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Energy Procedia 32 (2013) 3 – 10
Energy Procedia

International Conference on Sustainable Energy Engineering and Application

[ICSEEA 2012]

Combustion characteristics of diesel-hydrogen dual fuel engine at low load

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Abstract

In the present study, hydrogen utilization as diesel engine fuel at low load operation was investigated. Hydrogen cannot be used directly in a diesel engine due to its auto ignition temperature higher than that of diesel fuel. One alternative method is to use hydrogen in enrichment or induction. To investigate the combustion characteristics of this dual fuel engine, a single cylinder diesel research engine was converted to utilize hydrogen as fuel. Hydrogen was introduced to the intake manifold using a mixer before entering the combustion chamber. The engine was run at a constant speed of 2000 rpm and 10 Nm load. Hydrogen was introduced at the flow rate of 21.4, 36.2, and 49.6 liter/minute. Specific energy consumption, indicated efficiency, and cylinder pressure were investigated. At this low load, the hydrogen enrichment reduced the cylinder peak pressure and the engine efficiency. The reaction progress variable and combustion rate of reaction were slower as shown by the CFD calculation.

Keywords: Diesel; hydrogen; dual fuel; combustion; CFD.

1. Introduction

The advantages of using hydrogen as fuel for internal combustion engine is among other a long-term renewable and less polluting fuel, non-toxic, odorless, and has wide range flammability. Other hydrogen properties that would be a challenge to solve when using it for internal combustion engine fuel, i.e.: low ignition energy, small quenching distance, and low density [1].

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doi:10.1016/j.egypro.2013.05.002

The diesel-hydrogen dual fuel engine can be operated with less fuel than neat diesel operations, resulting in lower smoke level and higher brake thermal efficiency. NO_x emissions were also reduced except at full load operation [2]. Hydrogen induction, particularly when its energy share increased above 15% resulted in a sharp decrease in ignition delay, very high peak pressure rates, increase in smoke and loss in fuel efficiency [3]. The brake thermal efficiency of dual fuel with exhaust gas recirculation (EGR) is higher than that of neat diesel operation. Dual fuel operation without EGR resulted in the lowest smoke and unburned HC. EGR reduced NO_x emission effectively [4]. It was found that CO, FSN, and THC increase with EGR but NOx emission decrease drastically. Inversely, CO, FSN, and THC emission decrease with hydrogen, but NOx increases. This inverse relationship will allow the combination of EGR and hydrogen induction to be optimized to minimize both FSN and NOx [5].

Using port-injected hydrogen, there was an increase in brake thermal efficiency of the engine with a greater reduction in emissions [6]. Any decrease of emission, especially NOx is likely due to enhancement of turbulent mixing in the cylinder caused by the injection of pressurized hydrogen through the intake valve [7]. Timed manifold injection (TMI) of hydrogen gave higher thermal efficiency and avoided undesirable combustion [8-10]. Hydrogen induction with TMI coupled with EGR results in lowered emission level and improved performance level compared to the case of neat diesel operation [11]. Although research on hydrogen combustion in the internal combustion engine has intensified, the number of published papers in the field of hydrogen-diesel co-combustion is not as rich as for hydrogen used in spark ignited engines [12].

The aim of the work presented here is to investigate the effect of hydrogen enrichment on the diesel combustion process in a stationary diesel engine at a low load. To that end, experiments were performed to investigate the combustion process of a diesel-hydrogen dual fuel engine at various hydrogen flow rates. Based on experimental results, CFD calculations were conducted to have a deeper understanding of combustion processes of the dual fuel engine. This was done by simulating the closed volume cycle during compression and expansion stroke where both valves are closed.

2. Experimental setup

A single cylinder diesel engine was converted to utilize hydrogen as fuel. The engine was a single cylinder, air cooled, direct injection diesel engine with a bore of 100 mm and stroke of 85 mm. The compression ratio of the engine was 20.5. Hydrogen was introduced to the intake manifold by a mixer before entering the combustion chamber. It was supplied from a high-pressure cylinder (150 bar) and then reduced to a pressure of 1.5 bar using a pressure regulator.

The engine was coupled to a SCHENCK eddy-current dynamometer with a rated power of 70 kW. Engine torque and speed were measured by the dynamometer. In-cylinder pressure was measured using a Kistler water-cooled piezo electric pressure transducer and was sampled every 1 degree crank angle. Start of injection and injection duration were measured by a needle lift sensor. Diesel fuel consumption was measured using gravimetric fuel balance AVL 733S. Hot film anemometer was used to measure air consumption.

The engine was run at a constant speed of 2000 rpm and 10 Nm load. Hydrogen was introduced at the flow rate of 21.4, 36.2, and 49.6 liter/minute. The engine was started with diesel fuel at 2000 rpm and 10 Nm load. After allowing the engine to reach the steady state conditions, the following parameters were measured and recorded: fuel (diesel and hydrogen) consumption, air consumption, exhaust gas temperature, needle lift, and cylinder pressure. Hydrogen was introduced at the flow rate of 21.4 liter/minute; engine speed was kept constant by adjusting the injection pump lever's position. The above parameters were measured and recorded again. This procedure was repeated for different hydrogen flow rates.

3. CFD calculation and performance evaluation

A commercial software AVL FIRE CFD code was used to simulate the combustion process of the diesel-hydrogen dual fuel engine. Calculation was started at the compression stroke when both valves were closed. It is assumed that the mixture of air and hydrogen inside the cylinder is homogeneous at the start of calculation. The ECFM combustion model combined with “Diesel-ignited gas engine” ignition model was used throughout the calculation. The input data is taken from the experimental results. With the hydrogen flow rate of 21.4, 36.2, and 49.6 l/min, the equivalence ratio of 0.203, 0.367, and 0.530 respectively were defined as the initial value. Diesel fuel was directly injected into the cylinder at 14°CA before TDC. The boundary conditions were assumed as those of used in 1D thermodynamics cycle simulation.

The engine performance is evaluated for the three hydrogen enrichment level by computing and comparing the diesel fuel replacement, the brake specific energy consumption (BSEC), and the indicated efficiency (η_i).

4. Results and discussion

4.1. Effect of hydrogen enrichment on performance

During the hydrogen addition, the load and speed were kept constant. This mode can be realized by setting the dynamometer at fixed load. The engine speed was kept constant by controlling the diesel fuel governor. The percentage of diesel fuel on the energy basis of this load condition is depicted in Fig. 1a. It is noted that the diesel replacement for hydrogen flow rates at 21.4, 36.2, and 49.6 l/minute were around 50, 90, and 97% respectively. More energy was added when hydrogen was introduced. To keep the load and speed constant, the fuel governor was adjusted accordingly to reduce the diesel supply. As a result, part of diesel fuel was replaced by hydrogen enrichment.

Figure 1b depicts the variation in specific energy consumption (SEC) at 10 Nm load for different level of hydrogen enrichment. SEC indicates the amount of total fuel energy (diesel and hydrogen) needed to produce 1 kW power for an hour engine operation. The total fuel energy is calculated from the individual fuels (diesel and hydrogen) multiplied by their respective calorific value. An increasing hydrogen flow rate at the low load operation results in a higher SEC. The specific energy is found to be 20.73 MJ/kWh with hydrogen flow rate of 21.4 l/min. A further increase in SEC to 21.70 MJ/kWh is obtained when hydrogen flow rate increase to 36.2 l/min. A slightly increase in SEC to 21.8 MJ/kWh is noticed at hydrogen flow at 49.6 l/min.

Figure 1c shows the variation of indicated efficiency at each load when hydrogen was introduced. It relates the indicated power to the supplied fuel energy. At this low load, the efficiency decreases with hydrogen enrichment. The indicated efficiency of 57.9% is achieved at the hydrogen flow rate of 21.4 l/min. Further increase in hydrogen flow rate of 36.2 and 49.6 l/min reduce the efficiency to 54.3 and 49% respectively. The percentage of diesel fuel is reduced significantly with hydrogen enrichment at this low load condition. This low portion of the diesel fuel may not be sufficient to ignite the premixing mixture of hydrogen-air. The efficient combustion cannot be achieved and resulted in increasing SEC as shown in Fig. 1b.

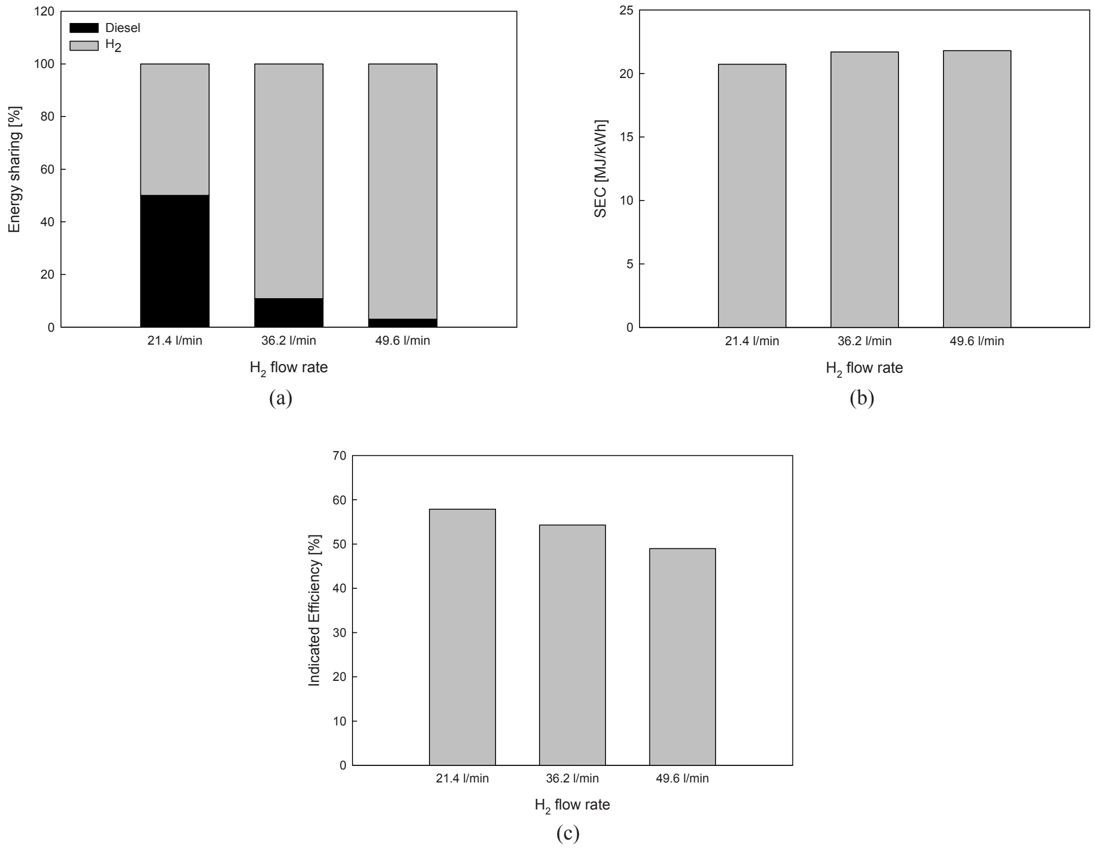


Fig. 1. (a) Diesel energy replacement by hydrogen; (b) Specific energy consumption; (c) Indicated efficiency

4.2. Effect of hydrogen enrichment on combustion

The variation of cylinder pressure traces and pressure rise at speed 2000 rpm and 10 Nm load for different hydrogen flow rates are shown in Fig. 2a and b. It is noted that hydrogen addition will reduce the cylinder pressure and the pressure rise. More hydrogen enrichment resulted in lower cylinder peak pressure. The peak pressure is found to be 73.50 bar with hydrogen flow rate of 21.4 l/min. Further increase in hydrogen flow rate of 36.2 and 49.6 l/min reduces the cylinder peak pressure to 64.28 and 62.29 bar respectively. Hydrogen enrichment also reduced the rate of pressure rise. The peak value of the rise shifted a few degree crank angle when the hydrogen flow rate increased. This indicates a slower combustion reaction rate. This may be due to the availability of diesel fuel needed to ignite the premixing of hydrogen with air. The combustion process was promoted by the auto-ignition of diesel fuel. The percentage of diesel fuel at 21.4 l/min and 36.2 l/min hydrogen enrichments were around 50% and 10% respectively. A further increase in hydrogen enrichment to 49.6 l/min reduced the percentage of diesel fuel to 3.1%. These portions of diesel may not be adequate to produce an efficient combustion. The amount of diesel fuel to ignite the premixing of hydrogen with air was reduced and resulted in a late start of combustion as shown in rate of heat release diagram in Fig. 2c.

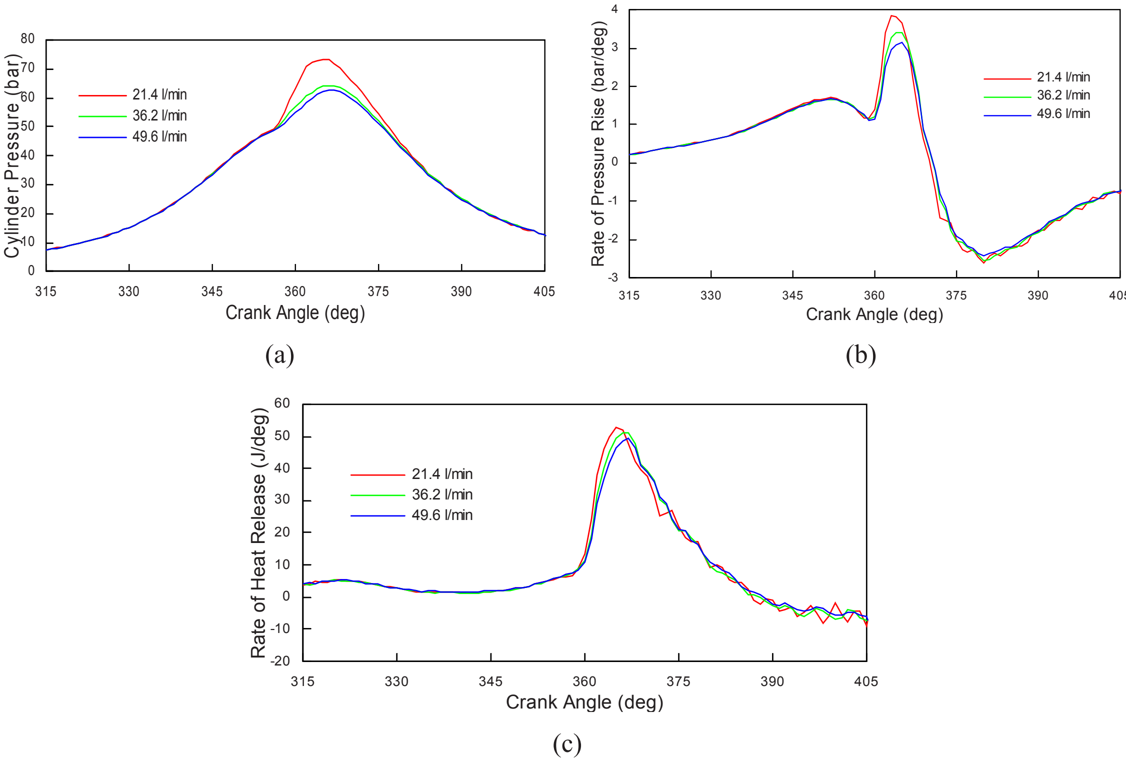
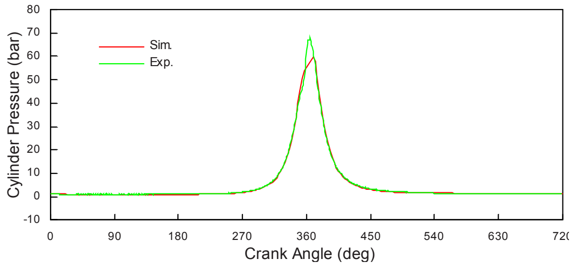


Fig. 2. Effect of hydrogen addition at 2000 rpm, 10 Nm on: (a) cylinder pressure; (b) rate of pressure rise; (c) rate of heat release

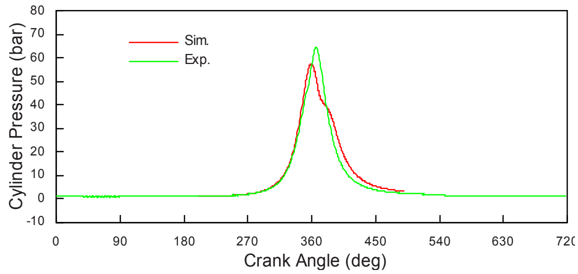
4.3. CFD analysis of dual fuel combustion

CFD calculation was carried out the have a better understanding on combustion process of this dual fuel engine. It was assumed that the boundary conditions were the same for all cases. The averaged cylinder pressure was compared to that of the experimental results to validate the simulation. The validations of cylinder pressures for all cases in this investigation were shown in Fig. 3a-c. In general, the simulation's results seem to have a good agreement with the experimental data. The cylinder peak pressures were slightly under predicted by the simulation. This may be due to the detailed input data, especially for the fuel injection profile. It was assumed the diesel fuel was injected at the same start of injection time and the end of injection time for all cases. Furthermore, the injection rate profile was also simplified.

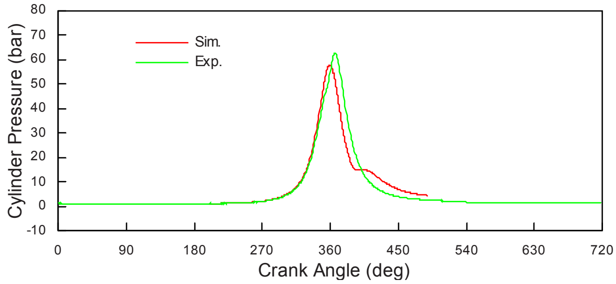
Figure 4a shows the mean total reaction rate for the three cases investigated. The quantity represents the fuel mass fraction depletion rate. It is assumed that the liquid fuel was injected at the same start of injection (SOI) and end of injection (EOI). It is shown that more hydrogen enrichment resulted in lower reaction rate and later start of combustion. The combustion started easier when the portion of diesel fuel was sufficient to promote the auto-ignition. The depletion rate of the fuel is faster for a less hydrogen enrichment.



(a) $H_2 = 21.4$ l/min



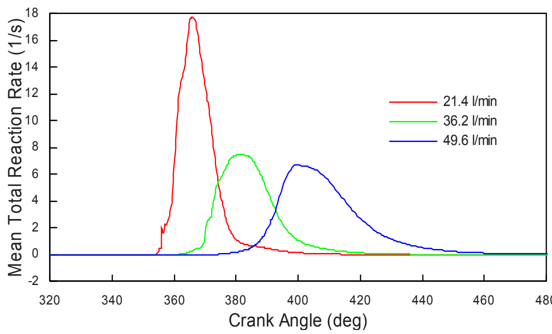
(b) $H_2 = 36.2$ l/min



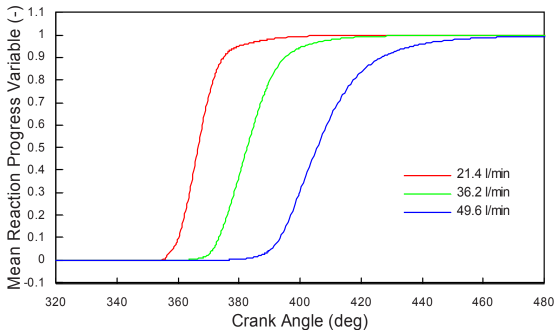
(c) $H_2 = 49.6$ l/min

Fig. 3. Comparison between simulation and experiment result on cylinder pressure at 2000 rpm

Other parameter to be investigated to explain the combustion process of dual fuel engine is the reaction progress variable. It represents the mass of combustion products over the theoretical maximum mass of combustion products. The reaction progress variable is shown in Fig. 4b. A higher fuel depletion rate can be achieved at the lower hydrogen percentage. The formation of combustion product started earlier. In addition, the slope of the graph is steeper. It means that the combustion process started earlier and faster.



(a)



(b)

Fig. 4. (a) Variation of mean total reaction rate with hydrogen enrichment; (b) Mean reaction progress variable

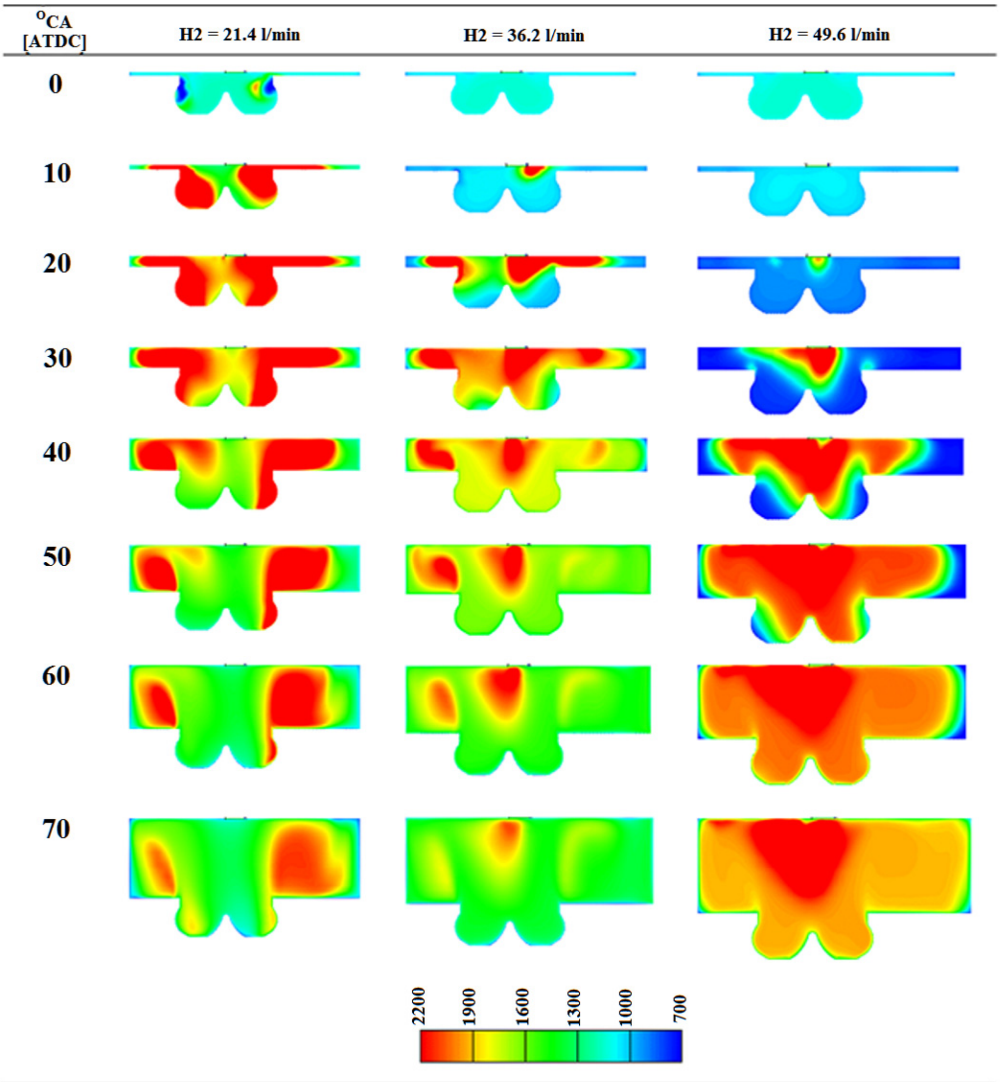


Fig. 5. Progress of temperature distribution at the spray axis

The combustion progress can be represented by the temperature distribution in the calculation domain. Figure 5 shows the progress of temperature distribution on the cut plane along the spray axis from TDC until 70°CA after TDC. It is noted from the previous explanation that more hydrogen enrichment resulted in a later start of combustion. When hydrogen was introduced at the flow rate of 21.4 l/min or about 50% of the total fuel energy, the start of combustion occurred at TDC. More hydrogen enrichment delayed the start of combustion for about 10°CA.

5. Conclusion

Experiments and simulation works were conducted on DI diesel engine with hydrogen in the dual fuel mode. Under constant load and speed engine operation, hydrogen induction into the intake manifold reduces the diesel fuel consumption. Diesel reduction of 50, 90, and 97% was achieved during the investigation. These relatively high percentages of hydrogen fuel are detrimental to the engine performance in terms of energy consumption and efficiency. An increasing hydrogen flow rate at the low load operation results in a higher SEC. It means that more fuel is necessary to produce the same power output. At this low load operation, the efficiency decreases with hydrogen enrichment. This condition affects the values of SEC. Measurement of in-cylinder pressure was carried out to investigate the combustion process inside the combustion chamber. Hydrogen enrichment reduced the peak pressure and retarded the start of combustion. CFD simulation reveals that hydrogen enrichment in such a high percentage resulted in slower reaction progress due to lower combustion rate of reaction. Temperature distributions along the cut plane at the spray axis showed the progress of the combustion processes.

Acknowledgment

The authors wish to thank Universiti Malaysia Pahang for supporting this research under GRS 100303. Fully support from LIPI by providing the experiment and simulation facilities are grateful acknowledged.

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