Parameters	Unit	Diesel	Hydrogen
Density	kg/m^3	840	0.082
Caloric value	MJ/kg	42.7	119.81
Ignition speed	m/s	0.3	2.70
Autoignition temperature	°C	280	585
Carbon residue	%	0.1	0.00

pressure (IMEP), fuel consumption, air flow rate, oil temperature, exhaust gas temperature, NO_x and smoke emission values were measured.

III. Results and discussions

A. Improvement of thermal efficiency

Thermal efficiency states the ratio between the powers produced to the amount of fuel needed for a certain period of engine operation. It is one of the factors to analyze the performance of the internal combustion engine. Although this paper also focuses on the discussion of engine emissions, in this case, it is worth mentioning a brief effect of hydrogen addition to thermal efficiency closely related to fuel consumption.

Figures 2 and Figure 3 show the thermal efficiency (brake thermal efficiency, BTE) of the CI engine based on the loads variation at 2000, and 2500 rpm, refer to the diesel consumption only. The occurred thermal efficiency patterns for both 2000 and 2500 rpm shows similarities. At 2000 rpm the addition of hydrogen causes an increase in thermal efficiency at every load variation as well as at 2500 rpm. This condition happens because a portion of diesel fuel is replaced by hydrogen which has a high ignition speed (around 3.24 to 4.40 ms^{-1}). Thus, the hydrogen causes the combustion process in the engine combustion chamber

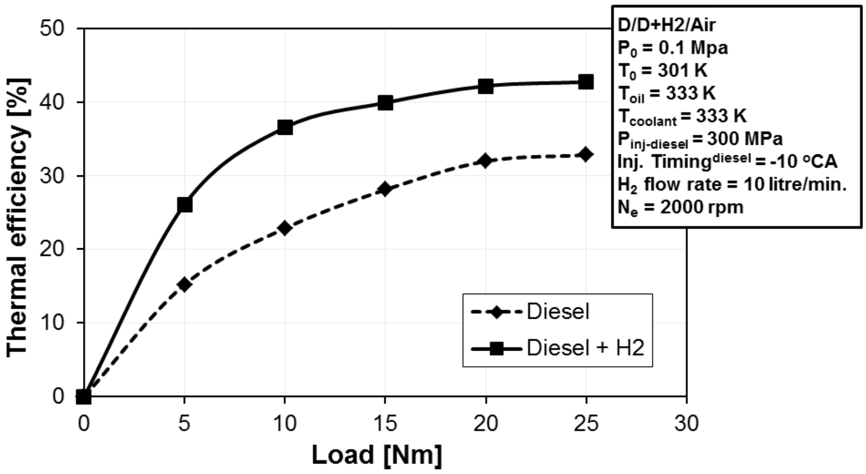

Figure 2. Engine thermal efficiency at 2000 rpm

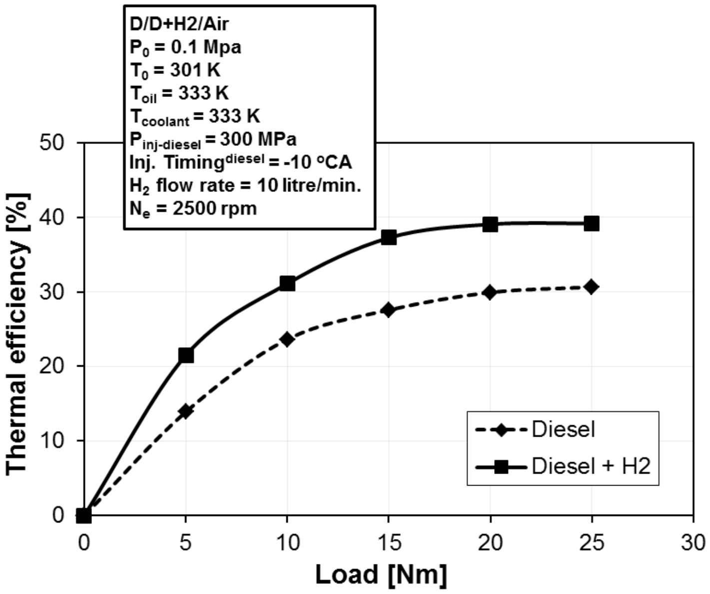

Figure 3. Engine thermal efficiency at 2500 rpm

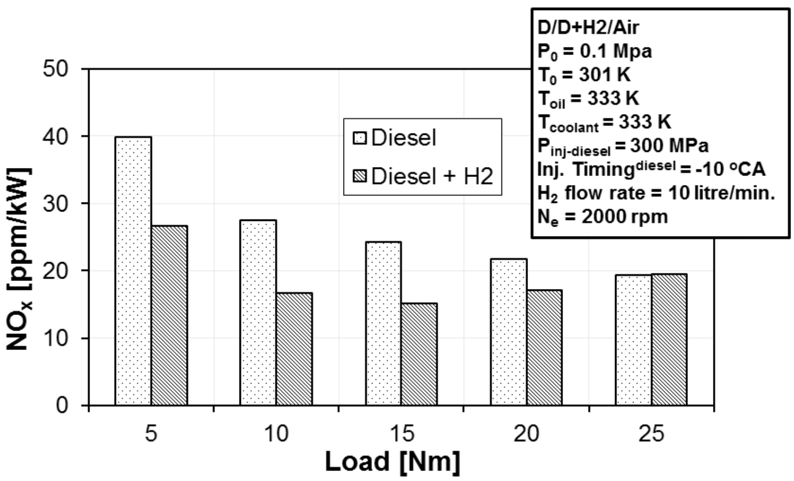

Figure 4. NO_x at 2000 rpm

occurred very rapidly. However, the exact amount of the consumed hydrogen cannot be measured. The amount of consumed hydrogen can be predicted only by the discrepancies of thermal efficiency between engine fueled with pure diesel fuel and hydrogen added diesel. The higher speed of the combustion process will produce greater combustion energy that can improve the performance of the diesel engine. Referring to the results of Adnan [17], the addition of certain amount of hydrogen, in the form of gas fuel, to a diesel engine

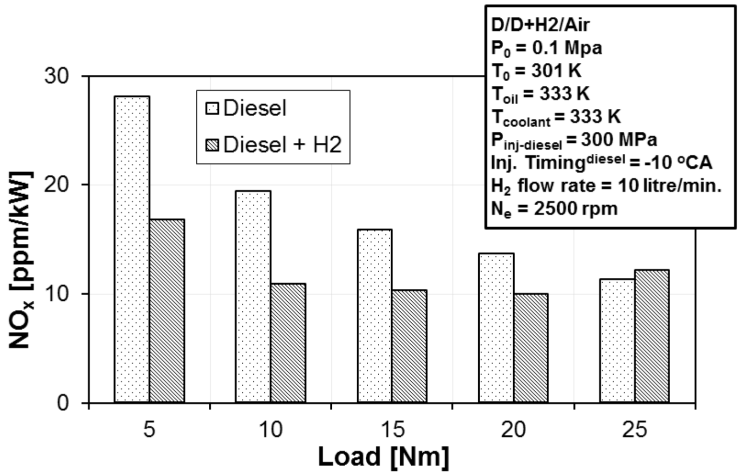

Figure 5. NOx at 2500 rpm

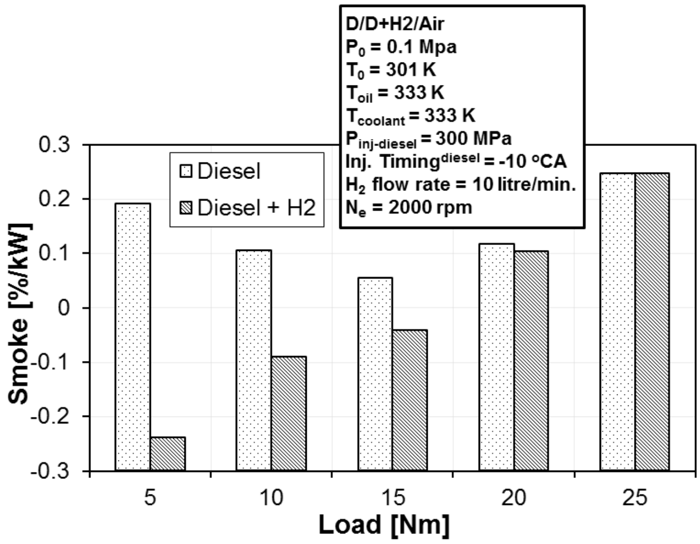

Figure 6. Smoke at 2000 rpm

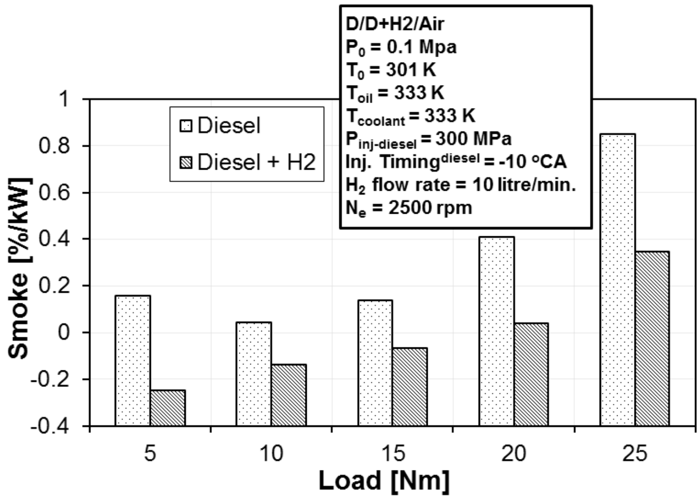

Figure 7. Smoke at 2500 rpm

mixed with air gives a significant impact on the cylinder load during compression and power during a combustion explosion.

B. NO_x reduction

Figures 4 and 5 show NO_x emissions against loads variation of the CI engines at 2000 and 2500 rpm. Both charts show the same pattern, where at low load, NO_x values are decreases in diesel with the addition of hydrogen. At 2000 rpm of engine speed, NO_x values are decreases with the loads variation from 0, 5, 10, 15, and 20 Nm by 16%, 33%, 39%, 37%, and 22%, respectively. Meanwhile, in the load value around 25 Nm, it tends to have no effect of decreasing on NO_x value of the diesel engine with the addition of hydrogen.

At engine speed around 2500 rpm, the NO_x reduction pattern still occurs at the variation of the load from 0, 5, 10, 15, and 20 Nm by 35%, 40%, 44%, 35%, and 27%, respectively. Also, for 2500 rpm, at an engine load around 25 Nm, the increase in NO_x value occurs by 7%. This NO_x reduction pattern is happened because at low loads there is an increase in the hydrogen fuel fraction. Therefore, the NO_x reduce significantly. This condition in line with the results of the research conducted by Miyamoto [19].

C. Smoke emissions reduction

The various values of smoke density for emissions test are shown in Figures 6 and Figure 7. Figure 6 shows smoke history on loads variation of diesel and diesel engines with hydrogen at 2000 rpm and Figure 7 is at 2500 rpm. By analyzing the two images, it can be observed that diesel-hydrogen dual fuel operation is a very potent strategy to reduce the massive smoke emissions of CI engines.

For diesel-hydrogen dual fuel operations with engine speed around 2000 and 2500 rpm, it can be revealed that the smoke emissions are reduced up to 0% and even minus at a low load from 20 Nm downwards. In other words, diesel-hydrogen dual fuel operations produce smokeless combustion. Meanwhile, at engine load. Meanwhile, at engine load around 25 Nm, both for engine speed around 2000 and 2500 rpm, smoke emissions began to appear. The decrease in smoke value was happened because of the partial replacement of diesel fuel by hydrogen inside the combustion process.

Based on Table 2, it is known that hydrogen addition in the combustion produces the main combustion residue in the form of water vapor only, and does not form any particulates. This is due to the absence of carbon atoms in hydrogen resulting in a low smoke percentage [15].

IV. Conclusion

The performance and emissions tests on 667 cm^3, single cylinder diesel engines have been carried out without or with the addition of hydrogen. Addition of hydrogen is carried out by inserting it through the intake manifold. From the performance test, it is obtained an increase in the value of thermal efficiency by adding hydrogen. Meanwhile, from emission tests with the addition of hydrogen at engine speed around 2000 and 2500 rpm, the NO_x value decreases from 16 to 43% in low load condition. Furthermore, the smoke emissions content is very clean or smokeless at 2000 and 2500 rpm with low load condition by a 0% of smoke value. This experimental work and extensive investigation show some valuable insight and new ideas. However, it is necessary to conduct a further study such as the application of various injection timing of diesel fuel to optimize the efficiency and emissions characteristics of the CI engine operated in dual-fueled with diesel-hydrogen.

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