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EXPERIMENTAL INVESTIGATION ON IN-CYLINDER PRESSURE AND EMISSIONS OF DIESEL ENGINE WITH PORT INJECTION HYDROGEN SYSTEM

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ABSTRACT

Towards the efforts of increasing the performance and reducing pollutant emissions of diesel engine, port injection gaseous fuel system is one of the solutions and it is applicable for dual fuel combustion engines. In this study, series of experiments were carried out to study the effect of continuous port injection hydrogen gas on in-cylinder pressure and emissions of unmodified single cylinder diesel engine. Injection of hydrogen results an increase in in-cylinder peak pressure in the range of 5 to 23 bars and exhaust gas temperature in the range of 3.1% to 10.2% throughout all engine speeds. There were also increases in NO_x, CO and CO_2 emissions due to presence of hydrogen ranges between 50 to 200 ppm, 420 to 760 ppm and 1.1% to 4.2% (by volume), respectively. On the other hand, continuous port injection hydrogen addition in diesel engine showed reduction of hydrocarbon (HC) at the average of 15 ppm and O_2 emissions at the average of 6% (by volume).

***Keywords*:** Diesel Engine; Port Injection Hydrogen; In-cylinder Pressure; Emissions

1. INTRODUCTION

The depleting resources of fuel in the world today as well as the understanding of the need of the world environment requires the search for other types of fuel sources that may be renewed if possible. Fuels such as liquid petroleum gas (LPG), natural gas (NG) and hydrogen (H_2) are some of the alternative fuels to traditional ones that are fossil based such as diesel and gasoline. Local and global environmental concerns are another driver in the push toward the alternative fuels. At the global level, scientists warn that the combustion of fossil fuels is causing significant changes to the global climate system by increasing the concentration of greenhouse gases and magnifying the greenhouse effect. The number of vehicles on the road increases everyday. With each vehicle, there exist a proportion of exhaust emissions, which consists of particles that are harmful to the environment and people. With the increase in vehicles, more fuel would be required to cater to the need of consumers. However, the conventional fuel for engine such as diesel and gasoline are fossil based fuel and as such is not renewable (Das, 1990). The availability of these fuels is fast diminishing and an alternative comparable fuel must be discovered quickly to avoid any possible future problems. Such a fuel should also be able to tackle the existing environmental problems of fossil fuel. Hydrogen usage as a fuel for internal combustion engines either directly or indirectly is not new. Experiments have been done decades before to investigate the effectiveness of hydrogen usage as a fuel in combustion engines. The low ignition energies of hydrogen-air mixtures cause frequent unscheduled combustion events, and high combustion temperatures of mixtures closer to the stoichiometric composition lead to increased NO_x production (White et al, 2006). Many studies have been reported on hydrogen combustion in diesel engines. Saravanan et al (2008) conducted research on mixture of hydrogen-diesel combustion in compression ignition engine. In their work, experiments were conducted to study the emission and brake-load performance characteristics at different diesel to hydrogen ratios. There were variable ranges of diesel to hydrogen ratios in between 10% to 90% (by volume). Results indicated that 30% diesel to hydrogen ratio was the optimal for better combustion knock and emissions. Szwaja et al (2009) investigated combustion of diesel and hydrogen mixtures at variable hydrogen percentage. Hydrogen percentages were changed in the range from 0% to 17% (by intake energy) under HCCI (homogeneous charge compression ignition) conditions. They focused more on engine performance especially combustion knock and concluded that 5% (by intake energy) of hydrogen contributed in knock suppression by decreasing rate of combustion pressure rise. Shirk et al. (2008) demonstrated that the addition of hydrogen in the range of 5% to 10% reduced NO_x emissions with negligible effect on brake thermal efficiency of a 4-cylinder light duty common-rail diesel engine. The investigation on the effect of hydrogen enrichment in 4-cylinder diesel engine with exhaust gas recirculation (EGR) was carried out by McWilliam et al. (2008). Hydrogen enrichment with EGR in diesel engine showed improvement of thermal efficiency but NO_x emission was increased substantially. Roy et al. (2009) conducted research on diesel-H_2-CO mixture combustion in single cylinder diesel engine. They observed that single-stage combustion phenomenon under normal load and two-stage combustion process under high load with high heat release at the middle of these combustion processes subsequently increased the amount of heat release rate and improved combustion period. Liew et al (2010) investigated the effect of hydrogen enrichment on a heavy-duty 6-cylinder Cummins diesel engine. They concluded that at 70% load operation with relatively high percentage of hydrogen addition enhanced peak heat release rate and dramatically reduced the combustion duration. With the same amount of hydrogen at 15% load prolonged the diffusion combustion but deteriorated the premixed combustion of hydrogen diesel fuel blends. Generally, in the gas fueled dual fuel compression ignition engine pilot ignition of diesel fuel helps to combust gaseous fuel which provides most of energy release. The optimal parameters for better combustion especially for avoidance of knock at high loads need to be determined for excellent performance and enhanced emissions characteristics (Karim, 2003).

In this paper, the effect of port injection technique of hydrogen gas on in-cylinder pressure and emissions were presented. Series of tests were conducted with continuous hydrogen gas injection at constant rate of 0.10 g/s. The results and analysis presented in this paper provide additional knowledge of hydrogen usage in internal combustion engines including issues in in-cylinder peak pressure, combustion knock analysis and hydrogen-diesel-air combustion in diesel engine.

2. EXPERIMENTAL SETUP

The main engine specifications are summarized in Table 1. The engine was installed with hydrogen injector at the intake manifold (near to intake port).

Table 1 Test Engine Specifications

Device name	Model & Description
Engine	Yanmar l100-AE, 4-Stroke, Air-cooled, direct injection, single cylinder diesel, displacement=406cm^3, compression ratio = 19.3, Diesel injection timing=13°BTDC Max. power output=7.4kW @ 3600rpm
Hydrogen mass flow meter	Model: OMEGA FMA1806 Range= 0-50mL/min
Pressure transducer	Model: KISTLER TYPE 6052C Range= 0-250 bar
Data acquisition system	Model: μ-MUSYCS IMC Mess-Systeme GmbH
Crank angle encoder	Model: KISTLER TYPE 2613B TTL pulse signals resolution = 0.1-0.6° Speed range: 1 - 20,000 rpm

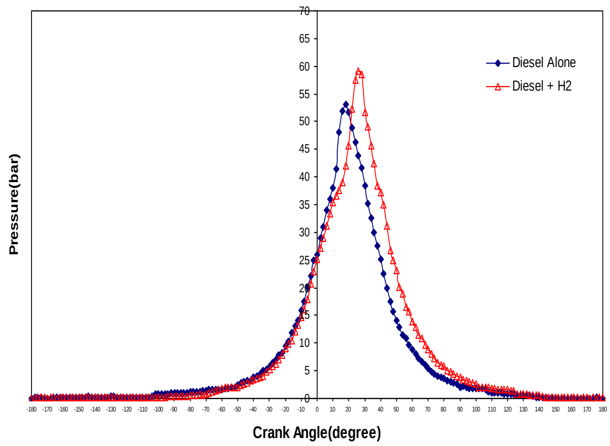
In addition to the operation of the test engine, an efficient safety measure for operating the engine need to be developed. Installation of a single-flow valve and water-flame trap in the hydrogen fuel management system prevents the backfire from entering hydrogen tank that causes massive explosion. Hydrogen is filled into hydrogen storage tank from hydrogen cell until it reaches 2 bar. Hydrogen is then passes through single-flow valve before it enter water-flame trap. Then it passes through flash back arrestor and digital hydrogen mass flow meter. Pressure transducer was installed into the cylinder head and exposed to in-cylinder pressure. Data Acquisition System (DAS) interprets the conditioned input signals from pressure transducer and crank angle encoder and sends them to the computer that was installed with IMC-μ LIGHT software for real-time visualization of P-θ diagram. Experimental works were conducted at the speeds of 1000, 1500, 2000, 2500 and 3000 rpm.

3. RESULT AND DISCUSSIONS

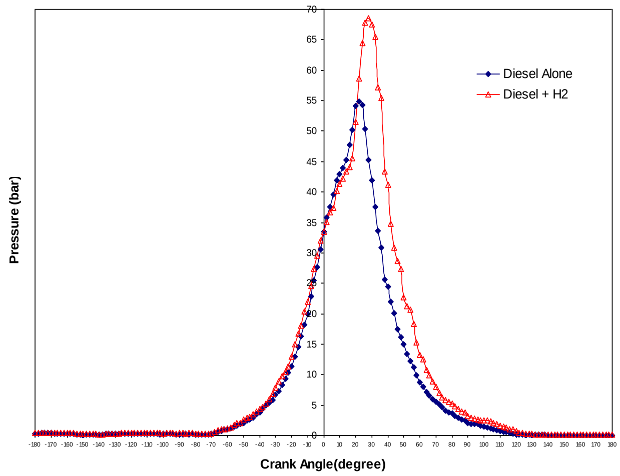
In this study, performance and emissions analyses of diesel engine with port injection hydrogen system ($CEPH_2$) were carried out experimentally. Hydrogen gas was continuously injected to intake airstreams using port injection technique at a constant rate of 0.10 g/s and the result of performance in the form of pressure versus crank angle were extracted from DAS. The emissions data acquired from gas analyzer were recorded for the purpose of comparison in diesel engine with and without hydrogen injection system.

3.1 In-cylinder Pressure

Figure 1 shows an example of measured in-cylinder pressure curves. It can be seen that all curves moves upwards with the same pattern before 10°ATDC (after top dead center) which indicates normal combustion of pilot fuel without pre-ignition and premixed combustion. The pressure curve has the tendency to shift to the right as hydrogen is added into the cylinder charge since hydrogen with high auto-ignition temperature (858K) ignites after pilot ignition of diesel (Shafer et al, 1995). Sudden increase in pressure after 20°ATDC indicates auto-ignition of hydrogen has been reached parallel to pilot ignition of diesel. This is perhaps due to high flame speed of hydrogen (3.24 to 4.40 ms^{-1}) causes fast combustion propagation of the in-cylinder charge which was only initiated from pilot ignition (Li et al, 2003). It can be observed that combustion of $CEPH_2$ occurs with higher peak pressure because of higher heating value (142 MJ/kg) and diffusivity (0.61cm^2/s) of hydrogen (Heywood, 1988). The high diffusivity facilitates the formation of a uniform mixture of hydrogen with other cylinder charge since this contributes greatly to ensure an equal supply of hydrogen to all regions in the cylinder (Joseph et al, 1996). Additionally, and wide range flammability of hydrogen promotes complete combustion of hydrogen throughout the cylinder even within the lean mixture



(a)



(b)

Figure 1 Variations of in-cylinder pressure with crank angle at (a) 1500RPM and (b) 3000RPM

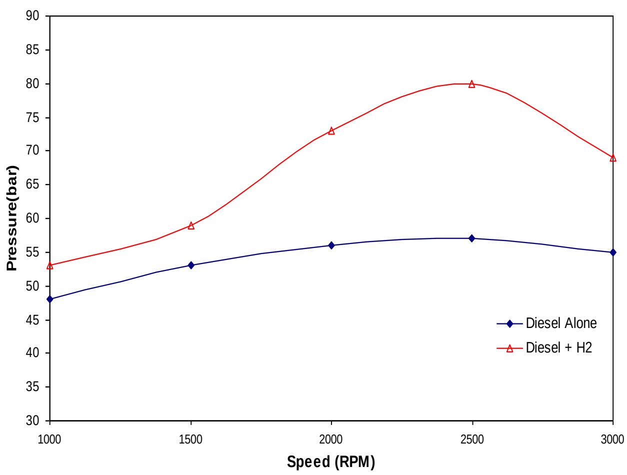


Figure 2 Variation of in-cylinder peak pressure with engine speed

regions. With very lean cylinder charge the bulk of the energy release comes from the ignition and subsequent rapid combustion of the small pilot zone. It comes also from the combustion of part of the charge entrained into the burning pilot fuel and from the immediate surroundings of such a zone where higher temperature and relatively richer mixture regions are present (Liu et al, 2008). The moment all the mixture ignites simultaneously, the heat release is much stronger resulting in a steep pressure gradient at 20°ATDC. The strong heat release also induces enhanced turbulent mixing due to thermal expansion which contributes toward rapid increase in pressure (Karim et al, 1988). Figure 2 shows the comparison between in-cylinder peak pressure of diesel alone and diesel mixed with hydrogen. It indicates that increase in peak pressure from 5 bar to a maximum 23 bar with port injection hydrogen system. At the speed of 2500 rpm, the peak pressure was the highest (80 bar) and this can be related to stronger heat release and more complete combustion as the effects from optimum equivalent ratio of the charge.

3.2 Emissions

3.2.1 Oxides of nitrogen (NOx) emissions and exhaust gas temperature

The variations of experimental NO_x emissions and exhaust gas temperature with engine speed are shown in Figure 3. It shows that NO_x concentration and temperature increases as speed increased until 2500 rpm, further increase in speed drops the temperature and consequently NO_x emissions. It shows the effect of hydrogen on combustion temperature leads to increase of NO_x emissions ranges between 50 to 200 ppm with port injection hydrogen system. Hydrogen increases the energy release, which has a positive contribution to enhance charge temperature to form NO_x (thermal NO_x) in both the flame front and the post flame of the charge.

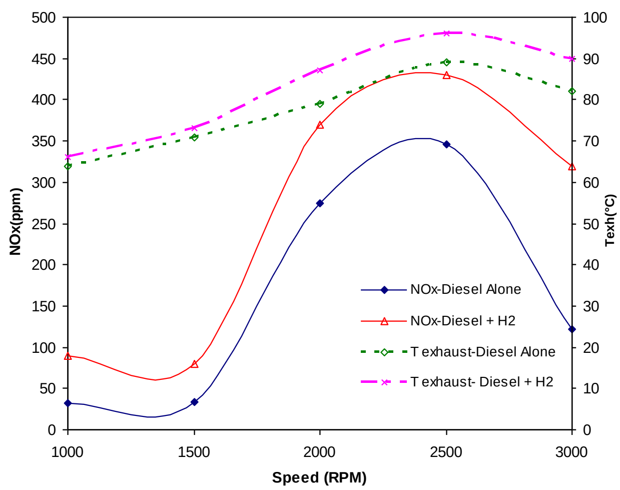


Figure 3 Variation of NO_x emissions and exhaust gas temperature with engine speed

This can be associated with very high local combustion temperature was achieved in the pilot ignition zone which lengthen the reaction time of nitrogen and oxygen in the cylinder. Hydrogen addition causes increase in exhaust gas temperature from 3.1% to 10.2% particularly at 2500 rpm due to faster combustion and high combustion temperature in the cylinder (Kumar et al, 2003).

3.2.2 *Hydrocarbon emissions*

The variation of hydrocarbon (HC) emissions with engine speed is shown in Figure 4. In the dual fuel operation with port injection hydrogen, there was a slight reduction of HC emissions at the average of 15 ppm. One of the possible reasons is the hydrocarbon oxidation. High diffusivity of hydrogen reduces the flame-quenching rate in diesel engine causes wall-quench hydrocarbons apparently diffuse into the burning charge and oxide following the quenching event. Flame quenching can be thought of as a two-stage process. The first step is the extinction of the flame at a short distance from the cylinder wall and determined by a balance between heat conduction from the hot flame zone to the wall and heat released in the reaction zone by the flame reactions. The second step is the post-quench diffusion and oxidation occurring on a time scale of one of a few milliseconds after quenching. The diffusion and oxidation process of hydrocarbon ultimately reduces the mass of wall quench hydrocarbons and leads to increase in other emissions such as CO_2 and CO (Westbrook et al, 1981).

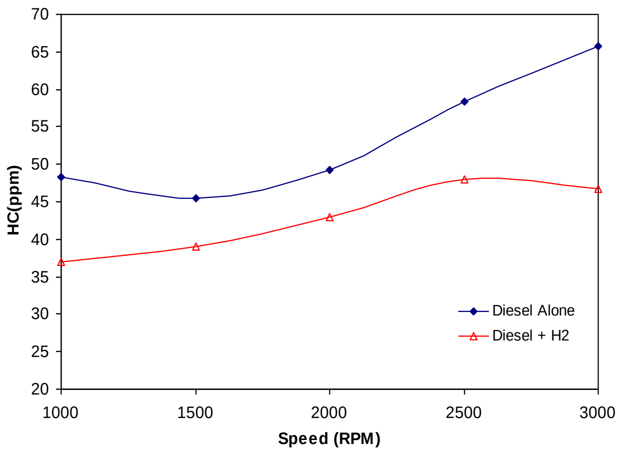


Figure 4 Variation of HC emissions with engine speed

3.2.3 *Carbon dioxide emissions*

In Figure 5, the measured emissions of CO_2 shows significant phenomenon with addition of hydrogen. Port injection technique of hydrogen in unmodified diesel engine causes slight increase in CO_2 emissions ranges between 1.1% to 4.2% (by volume) throughout all engine speeds as comparable with that of conventional diesel fuel. One possible explanation of this phenomena is the dissociation of CO_2 (>1000°C) and H_2O (>1300°C) produces more O_2 at high temperature combustion zone and introduces more complete combustion of the charge at the beginning of expansion stroke. While piston moving down to BDC, pressure and temperature of the charge drops gradually and causes re-association of H_2O and CO_2 which leads to increase of CO_2 emissions

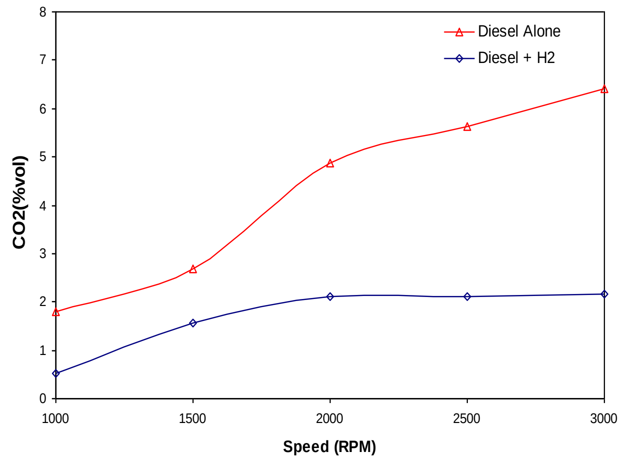


Figure 5 Variation of CO_2 emissions with engine speed

3.2.4 *Oxygen and carbon monoxide emissions*

The variation of emissions of O2 and CO with engine speed is shown in Figure 6. It is observed that the presence of hydrogen fuel in unmodified diesel engine causes increase in CO ranges between 420 to 760 ppm and reduction of O_2 emissions at the average of 6% (by volume) throughout all engine speeds as comparable with that of diesel alone operation. This might be due to higher compression pressure of $CEPH_2$ during compression stroke pushes cylinder charge (containing hydrogen) into the crevices which will return to the cylinder later in the expansion stroke.

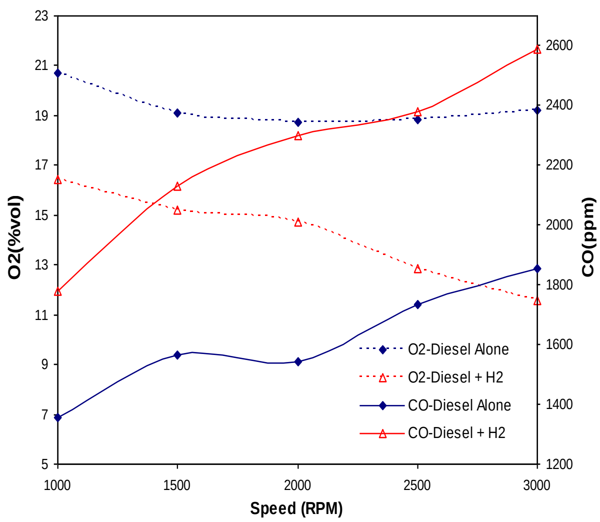


Figure 6 Variation of O_2 and CO emissions with engine speed

The moment exhaust port is opened, blowdown of exhaust gases provides less time for the newly released fuel (from crevice) to oxide and causes fuel rich region and overmixing. With extra formation of local rich zones in the cylinder towards at the end of expansion stroke causes increase of CO emissions due to hydrocarbon oxidation. Another effect of high in-cylinder pressure is dribbling of liquid diesel fuel on the tip of injector nozzle. This small amount of liquid diesel evaporates very slowly because it is surrounded by a fuel-rich region, and once the injector nozzle closes, there is no pressure pushing it to the adjacent combustion region which leads to enlargement of fuel-rich region nearby the injector (Pulkrabek, 2004).

4. CONCLUSIONS

A single cylinder unmodified diesel engine was researched to study its performance and emissions. In the experimental works, the engine was installed with port injection hydrogen system in order to supply constant amount of hydrogen gas into the combustion chamber. Input data such as in-cylinder pressure and crank angle were obtained from data acquisition system. Exhaust gas emissions was analyzed based on data acquired from gas analyzers. From the above analysis and discussion, the conclusions and recommendations were provided as following:

- Port injection of hydrogen increases the in-cylinder peak pressure ranges between 5 bar to 23 bar comparable to diesel alone operation and the highest peak pressure occurs at 2500 rpm.
- Higher peak pressure shows better network output of the engine as compared to the engine running on diesel alone.
- The presence of hydrogen causes a slight decrease in HC emissions at the average of 15 ppm as compared to diesel alone operation due to hydrocarbon oxidation.
- Hydrogen injection causes CO_2 and CO emissions increased from 1.1% to 4.2% (by volume) and 420 to 760 ppm, respectively as compared to diesel alone operation.
- The reduction of O_2 emissions at the average of 15 ppm (by volume) is due to hydrocarbon oxidation, crevice effect and formation of local fuel rich region.
- Hydrogen increases the energy release, which has a positive contribution to enhance charge temperature causes increase in NO_x concentration ranges between 50 to 200 ppm and exhaust gas temperature ranges between from 3.1% to 10.2% throughout all engine speeds.

The above results suggest that port injection hydrogen increases the performance and reduces HC emissions. The most significant environment penalty will be a slight increase of NO_x and CO emissions. Port injection technique of hydrogen gaseous fuel has the potential to overcome much of problems faced by diesel engine especially on its emissions matters. Thus, it seems that $CEPH_2$ shows a promising technique for controlling combustion pressure and HC emissions on unmodified engine. The observed disadvantages concerning NO_x and CO emissions can be possibly overcome by applying modifications in fuels injection timing. After all, there is room for continuous improvement to optimize the emissions, efficiency and performance through better understanding of combustion processes in diesel engine equipped with port injection hydrogen system.

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