Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879

Experimental Investigation on the Effects of Hydrogen Rate and Loading Towards Engine Performance and Exhaust Emission

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ARTICLE INFO

Article history:
Received 3 January 2018
Received in revised form 13 April 2018
Accepted 5 July 2018
Available online 12 August 2018

Keywords:
Diesel engine, hydrogen and diesel fuel, performance and emission

ABSTRACT

Fuel crisis and environmental pollution are the main problems for automobiles. The impact of this issue has encouraged the researchers to explore alternative resources which are sustainable, efficient and safe. Hydrogen is one of the potential resources in fulfilling those criteria. The objective of this research is to study the effects of hydrogen rate and loading towards engine performance and emission. The continuous hydrogen flow rate (0 l/min, 3 l/min and 6 l/min) method is being introduced at the air intake component. The engine was running at constant speed of 3500 rpm ± 100 rpm with two conditions consisted of only diesel fuel and the mixed diesel fuel. Each condition was operated with different rate of hydrogen and range of hydraulic loads from 1000 kPa to 4000 kPa. Based on the results, the engine power shows an increment up to 3.34% and the brake specific fuel consumption can be saved around 29.03%. The exhaust emissions analysis indicates that the carbon monoxide (CO), hydrocarbon (HC) and carbon dioxide (CO2) has decreased by 61.68%, 23.35 % and 31.47% respectively. However, the nitrogen oxide (NOX) emission creates 344.33 ppm higher than only diesel fuel.

1. Introduction

With the advancement of transportation and increasing population, the demand for fossil fuel such as petroleum, natural gas and coal are always high. However, this type of energy resources will deplete rapidly years by years and their combustion product can cause global environmental problem, such as the ozone layer depletion, greenhouse effect, acid rain and pollution. Conventional hydrocarbon of fossil fuel releases unburned/partially hydrocarbon (UBHC), carbon monoxide (CO), nitrogen oxide (NOX), smoke and particulate matter.

Clean fuel such as hydrogen can be one of the alternative resources in reducing the negative impact to the environment. Also, it is eco-friendly and renewable energy sources. By all means,

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hydrogen resource is diverse and having high potential towards zero emission. This is due to the absent of carbon element in hydrogen and make it a very efficient and clean fuel [1]. Based on the previous works, the usage of hydrogen in SI engines is limited only at certain operating condition [2]. Yet, hydrogen gasoline blends by Tyagi and Ranjan [3] shows an increment in SI engine performance. For compression ignition engine (CI) with hydrogen exploration by [4-6] shows increase in thermal efficiency. Nevertheless, there are some drop in thermal efficiency in works [7]. This pattern depends on how the hydrogen is being supplied to the CI engine whether through naturally aspirated or modified aspirated injection. Various techniques have been tested such as carburetion timing manifold/port injection (TMI), direct hydrogen injection (DHI) and continuous manifold induction (CMI). Hydrogen mixed with air inside the intake port is called external mixing method, where the operation control is pretty straightforward and simple. However, there is an abnormal knocking combustion, pre-ignition and backfire problem [8].

The performance and emission characteristics of a direct injection diesel engine can be enriched with hydrogen as indicated by Saravanan *et al.,* [4]. In his studies, he conducted the tests by varying the percentage of hydrogen (10%, 20%, 30%, 50%, 60%, and 90%) and load where the results are then compared with base fuel operation at constant engine speed. The best brake thermal efficiency (BTE) obtained is about 26.9% at 30% hydrogen addition. Besides that, the specific energy consumption (SEC) is decreased as the hydrogen percentage increased and low level of NOX emission was noted at 90% enrichment with 60 % load. There is also a significant decrement for particulate matter about 65 % with addition of 90 % hydrogen. The studies also viewed on the performance and emission characteristic of diesel engine using hydrogen through carburation technique and timed port injection (TPI). They concluded that at full load with 20 l/min condition, the brake thermal efficiency, nitrogen oxide, hydrocarbon, carbon monoxide, carbon dioxide and smoke level using TPI is better than the carburetor technique almost 16%, 34%, 66%, 80%, 33% and 45% respectively. At full load condition, the carburetor technique performed better than TPI with specific energy consumption is decreased by 15 % [6].

Next, Saravanan *et al.,* [9] found the optimum hydrogen flow rate at 7.5 l/min for the performance and emission studies on port injection of hydrogen with flow rates range from 2 l/min to 9.5 l/min where Diesel as an ignition source. By using electronic control unit (ECU), he regulated the injection system at 5º of crank angle (ºCA) before top dead center (BTDC) and 30ºCA injection duration. He found an increment of 15 % in brake thermal efficiency and 1-2% NOX emission compare to diesel fuel. While smoke emission reduced by 44 % and both CO and HC are same at overall diesel fuel. Madhujit *et al.,* [5] investigated its effects on the performance and emissions of the engine by supplying various hydrogen energy rates. They are using an LPG-CNG injector with constant speed and full load to be measured. Based on the observation, the brake thermal efficiency and the NOX emission increased to 15.8% and 344.33ppm respectively. However, the brake specific energy consumption (BSFC) is decreased by 18.6%, while CO_2 emission decreased about 60.3% and CO reduced to 0.52 g/kWhr with addition 42% of hydrogen. The scopes of this works is related between engine performance and emission on unmodified diesel engine with comparison of continuous variable hydrogen rates and hydraulic loading. The experiments are carried out under constant engine speed by using sole diesel fuel and later followed with different hydrogen flow rates (0 l/min, 3 l/min and 6 l/min) at hydraulic loading ranged from 1000 kPa to 4000 kPa of hydraulic loading.

2. Methodology

2.1 Equipment and Apparatus Arrangement

The test engine setup, consists of a single cylinder diesel engine, Model KIPOR KM 160 F, 4-stroke, air cooled, with direct injection. For the resistant system, the diesel engine is connected with a hydraulic pump as absorbant dynamometer using belting from the crankshaft towards a pulley pump. Figure 1 shows a schematic layout of the diesel engine test setup for this experiment. Other equipment includes a stopwatch, measuring beaker and hydrogen flow meter which is used to measure diesel fuel and hydrogen flow rate. In addition, the gas analyzer used in this experiment was a portable gas monitoring system by MRU Varioplus.

The engine was first run with diesel fuel for about 10 to 15 minutes without any load condition and the hydrocarbon, carbon monoxide, carbon dioxide, and nitrogen oxide level are measured by using gas analyzer device. This is to ensure that the engine had proper combustion at optimum level. After that, the test began with the reference fuel, diesel at 1000 kPa hydraulic loading. The reading of engine and pump speed (rpm) are taken from the tachometer device. The end rod of gas analyzer is attached at the inside of the engine exhaust. The reading for gas emissions are recorded automatically by the device and it can be printed directly from the device for analysis. All reading measurements are taken more than 3 times in order to increase the data reliability.

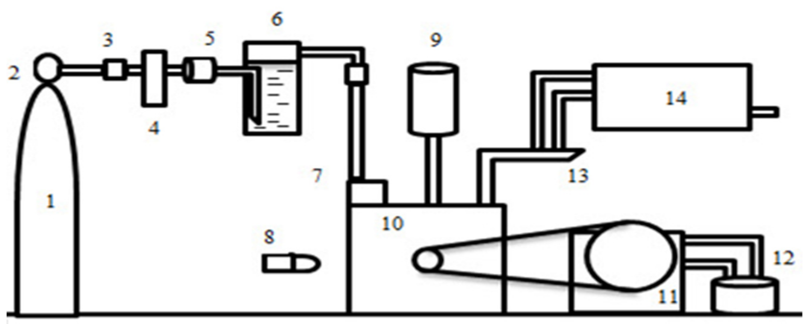

Fig. 1. Schematic layout

Description: 1-Hydrogen tank, 2-Pressure regulator, 3-Flashback arrestor, 4-Flow meter, 5-One ways flow valve, 6-Flame trap, 7- Air intake, 8-Tachometer, 9-Diesel tank, 10-KM 170-F engine, 11-Hydraulic pump, 12-Hydraulic tank, 13-Exhaust manifold, 14- Gas analyser.

2.2 Test Conditions

The test is conducted in two steps: (i) running engine with diesel fuel and (ii) running engine with diesel fuel at different rate of hydrogen intake and variable hydraulic load

Table 1
Trial Experiment Parameter

Speed (rpm)	Hydraulic loading (kPa)	Hydrogen rate (l/min)
3500±100	1000, 1500, 2000, 2500, 3000, 3500 and 4000	0, 3 and 6

For this test, the experiment parameter is shown in Table 1. Diesel fuel (0 l/min) is tested with speed of 3500±100 rpm at hydraulic loading of 1000 kPa, 1500 kPa, 2000 kPa, 2500 kPa, 3000 kPa, 3500 kPa and 4000 kPa. The data are recorded for every loading increment. Next, the trial is repeated using diesel fuel with additional 3 l/min and 6 l/min of hydrogen gas at the same speed and increment of hydraulic loading. After the last test finished, the engine is running with diesel fuel for over 10 minutes, in order to flush out the remaining hydrogen gas in the fuel line.

3. Results and Discussion

3.1 Engine Performance

Figure 2 shows the plot of power with different hydrogen rate and hydraulic loading. The peak of brake power displays separately the pressure of 4000 kPa with 1597.12W, 1606.33W and 1653.92W of 0 l/min, 3 l/min and at 6 l/min. This brake power pattern increase up to 3.43% at 4000 kPa hydraulic loading with addition 6 l/min of hydrogen flow rate compared to original fuel baseline. This occurs due to different combustion mixture.

The brake specific fuel consumption (BSFC) of the engine is shown in Figure 3. At 4000 kPa loading, the reduction of BSFC level indicates 0.496 kg/kWh, 0.385 kg/kWh and 0.352 kg/kWh at 0 l/min, 3 l/min and at 6 l/min correspondingly. This means by supplying 6 l/min hydrogen into the system, the fuel savings can reach almost 29.03 % compare to neat diesel fuel. This savings is due to improvement of the fuel combustion process with the addition of the hydrogen which has high flame velocities and high calorific content [5].

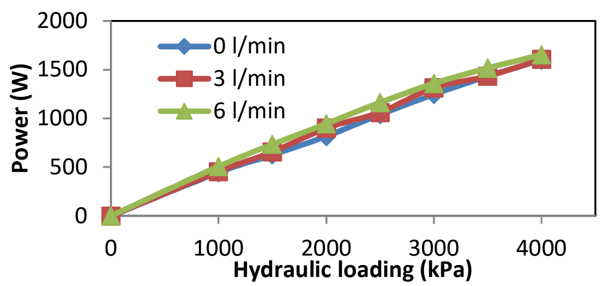

Fig. 2. Power vs hydraulic loading and hydrogen rate

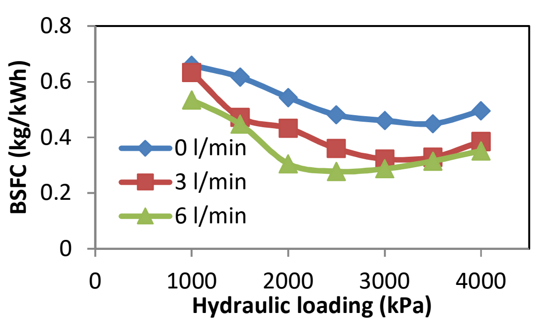

Fig. 3. BSFC vs hydraulic loading and hydrogen rate

3.2 Exhaust Gas Emission

The outcome of the different hydraulic loading and flow rate of hydrogen as additive on the exhaust gas temperature is shown in Figure 4. As estimated, the increment of hydrogen in the diesel operation drives the flame temperature, energy content and therefore the exhaust gas temperature. The result of Hamdan *et al.,* [10] is similar for exhaust gas temperature. In this experiment, the hydrogen additive does not exceed 7-8 l/min in order to limit the knocking tendency. If the quantity hydrogen increases without proper mixing control and time of injection, it can cause severe damage to engine component and dangerous to the surroundings.

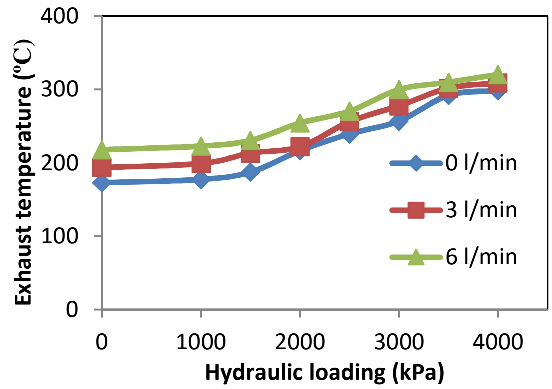

Fig. 4. Exhaust temperature vs hydraulic loading and hydrogen rate

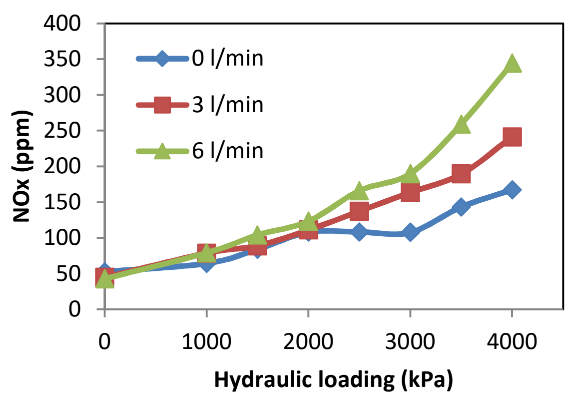

Fig. 5. NO_X vs of hydraulic loading and hydrogen rate

The variation of Nitrogen oxide (NO_X) emission with the increasing hydrogen flow rate and hydraulic loading is displayed in Figure 5. With only diesel fuel, the initial value of NO_X emission is 52.67ppm at 0 kPa, 64.33ppm at 1000 kPa, 84ppm at 1500 kPa, 108ppm at 2000 kPa, 108.33ppm at 2500 kPa, 107.67ppm at 3000 kPa, 143.33ppm at 3500 kPa and followed by 167.25ppm at 4000 kPa hydraulic loading. Next, diesel fuel with 3 l/min produces 45ppm, 78.67ppm, 89ppm, 111ppm, 137.33ppm, 163.67ppm, 189.33ppm to 241.33ppm of NO_X emission at 0 kPa, 1000 kPa, 1500 kPa, 2000 kPa, 2500 kPa, 3000 kPa, 3500 kPa and 4000 kPa loading respectively. Later, at 6 l/min with 0 kPa, 1000 kPa, 1500 kPa, 2000 kPa, 2500 kPa, 3000 kPa, 3500 kPa and 4000 kPa hydraulic loading the NO_X emission reading are 43ppm, 79ppm, 104ppm, 123.33ppm, 166ppm, 190ppm, 259.17ppm and 344.33ppm respectively. Hamdan *et al.,* [10] found that the amount of NO_X emission depends on the reaction duration, oxygen concentration, pressure and temperature especially inside the cylinder.

Thus, similar with Saravanan *et al.,* [9] and also shows that the NO_X emission level corresponds to the exhaust temperature and pressure. However, it is then decreased because of the oxygen concentration at the intake. Besides, hydrogen has faster flame speed of 2.54 m/s than diesel fuel and larger heating value of 77.62 MJ/kg [11].

Figure 6 demonstrates the carbon monoxide with different hydrogen flow rate and hydraulic loading. Carbon monoxide is formed from incomplete combustion process due to inadequate oxygen to convert all carbon to carbon dioxides. At 3 l/min of hydrogen flow rate, the CO emission level is decreased to 24.33%, 7.46%, 21.11%, 22.22%, 18.40%, 24.82%, 42.12% and 43.66% compared to diesel fuel that appeared at 0 kPa, 1000 kPa, 1500 kPa, 2000 kPa, 2500 kPa, 3000 kPa, 3500 kPa and 4000 kPa. The following CO emission level decrement at 6 l/min of is better than sole diesel, which are 28.52%(0 kPa), 25.67% (1000 kPa), 28.53%(1500 kPa), 25.20%(2000 kPa), 45.79%(2500 kPa), 51.98%(3000 kPa), 58.70%(3500 kPa) and 61.68% (4000 kPa). This pattern occurred due to the lean mixture of oxygen is present and hydrogen does not have a carbon atom in it. This correlated with the works by Saravanan *et al.,* [4] and Guo *et al.,* [12].

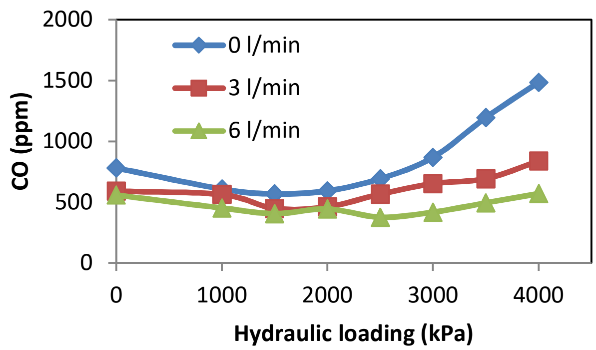

Fig. 6. CO vs of hydraulic loading and hydrogen rate

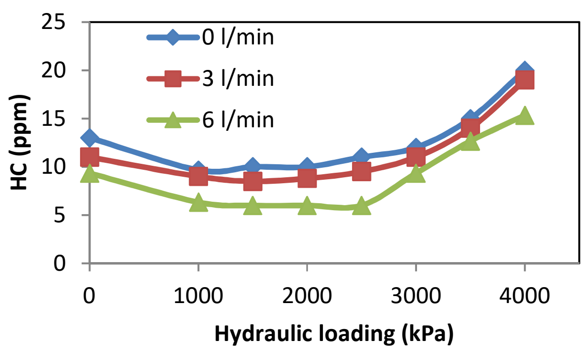

Fig. 7. HC vs hydraulic loading and hydrogen rate

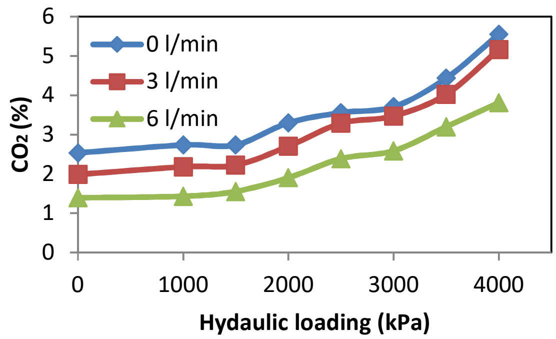

Fig. 8. CO_2 vs hydraulic loading and hydrogen rate

Incomplete combustion of the compression engine, resulting hydrocarbon (HC) emission which are organic compounds in engine exhaust. Figure 7 shows a relationship between hydrocarbon emission and hydrogen flow rate. The minimum HC for diesel fuel, diesel fuel with 3 l/min hydrogen rate and diesel fuel with 6 l/min hydrogen rate starting at 13ppm, 11ppm and 9.33ppm individually. The maximum hydrocarbon emission level is observed at 4000kPa, which are 20ppm, 19ppm and 15.33ppm for diesel fuel, diesel fuel with 3 l/min hydrogen rate and diesel fuel with 6 l/min hydrogen flow rate respectively. The HC emission level at 4000kPa is reduced to 5% for diesel fuel for 3 l/min hydrogen flow rate and 23.35% diesel fuel for 6 l/min hydrogen flow rate against diesel fuel. According to Figure 7, the oxidation of HC emission line is turning low as the hydrogen flow rate increased because of HC depending on OH, H and so on [12].

The percentage of carbon dioxide emitted during the experiment is shown in Figure 8. At hydraulic loading of 0 kPa, the CO_2 emission indicates 2.53 %, 1.98 % and 1.39 % at 0 l/min, 3 l/min and at 6 l/min correspondingly. Next, the reduction of CO_2 emission at 1000 kPa with hydrogen flow rate (0 l/min 3 l/min and 6 l/min) are 2.73 %, 2.18 % and 1.43 %. Then, at 1500 kPa, the CO_2 emission drop from 2.74 % (0 l/min) to 2.22 % (3 l/min) and 1.55 % (6 l/min). Followed by 3.30 %, 2.70 % and 1.9 % CO_2 emission at 2000 kPa loading. At 2500 kPa, the CO_2 level indicates 3.56 %, 3.29 % and 2.39 % at 0 l/min, 3 l/min and at 6 l/min correspondingly. The CO_2 emission observed at 3000 kPa hydraulic loading is reduced from 3.71 % (0 l/min) to 3.47 % (3 l/min) and 2.59 % (6 l/min). Meanwhile, CO_2 emission at 3500 kPa loading is reduced from 4.43 % (0 l/min) to 4.02 % (3 l/min) and 3.20 % (6 l/min). Finally, at 4000 kPa loading, the CO_2 level indicates 5.56 %, 5.16 % and 3.81 % at 0 l/min, 3 l/min and at 6 l/min correspondingly. The carbon dioxide emission trend line has reduced steadily with the increment of hydrogen rate. This shows that by injecting hydrogen into diesel engine, it can helps to reduce carbon dioxide emission level. However, there is no significant effect on the nitrogen oxide (NOx) emission level. The CO_2 emission line happens due to the absence of carbon in hydrogen fuel also low carbon atom. The result aligns with the works by Jhang *et al.,* [13].

4. Conclusion

In this work, the effects hydrogen addition on engine performance and emission were studied. The operation has been conducted at (3500 ± 100) rpm engine speed with multiple hydrogen rate and hydraulic loading. The presence of hydrogen is introduced to the engine by adding the continuous hydrogen supply through the intake manifold. The brake power pattern has increased up to 3.43% and the fuel savings can reach almost 29.03%. This savings is due to the improvement of fuel combustion process with the addition of the hydrogen which has high flame velocities and high calorific content. Based on the experiment, the CO emission percentage reduces to 61.68%, the HC emission reduces 23.35% and the CO_2 emission percentage drop 31.59% but NO_X emission creates 344.33ppm at 4000 kPa hydraulic loading for 6 l/min of hydrogen rate. Hydrogen gas can be produced through a variety of ways in which different techniques such as fuel cell, coal gasification, partial oxidation process and etc. Every way and technique of production cost depends on the main demand such as electricity and so on [14, 15].

References

[1] Tomita, Eiji, Nobuyuki Kawahara, Zhenyu Piao, Shogo Fujita, and Yoshisuke Hamamoto. "Hydrogen combustion and exhaust emissions ignited with diesel oil in a dual fuel engine." No. 2001-01-3503. *SAE Technical Paper*, 2001.

[2] Lee, Jong T., Y. Y. Kim, C. W. Lee, and J. A. Caton. "An investigation of a cause of backfire and its control due to crevice volumes in a hydrogen fueled engine." *Journal of engineering for gas turbines and power* 123, no. 1 (2001): 204-210.

[3] Tyagi, R. K., and Ravi Ranjan. "Effect of hydrogen and gasoline fuel blend on the performance of SI engine." *Journal of Petroleum Technology and Alternative Fuels* 4, no. 7 (2013): 137-142.

[4] Saravanan, N., and G. Nagarajan. "An experimental investigation of hydrogen-enriched air induction in a diesel engine system." *International Journal of Hydrogen Energy* 33, no. 6 (2008): 1769-1775.

[5] Deb, Madhujit, G. R. K. Sastry, P. K. Bose, and Rahul Banerjee. "An experimental study on combustion, performance and emission analysis of a single cylinder, 4-stroke DI-diesel engine using hydrogen in dual fuel mode of operation." *International journal of hydrogen energy* 40, no. 27 (2015): 8586-8598.

[6] Saravanan, N., G. Nagarajan, and S. Narayanasamy. "An experimental investigation on DI diesel engine with hydrogen fuel." *Renewable energy* 33, no. 3 (2008): 415-421.

[7] Santoso, W. B., R. A. Bakar, and A. Nur. "Combustion characteristics of diesel-hydrogen dual fuel engine at low load." *Energy Procedia* 32 (2013): 3-10.

[8] Maki, Duraid F., and P. Prabhakaran. "An experimental investigation on performance and emissions of a multi cylinder diesel engine fueled with hydrogen-diesel blends." In *World Renewable Energy Congress-Sweden; 8-13 May; 2011; Linköping; Sweden*, no. 57, pp. 3557-3564. Linköping University Electronic Press, 2011.

[9] Saravanan, N., and G. Nagarajan. "Performance and emission studies on port injection of hydrogen with varied flow rates with Diesel as an ignition source." *Applied Energy* 87, no. 7 (2010): 2218-2229.

[10] Hamdan, Mohammad O., Mohamed YE Selim, Salah-AB Al-Omari, and Emad Elnajjar. "Hydrogen supplement co-combustion with diesel in compression ignition engine." *Renewable energy* 82 (2015): 54-60.

[11] Homan, H. S., R. K. Reynolds, P. C. T. De Boer, and W. J. McLean. "Hydrogen-fueled diesel engine without timed ignition." *International Journal of Hydrogen Energy* 4, no. 4 (1979): 315-325.

[12] Guo, Hongsheng, and W. Stuart Neill. "The effect of hydrogen addition on combustion and emission characteristics of an n-heptane fuelled HCCI engine." *International journal of hydrogen energy* 38, no. 26 (2013): 11429-11437.

[13] Jhang, Syu-Ruei, Kang-Shin Chen, Sheng-Lun Lin, Yuan-Chung Lin, and Way Lee Cheng. "Reducing pollutant emissions from a heavy-duty diesel engine by using hydrogen additions." *Fuel* 172 (2016): 89-95.

[14] Hydrogen Fuel Cell. Accessed on May 2017. Web page: http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/production.pdf/.

[15] U.S Department of Energy, Office of Basic Energy Science, Committee on Alternatives and Strategies for Future Hydrogen Production and Use, The Hydrogen Economy: Opportunities, Costs, Barriers and R&D Needs, National Research Council, National Academies Press, Washington, Available at: http:/www.nap.edu/ctalog/10922.html. 2004.

[16] Norani, M. N. M., B. T. Tee, M. Z. Zulfattah, M. N. A. Saadun, A. Hussain, and M. N. Mansor. "Effect of hydrogen injection on diesel engine performance intake: Preliminary result." *Proceedings of Mechanical Engineering Research Day 2016*2016 (2016): 21-22.

[17] M.N.M. Norani, B. T. Tee, M. Z. Zakaria, "Optimizing The Emission Effects of Continuous Hydrogen Injection on Diesel Engine Intake using Taguchi Method." Proceedings of Mechanical Engineering Research Day, UTeM, pp. 35-37. 2017.

[18] M.N.M. Norani, B. T. Tee, M. Z. Zakaria, M. I. Ali. "Effect of Continuous Hydrogen Injection on Diesel Engine Performance and Emission." *International Review of Mechanical Engineering (IREME)*, Vol. 4. pp. 213-221. 2017.