Research Article

Study of Knocking Effect in Compression Ignition Engine with Hydrogen as a Secondary Fuel

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Received 5 November 2013; Accepted 3 December 2013; Published 24 February 2014

Academic Editors: Z. Li and Z. Sha

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The aim of this project is detecting knock during combustion of biodiesel-hydrogen fuel and also the knock is suppressed by timed injection of diethyl ether (DEE) with biodiesel-hydrogen fuel for different loads. Hydrogen fuel is an effective alternate fuel in making a pollution-free environment with higher efficiency. The usage of hydrogen in compression ignition engine leads to production of knocking or detonation because of its lower ignition energy, wider flammability range, and shorter quenching distance. Knocking combustion causes major engine damage, and also reduces the efficiency. The method uses the measurement and analysis of cylinder pressure signal for various loads. The pressure signal is to be converted into frequency domain that shows the accurate knocking combustion of fuel mixtures. The variation of pressure signal is gradually increased and smoothly reduced to minimum during normal combustion. The rapid rise of pressure signal has occurred during knocking combustion. The experimental setup was mainly available for evaluating the feasibility of normal combustion by comparing with the signals from both fuel mixtures in compression ignition engine. This method provides better results in predicting the knocking feature of biodiesel-hydrogen fuel and the usage of DEE provides complete combustion of fuels with higher performance, and lower emission.

1. Introduction

The demand for fossil fuels gets increased by more usage of transportation and automobile. The use of fossil fuels emits more emissions such as HC, CO, CO₂, and NO_x and also makes harmful environmental condition. The best solution for this problem is to move on to alternative fuels. Hydrogen is the most effective alternative fuel which reduces the emission and fuel consumption and also provides better performance. Hydrogen has some limitations such as backfire and preignition. Saravanan et al. [1] proposed that the direct injection (DI) diesel engine was used to test the performance and emission of an engine. Hydrogen was injected at the intake port of the engine and diesel can be used as an ignition source. In order to improve the efficiency, the knocking combustion occurred as a major problem due to some properties of hydrogen fuel such as wider flammability range and shorter quenching distance. The biodiesel can be used as an ignition source instead of diesel which reduces the

emissions of particulate matter and limits the autoignition condition. There is a possible minimum emission of NO_x at higher load conditions.

Zhen et al. [2] projected that the knock detection is to be done on several types of methods. These methods are in-cylinder pressure analysis, heat transfer analysis, light radiation, cylinder block vibration analysis, intermediate radicals and species analysis, ion current analysis, and exhaust gas temperature analysis. The most suitable methods are in-cylinder pressure analysis and heat transfer analysis. The knock intensity is the maximum amplitude of cylinder pressure fluctuation and rapid increase of pressure signal and heat release rate provides the information about abnormal combustion.

Wannatong et al. [3] determined that the knocking in engines leads to damaging the engine and limits the performance of the engine. The combustion and knock characteristics can be determined for diesel and dual fuel (Diesel and Natural Gas) by varying the temperature of intake

TABLE 1: Fuels properties.

Properties	Biodiesel	Hydrogen	Diethyl ether
Chemical formula	—	H ₂	C ₂ H ₅ OC ₂ H ₅
Auto Ignition Temperature (K)	535	858	433
Calorific value (MJ/kg)	38.5	119.9	33.9
Density (kg/m ³)	885	0.0837	713
Viscosity at 15.5°C, centipoises	—	—	0.023

mixture, increasing the amount of natural gas, mixture of diesel and natural gas. Engine knocks were noted for every increase of temperature of intake mixture and increasing the amount of natural gas. In this process, the higher intake temperature fastened the combustion and made autoignition of fuel before flame arrival. The rapid increase of cylinder pressure has shown the onset of knock in engine.

The knock detection method is to be done on the cylinder pressure, block vibration, and sound pressure signal in spark ignited (SI) engine. The three knock harmonic frequencies were estimated by analyzing the cylinder pressure signal under various operating conditions in spark ignited (SI) engine. The filtered pressure signal can be used to predict knock intensity and also helps to remove background noise. The knock windows and knock frequencies were determined by Lee et al. [4].

Brunt et al. [5] have made a comparison of calculated peak pressures at crank angle resolution for constant speed and also found out the peak knock pressure for all cycles. The measurement and analysis of cylinder pressure is used to obtain accurate knocking combustion. The knock intensity is to be determined by the maximum variability of peak pressure and its filtered data.

2. Fundamentals

2.1. Hydrogen Fuel. Hydrogen has clean burning characteristics that provide an efficient operation in CI engine. Hydrogen can be used as a secondary fuel in an internal combustion engine. The hydrogen burning combines with oxygen to form water and no other combustion products (except for little amounts of NO_x). Hydrogen cannot be ignited by compression due to higher autoignition temperature (585°C) than diesel fuel (180°C). Biodiesel is used as an ignition source for hydrogen fuel during combustion of compression ignition engine (Table 1).

2.2. Knock Fundamentals. Due to presence of some constituents in the fuel used, the rate of oxidation becomes so great that the last portion of the fuel-air mixture gets ignited instantaneously, producing an explosive violence, known as knocking. The explosive ignition of fuel-air mixture before the propagating flame is increasing successive cylinder pressure oscillations. The well-examined external mixing of hydrogen with the intake of air causes backfire and knock, especially at higher engine loads. The abnormal combustion of hydrogen fuel in CI engine will produce an increased chemical heat release rate, which results in a rapid pressure

Experimental setup

FIGURE 1: Experimental setup.

TABLE 2: Engine specification.

Name	Specification
Type	4-Stroke, Single Cylinder Diesel
Engine Make	Kirloskar
Power	5.2 kW
Speed	1500 rpm
Stroke	110 mm
Bore	87.5 mm
Capacity	661 cc

rise and higher heat rejections. The maximum amplitude of pressure oscillation and analysis of exhaust temperature is a good indicator for severity of the knock.

3. Experimental Setup

In this study, a single cylinder, four strokes, water cooled direct injection diesel engine was operated as dual fuel engine which uses hydrogen and biodiesel shown in Figure 1. The engine details are shown in Table 2. Hydrogen fuel is stored in a storage cylinder. A pressure regulator was used to regulate hydrogen passed to flame arrester through flow control valve and check valve. Check valve is used to pass hydrogen in forward direction alone and it can be closed if any gas returns from CI engine. Flame arrester can have 3/4th filled water in an enclosed tank to restrict backfire to hydrogen cylinder during combustion. Hydrogen fuel is fed at the inlet manifold in diesel engine. DEE is to be fed at the inlet port before the hydrogen port is used. A pressure transducer was used to pick up peak pressure oscillation during the combustion of fuel. The pressure signal is acquired by PC data acquisition system.

4. Frequency Analysis of Pressure Signal

The pressure transducer is used to record the in-cylinder pressure signal with respect to crank angle. This signal can be acquired using PC data acquisition system and the crank angle is got from rotary encoder coupled with crank shaft.

FIGURE 2: Program for FFT conversion.

This signal is given to power spectral analysis tool in LabView software which converts the given signal into frequency domain. The conversion of pressure signal into frequency domain is shown in Figure 2. The frequency signal is used to predict the knocking combustion of engine during abnormal conditions.

5. Result and Discussion

Experimental tests were carried out for biodiesel-hydrogen mixtures and biodiesel-hydrogen mixture with DEE at various loads. The pressure signal variation and its power spectrum can be shown in Figures 3 and 4. The engine has been run on biodiesel-hydrogen mixtures from no load to full load. In normal combustion, the pressure signal gradually reaches the peak value after Top Dead Centre of the piston (TDC) of greater than 3600 of crank angle and again smoothly decreases to minimum value of the pressure.

In knocking combustion, the peak pressure signal gets rapid oscillation at every crank angle. After crossing the load of 52%, there could be a maximum oscillation in peak pressure compared to light load, as well as a significant notification from power spectrum of pressure signal. From the power spectrum signal, the first harmonic knocking frequency can be found as 1.65 kHz for 70% and 80% load and second harmonic frequency is 2.4 kHz and 2.3 kHz for 70% and 80% load, respectively. There are no harmonic frequencies found for biodiesel-hydrogen with diethyl ether. Next, the engine was run on biodiesel-hydrogen mixture and diethyl ether can be injected at the intake valve opening moment in an engine. The different types of load can be applied to these mixtures and the signal can be noted down. This result shows that complete combustion of engine during

the application of higher loads. Along with the analysis of pressure signal, the exhaust gas temperature and brake specific fuel consumption can be considered to find out the knocking behavior of the engine.

5.1. Combustion Characteristics. The cylinder peak pressure variation and its power spectrum are given in Figures 3 and 4. The peak pressure and pressure oscillation are higher for the biodiesel-hydrogen fuel mixture when compared to the diethyl ether. The biodiesel fuel can act as a main fuel which can be injected at direct injection port and hydrogen is supplied at intake manifold whose flow rate is fixed at 0.5 lpm. In biodiesel-hydrogen, the hydrogen fuel properties make the abnormal combustion in compression ignition engine. This can be got from analysis of pressure signal and its power spectrum. The pressure signal can be got from PC data acquisition system which is given in the LabView software. This can be converted into frequency domain. In part load, there is no rapid rise or oscillation of pressure signal during combustion phase. This shows that the complete combustion fuel mixture takes place at minimum load. After injecting the diethyl ether with the biodiesel-hydrogen, there are no changes in pressure signal during minimum (<60%) load. The flow rate of diethyl ether is optimized at 0.25 g/min, according to the signal got from the engine during the operation. The diethyl ether helps to reduce the abnormal combustion to take place at maximum (>60%) load. The diethyl ether reduces the peak pressure occurring during the combustion of fuel due to lag in ignition timing and acts as an ignition improver. The autoignition can be prevented by supplying diethyl ether as an additive. The knocking combustion can be found at higher load and after applying

FIGURE 3: (a) In-cylinder pressure signal for biodiesel and hydrogen at various loads. (b) Power spectrum of pressure sign.

diethyl ether smooth combustion of fuel mixture takes place inside the engine.

5.2. Performance Characteristics. The performance of biodiesel-hydrogen fuel and biodiesel-hydrogen fuel with DEE can be shown in Tables 3 and 4, respectively. The performance

can be noted for various applications of load up to 80% load. The exhaust temperature is taken from the thermocouple sensor. The performance of engine during knocking and nonknocking can be evaluated using these equations.

The power and efficiency can be calculated from these formulas.

FIGURE 4: (a) In-cylinder pressure signal for biodiesel and hydrogen with DEE at various loads. (b) Power spectrum of pressure signal.

(i) Indicated power

$$IP = \frac{n P_{mi} L A N k * 10}{6} \text{ kW}, \quad (1)$$

where P_{mi} indicated mean effective pressure in bar, n indicated number of cylinders, L indicated length of stroke in m, A indicated area of piston in m^2 , N

indicated speed in rpm, and k indicated 1/2 (for four-stroke engine).

(ii) Brake power

$$BP = \frac{2\pi N T}{60 * 1000} \text{ kW}, \quad (2)$$

where N is speed in rpm and T is torque in Nm.

TABLE 3: Performance of Biodiesel and hydrogen.

Sl. no.	Load (kg)	Exhaust temperature T_3 ($^{\circ}\text{C}$)	Indicated power, IP (kW)	Brake power, BP (kW)	BSFC = FC/BP (kg/kW-hr)	Mech Efficiency = BP/IP (%)
1	0	198	2.68715	0.2835	1.84282	10.55151
2	2	229	3.084022	0.8506	0.69387	27.58103
3	4	247	3.472626	1.4176	0.46834	40.8243
4	6	273	3.753743	1.9847	0.37341	52.87376
5	8	338	4.274637	2.5518	0.32021	59.69665
6	10	375	4.812067	3.1188	0.30051	64.81384
7	12	410	5.275084	3.6859	0.28817	69.81384
8	14	505	5.820782	4.2530	0.27749	73.06622
9	16	564	6.449162	4.8200	0.27545	74.73987

kW: Killowatt, $^{\circ}\text{C}$: Degree Celcius, kg: killogram; hr: hourhenry.

TABLE 4: Performance of biodiesel and hydrogen with DEE.

Sl. no.	Load (kg)	Exhaust temperature T_3 ($^{\circ}\text{C}$)	Indicated power, IP (kW)	Brake power, BP (kW)	BSFC = FC/BP (kg/kW-hr)	Mech Efficiency = BP/IP (%)
10	0	194	2.48045	0.283	2.14154	11.4308
11	2	224	2.70369	0.850	0.80882	31.46093
12	4	255	3.47263	1.417	0.55646	40.8243
13	6	291	3.81162	1.984	0.42659	52.07091
14	8	327	4.23330	2.551	0.38290	60.27963
15	10	361	4.72112	3.118	0.34491	66.06244
16	12	404	5.21721	3.685	0.30774	70.64998
17	14	451	5.69676	4.253	0.30015	74.65692
18	16	520	6.18458	6.184	0.29316	77.9373

kW: Killowatt, $^{\circ}\text{C}$: Degree Celcius, kg: killogram; hr: hourhenry.

(iii) Mechanical efficiency

$$\eta_{\text{mech}} = \frac{\text{BP}}{\text{IP}}. \quad (3)$$

Figure 5 shows the variation of exhaust gas temperature with respect to load. It is observed that the exhaust gas temperature of biodiesel-hydrogen is similar to that of those fuel mixtures along with DEE for below 60% of load. When the amount of load was increased, the engine experienced knocking level due to improper combustion of fuel (fuel mixture remains same to find out knocking level). The exhaust gas temperature gets increased for the load above 70% due to late combustion of fuel increasing the exhaust gas temperature. The hydrogen fuel gets accumulated in full throttle running of an engine during higher load. The injection of diethyl ether leads to providing normal combustion of engine, and the complete combustion of fuel takes place due to timed injection of DEE at the inlet port.

Figure 6 shows the variation of brake specific fuel consumption for various fuel mixtures with respect to load. The brake specific fuel consumption is mainly based on the torque

FIGURE 5: Exhaust temperature variation with load.

FIGURE 6: Brake specific fuel consumption variation with load.

delivered by the engine with respect to the mass flow rate of fuel delivered to the engine.

It is observed that the brake specific fuel consumption of biodiesel-hydrogen with DEE is decreased with the load increasing to maximum. In case of hydrogen-biodiesel, brake specific fuel consumption is increased because of knocking combustion. When there is a decrease in brake specific fuel consumption, it also decreases the brake thermal efficiency of the engine. The brake specific fuel consumption is well decreased at minimum load compared to higher load, while applying diethyl ether during the combustion of fuel mixture.

Figure 7 shows the variation of mechanical efficiency for various fuel mixtures with respect to load. The mechanical efficiency is defined as the ratio of brake power to the indicated power. It is observed that the mechanical efficiency of biodiesel-hydrogen with DEE increases for load above 50%. There is a slight increase of mechanical efficiency for the 10% load. The increase in mechanical efficiency in the case of hydrogen-biodiesel with DEE operation is mainly due to higher charge intake leading to complete combustion and the energy release is higher in case of DEE. The diethyl ether helps to make complete burning of fuel during combustion at higher load.

6. Conclusions

An experimental model of knock detection for biodiesel-hydrogen fuel and biodiesel-hydrogen fuel mixtures with diethyl ether has been developed. The most suitable knock techniques have been applied to detect knock in compression ignition engine.

- (i) The knock measurement and analysis can be done for the biodiesel-hydrogen fuel and biodiesel-hydrogen fuel with DEE.

FIGURE 7: Mechanical efficiency variation with load.

- (ii) The pressure signal could be got from a pressure transducer and converted into frequency domain for analysis of the knock.
- (iii) The exhaust temperature can also be used to find out the knocking combustion for the same fuel mixture (biodiesel-hydrogen fuel at 10 lpm) at higher loads.
- (iv) The performance and knock limiting operation of engine could be improved by using DEE as an additive fuel.
- (v) The diethyl ether is taken to suppress the knocking behaviour in compression ignition engine during combustion of mixture of hydrogen-biodiesel fuel.

The performance characteristics of both hydrogen-biodiesel fuel and hydrogen-biodiesel fuel with DEE could be computed for various applications of load.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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