Load Variation Effects on Combustion Regimes in A Hydrogen-Diesel Dual Fuel Engine

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Abstract

This work presents an experimental study about the impacts of the use of hydrogen as a partial substitution in a direct injection diesel engine. Hydrogen gas was fumigated into the intake manifold of a single cylinder diesel engine to mix with fresh air before entering the combustion chamber of the engine at constant speed with load variation. The homogeneous charges of air-hydrogen mixture were then ignited in the chamber by the main diesel injected. The added hydrogen amounts generated the hydrogen-to-diesel ratios. These affect combustion pressure, heat release rate, and combustion variation in the three regimes investigated, i.e. ignition delay, premixed combustion phase, and mixing-controlled combustion phase as well as the heat release in each combustion phase due to the different hydrogen-to-diesel ratios. The obtained results have shown the reductions in diesel and total fuel consumptions, including exhaust gas emissions when adding hydrogen. These lead the thermal efficiencies to be higher when adding hydrogen. The benefits of this research will be appropriately used in the improvement and development of hydrogen-diesel dual fuel engine and its fuel strategy management in the near future.

Keywords : Hydrogen, dual fuel, diesel, engine, thermal efficiency

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1. Introduction

Current economic growth has posted a significant increase in power consumption, especially diesel fuel used for both in industrials and transportation. In effects, an amount of fossil diesel fuel is likely to decline in contrast to the continuously increased fuel price. To mitigate this trade-off, a number of renewable energy resources are pursued and discovered in order to lower the fossil diesel consumption. Hydrogen is one of the popular alternatives widely used today [1-3] due to its high power element and is available in a number of compounds which can be produced from various sources such as natural gas, coal, biomass, water and other [4].

Hydrogen can be industrially produced by the current available methods [5-8] such as steam reforming (Eq.1), partial and complete oxidation (Eq.2 and Eq.3, respectively), water-gas-shift reaction (Eq.4), and auto-thermal reforming (Eq.5) [9].

$$C_xH_yO_z+(x-z)H_2O \rightarrow xCO+(x+\frac{y}{2}-z)H_2, \Delta H_r>0 \quad (1)$$

$$C_xH_yO_z+(\frac{x}{2}-\frac{z}{2})O_2 \rightarrow xCO+\frac{y}{2}H_2, \Delta H_r<0 \quad (2)$$

$$C_xH_yO_z+(x+\frac{y}{4}-\frac{z}{2})O_2 \rightarrow xCO_2+\frac{y}{2}H_2O, \Delta H_r<0 \quad (3)$$

$$CO+H_2O \rightarrow CO_2+H_2, \Delta H_r<0 \quad (4)$$

$$C_xH_yO_z+(x-\frac{z}{2}-\frac{1}{2})O_2+H_2O \rightarrow xCO_2+(\frac{y}{2}+1)H_2, \Delta H_r<0 \quad (5)$$

Steam reforming is the most common method to produce commercial bulk hydrogen but it involves a strongly endothermic reaction [10]. At high temperatures in the presence of a catalyst, steam reacts with hydrocarbons to yield carbon monoxides and hydrogen. Partial oxidation reforming reacts preferably with the fuel at sub-stoichiometric oxygen/fuel ratio. The limited amount of oxygen restricts the oxidation of the fuel to yield carbon dioxide and water. This process and complete oxidation in Eq.3 are not efficiently due to their inherently exothermal reaction. The produced carbon monoxide from steam reforming can combine with excess steam to produce further hydrogen via the water-gas-shift reaction [11]. The auto-thermal reforming is taken place by feeding the fuel, steam, and oxygen together into the catalytic reactor. The overall reaction is a slightly exothermic process [10].

Alternative fuels such as natural gas, methane and hydrogen are applied in the diesel engines [12-13]. Diesel dual-fuel engine concepts using gaseous hydrogen addition as a pre-mixed charge have been studied [14]. Either by direct mixing in the intake manifold with air or by injection directly into the cylinder [12]. After compression, the well mixed charge is then ignited just before top dead centre by the conventional injection of the main diesel fuel. Tomita et al. [14] found on the hydrogen-diesel dual engine that, due to the hydrogen-premixed charge, lean mixture combustion results in the reduction of some regulated emissions while maintaining comparable thermal efficiency to that of diesel combustion. In addition, hydrogen is also used to enhance the performance of diesel engine fuelled with biodiesel [15].

Saravanan and Nagarajan [16] injected hydrogen into the engine manifold in conjunction with electronic control fuel injection timing and duration. The study found that the timely injection of hydrogen gas results in 15% improvement of engine efficiency, 3% NO_x emissions penalty while black smoke reduced by nearly 100%.

Roy et al. [17] investigated the air pollution emitted from hydrogen-diesel dual fuel supercharging engine. Diesel fuel is injected into the cylinder as a pilot injection at constant pressure and injection quantity. Their experiments focused on the optimisation of the fuel injection timing to get the maximum power from the engine without knocking. The lean limit was found to be 0.3 (if less than this will cause engine knock). At this point, the indicated mean effective pressure was 908 kPa and thermal efficiency was 42%.

Gatts et al. [18] tested six-cylinder diesel engines, heavy-duty 10.8 l cylinder with a turbocharger running on hydrogen-diesel dual fuel mode. Their study found that the addition of hydrogen to the engine at high load results in better combustion efficiency. The hydrogen emission was 0.13% when adding 6% hydrogen at the engine load of 70%. However, adding hydrogen at low engine load gave a controversy effects to the pollution from hydrogen emission. The highest hydrogen emission was 1.4% when adding hydrogen 6% at 10% engine load. A large additional quantity of hydrogen gas at low engine load showed adverse impacts on brake thermal efficiency.

This research is an experiment of one cylinder of diesel engine that uses hydrogen as a fuel adding to the diesel engine in dual fuel mode at constant engine speed of 1600 rpm. The behaviors in the combustion chamber are considered including pressure in the cylinder, temperature and the process of burning are analyzed to enhance the phenomenon of the combustion [3]. The results affect exhaust gases which release from engine including smoke and oxides of nitrogen which has a direct impact on the environment [19]. The load variations are concerned in the term of indicated mean effective pressure 3.2 and 4.3 bar. The results are shown and discussed in the paper.

2. Experimental apparatus and methods

2.1 Test engine

All test protocols were experimentally studied using a single cylinder Kubota RT100 diesel engine, which is naturally aspirated and water-cooled with a pump-line-nozzle direct injection system. More detailed engine specification is given in Table 1.

2.2 Engine instrumentation

The single cylinder diesel engine test rig consists of a prony type brake dynamometer used to load the engine and coupled with a load cell type 613 from Tedea-Huntleigh Electronics combined with digital indicator type CM-013 from Primus (±0.25% FS error). In-cylinder pressure traces were acquired by a Kistler 6052C type pressure transducers with a Dewetron DEWE-30-4 charge amplifier at crank shaft positions determined by a 360-ppr incremental shaft encoder from Kübler, and recorded by a data acquisition board Dewetron DEWE-ORION-0816-100x installed in a Windows-based PC. The DEWEsoft 6.6.9 software was used to obtain pressure data and also analyses combustion parameters. Readings of atmospheric conditions in terms of temperature, pressure, and humidity were recorded by the in-house developed LabVIEWv.8.6 Full Development System based software with the acquisition card National Instruments NI USB-6218 in order to use as input to the software for cylinder pressure corrections. The experimental system also involved other standard engine test rig instrumentation, i.e. a volumetric fuel flow meter and several local temperature measurement devices.

2.3 Test fuel

The liquid main fuel used throughout the experiment was local diesel with key properties listed in Table 2 [20].

The analytical grade hydrogen gas in bottle with 99.99% purity from Praxair was regulated, filtered and equipped with flash-back arrestor prior to entering the hydrogen volumetric gas meter. The hydrogen was fed to the engine by fumigation through a manual valve and a rev-detected solenoid valve at the intake manifold 10 cm upstream of the intake valve.

Table 1 Engine specification

Measurement	Specification
Displaced volume (cc)	547
Bore (mm)	88
Stroke (mm)	90
Maximum Power	7.4 kW @ 2400 rpm
Maximum Torque	33.4 Nm @ 1600 rpm
Compression ratio	18 : 1

Table 2 Fuel properties

Fuel analysis	Method	Diesel	Hydrogen
Cetane number	ASTM D613	53.9	Very low
Density@15°C (kg/m3)	ASTM D4052	827.1	0.084
Viscosity@40°C (cSt)	ASTM D445	2.467	N/A
LHV (MJ/kg)		42.7	120.0
Sulphur (mg/kg)	ASTM D2622	46.0	0.0
Total aromatic (wt%)		24.4	0.0
Molecular weight		209	1
C (wt%)		86.5	0.0
H (wt%)		13.5	100.0

2.4 Emission analysis

Nitrogen oxides (NO_x) emissions from the engine including nitric oxide (NO) and nitrogen dioxide (NO_2) were measured on a dry basis using Testo 350XL exhaust gas analyzer. The range of NO measurement is in 3,000 ppm range while that of the NO_2 is in 500 ppm range. Both measurements are within 5 ppm accuracy.

Smoke was partially sampled at engine-out condition and measured by Motorscan Smoke Module 9010 in the unit of opacity percentage. The smoke meter is able to measure within the range of 0 to 100% opacity and is within 0.05% opacity accuracy.

2.5 Test condition and procedures

All steady-state test schemes were set at the engine speed of 1,600 rpm. Studying the load variation was carried out at 3.2 bar and 4.3 bar imep (indicated mean effective pressure) covering a major range of the load conditions at this engine speed, without exhaust gas recirculation (EGR). The effects of the hydrogen addition were carried out using hydrogen flow rate of 0 and 20 lpm. The recorded engine brake power and fuel mass flow rate for both diesel and hydrogen were used to calculate the brake specific fuel consumption (bsfc) for diesel, hydrogen and total fuel consumption for each engine test condition.

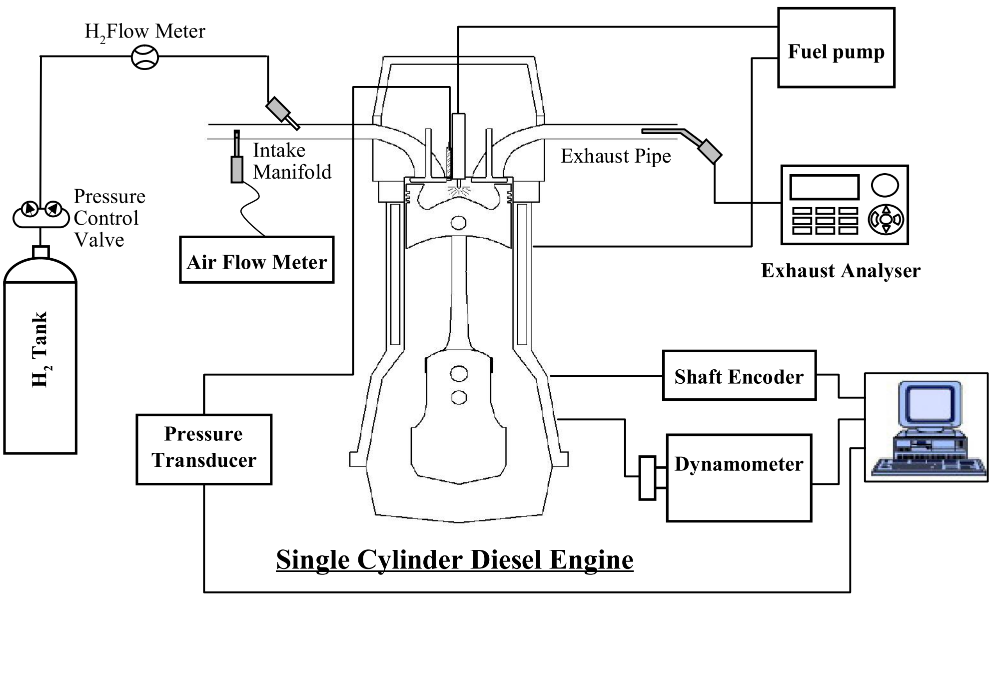

Fig. 1. Engine test installation diagram

In performing the combustion analysis, the aforementioned software has been used to acquire data in consecutive engine cycles in order to study the statistics of cylinder pressure, imep, coefficient of variation (COV) of imep etc. For each test condition, the cylinder pressure data from 100 consecutive engine cycles has been acquired, and averaged values are presented here as typical representatives. Such combustion characteristics i.e. rate of heat release (RoHR), ignition delay and combustion duration were derived for discussion using the first law of thermodynamics for a single open system.

The engine and all instruments were installed and they can be depicted as shown in Fig. 1.

3. Results and Discussion

3.1 Cylinder pressure and heat release rate

The in-cylinder pressure and heat release rate versus crank angle degree data over the end of compression and the early expansion strokes of the engine running with and without hydrogen addition are shown in Fig. 2 and 3 for 3.2 and 4.3 bar imep load, respectively.

For the same load, the combustion of hydrogen-diesel dual fuels apparently resulted in decreasing peak cylinder pressures. These effects can also be seen for different engine loads. This may be from the use of hydrogen fumigation generating a homogeneous intake charge. When reaching to the end of the compression stroke as the main diesel is injected, the mixture combusts without the pressures beyond those when hydrogen is not added. It can be seen evidently that when hydrogen was added, at the same load, the heat release rate after the main diesel fuel injection was manifestly negative. Prior to releasing heat of combustion, the reaction was endothermic at higher level for the hydrogen dual fuel mixture. This may deteriorate the premixed combustion phase by lowering the heat release rate as a result of decreasing cylinder pressure when adding hydrogen. As the load increases, the peak pressures were also increased as the gas residual and combustion chamber wall temperature, and hence higher gas temperature and pressure.

The rate of heat release in Fig. 2 and 3 shows eminent premixed combustion while the mixing controlled combustion are not outstanding. This is due to engine characteristics which is a direct injection combustion chamber. The rate of heat release in the premixed combustion decreased when adding hydrogen and, prior to ignition, heat consumptions were more pronounce when hydrogen was added.

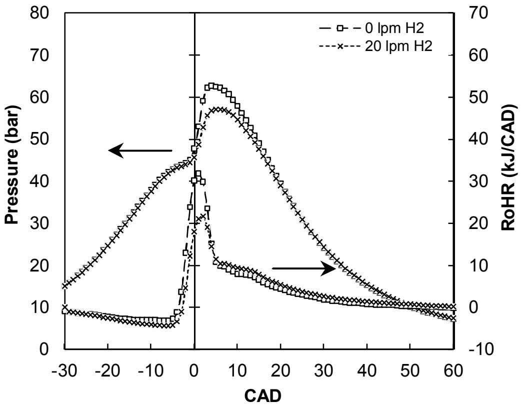

Fig. 2. Cylinder pressure and rate of heat release (RoHR) from dual fuel engine at 1600 rpm, 3.2 bar imep

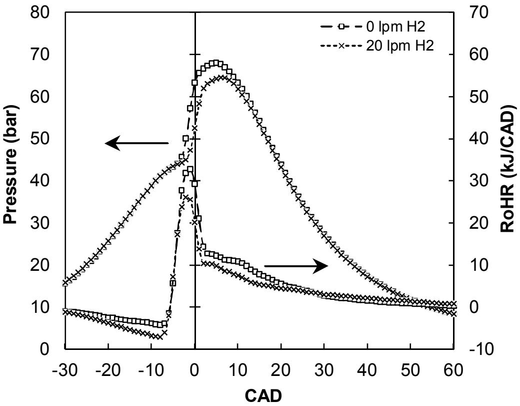

Fig. 3. Cylinder pressure and rate of heat release (RoHR) from dual fuel engine at 1600 rpm, 4.3 bar imep

3.2 Fuel consumption and efficiency

The diesel and hydrogen brake specific fuel consumptions are shown in Fig. 4. The increase in engine load results in bsfc reductions for both diesel and hydrogen, due to enhanced brake output. At the same load, the added hydrogen results in the reduction of diesel consumption. The hydrogen consumption at low load was greater than that at high load as at the low load; the engine produces lower brake output.

The total bsfc values shown in Fig. 5 were lower when adding hydrogen for both loads. The greater effect has been seen for the higher load. These bring about the thermal efficiencies to be higher when adding hydrogen.

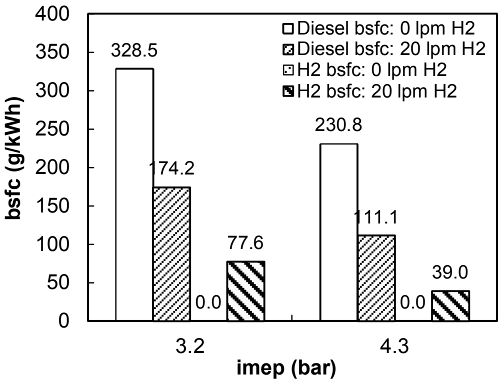

Fig. 4. Diesel and hydrogen brake specific fuel consumption

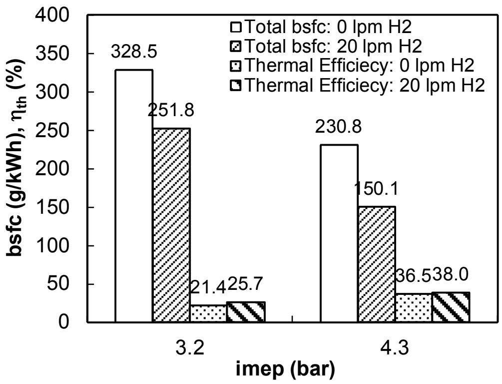

Fig. 5. Total fuel consumption and thermal efficiency

3.3 Delay, combustion duration and stability

Fig. 6 shows the ignition delay in crank angle degree (CAD). When hydrogen was added, the ignition delay was longer. Meanwhile, the greater the load of the engine, the shorter the ignition delay of the mixtures. This is due to higher temperatures of the residual gas and the combustion chamber wall, preferable ease to combust. With the greater effects at high load, the combustion durations were longer when hydrogen was added, due to the aforementioned homogeneous charge gently ignites, leaving the fuel for the late combustion, hence longer duration but generating more combustion instability (Fig. 7).

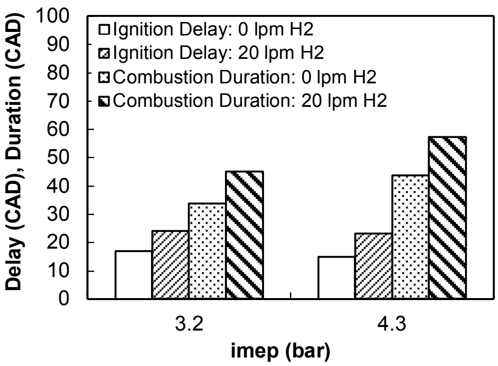

Fig. 6. Ignition delay and combustion duration

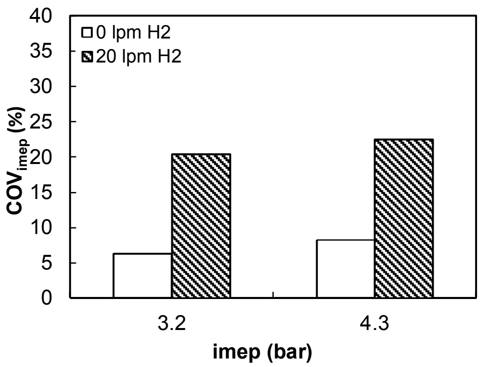

Fig. 7. Coefficient of variation of imep

3.4 NO_x-smoke trade-off emissions

The NO_x and smoke emissions at two different loads with and without hydrogen addition are shown in Fig. 8. Without hydrogen addition, the lower load combustion generates greater smoke at lower NO_x emissions, due to the lower combustion temperatures. When hydrogen was added, smoke drastically reduced while NO_x emissions penalty can be observed. By this manner, it is possible to use the EGR to break this NO_x-smoke trade-off. However, an optimization between hydrogen addition and EGR is rudimentarily required in order to maintain this trade-off to be within scope of acceptability.

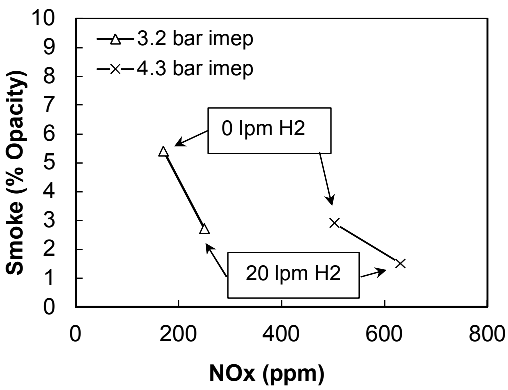

Fig. 8. NO_x–smoke emissions

4. Conclusions

The load variation at constant speed of the diesel engine running on diesel-hydrogen dual fuel affects combustion pressure and characteristics. As the load increases, the peak pressures were increased due to the higher gas residual and wall temperature. When hydrogen was added, the ignition delay was longer. Meanwhile, the greater the load of the engine, the shorter the ignition delay of the mixtures. The heat release in each combustion phase was due to the different hydrogen-to-diesel ratios. It shows eminently in the premixed combustion and decreases when adding hydrogen and, prior to ignition, heat consumptions were more pronounce. These change diesel, hydrogen and total fuel consumptions. The total bsfc values were lower when adding hydrogen especially at higher load. These lead the thermal efficiencies to be higher when adding hydrogen. This work benefits to future development of hydrogen-diesel dual fuel engine with its fuel strategy management.

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