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Hydrogen supplement co-combustion with diesel in compression ignition engine

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ABSTRACT

The present work investigates experimentally the behavior of compression ignition engine while boosting the combustion by enriching air-intake manifold with hydrogen supplement at the atmospheric condition. The study reports the engine thermal efficiency, NO_x emissions and engine exhaust temperature while varying hydrogen content, engine speed and ignition timing. The results show that thermal efficiency of the compression ignition engine increases as hydrogen content increases in the air-intake manifold for the same diesel mass flow rate. The effect of hydrogen supplement on engine efficiency is more pronounced at low engine speed and part-load. The hydrogen supplement causes an increase in NO_x emissions which is attributed to the increase in the combustion temperature and as a result, lower smoke opacity numbers are attained.

1. Introduction

Liquid diesel originating from crude oil is the most common fuel used in compression ignition engines. The recent price climbs of crude oil products has led scientists and engineers to explore the use of alternative possible fuels to run compression ignition engines such as LGP [1] and hydrogen [2,3], in order to replace diesel or at least reduce its use as a fuel for engines. The use of hydrogen in diesel engines is driven by multiple reasons [2] which are (1) increases the hydrogen to carbon ratio of the entire fuel supplied to the engine, (2) injecting small amounts of hydrogen into a diesel engine can decrease the heterogeneity of diesel fuel spray, and (3) reduces the combustion duration. Stoichiometric hydrogen air mixture burns seven times faster than the corresponding gasoline air mixture [4]. This gives great advantage to internal combustion engines, leading to higher engine speeds and greater thermal efficiency [4]. The high heating value and clean burning characteristic of hydrogen make hydrogen one of the most promising alternative fuels that can play great role in replacing fossil fuels.

The use of hydrogen as a fuel in spark ignition (SI) engine [5] has showed a significant reduction in power output. In addition, at high load, pre ignition, backfire and knocking problems have been reported. Hence these problems have limited the use of hydrogen in SI engine [6,7]. Recent work [8] showed that hydrogen-gasoline blend can boost SI engine performance. These contradicting conclusions indicate that more research work is needed to further clarify the features and benefits of hydrogen as a fuel for SI engines.

On the other hand, the use of hydrogen in compression ignition (CI) engines [9] has showed a significant increase in thermal efficiency (by 20%) when compared to pure diesel combustion and an increase of 13% in NO_x emission. Hydrogen fuel cannot be used as a sole fuel in a compression ignition engine, since the compression temperature is not enough to initiate the combustion due to its high self-ignition temperature [9]. Therefore, hydrogen is used as dual fuel and co-combusted in the presence of diesel. In the dual fuel engine arrangement, the diesel fuel is used as the main fuel to initiate the ignition and combustion process while hydrogen is introduced as supplementary fuel through the air-intake manifold or directly injected into the engine cylinders. Hence, major energy is obtained from diesel while the rest of the energy is supplied by the hydrogen. With compression ratio of 24.5, Masood et al. [10] reported an increase of 30% in brake thermal efficiency when hydrogen is co-combusted in the presence of diesel fuel. Lee et al. [7] has reported an increase in thermal efficiency of 22% for dual injection at low loads and 5% at high loads compared to direct injection. Lee et al. [7] studied the dual engine performance of hydrogen-diesel fuel while introducing the fuel solenoid in-cylinder injection and external fuel injection technique. Lee et al. [11] concluded that for dual injection the stability and maximum power are accomplished by direct injection of hydrogen. Das [12] reported experimental results on continuous carburation, continuous manifold injection, timed manifold injection and low pressure direct cylinder injection in which he showed that the maximum

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Nomenclature

CI	compression ignition
LHV	lower heating value, MJ/kg
LPG	liquefied petroleum gas
LPM	liter per minute
$\dot{m}$	mass flow rate, kg/s
PM	particulate matter
$\dot{Q}$	heat rate, kW
SI	spark ignition
sfc	specific fuel consumption, kgN.m
T	torque, N.m
$\dot{W}$	power, kW
Greek symbols	
η	thermal efficiency
ω	angular velocity, Rad/s
Subscripts	
in	input
out	output

brake thermal efficiency of 31.3% is obtained at 2200 RPM with 13 N-m torque.

The use of hydrogen fuel, as a potential supplement fuel to reduce the use of liquid diesel fuel, comes with a drawback of increasing NO_x emission. Thus the need for techniques to reduce NO_x becomes more vital for engines operating with dual hydrogen-diesel fuel. One common method to reduce NO_x emission in diesel engine is by injecting steam to the combustion [13]. Another way to reduce NO_x is by operating the engine with lean mixtures. Lean mixture results in lower temperature that would slow the chemical reaction, which weakens the kinetics of NO_x formation [14,15].

One of the main advantages of hydrogen combustion over diesel fuel is that it does not produce major pollutants such as hydrocarbon (HC), carbon monoxide (CO), sulfur dioxide (SO_2), smoke, particulate matter, lead, and other carcinogenic compounds. This is due to the fact that it is only water what comes out of the complete hydrogen combustion in air, in addition of course to the generated NO_x due to the presence of Nitrogen in the air [16]. So, the hydrogen-operated engines' main disadvantage is the NO_x emissions. Under the clearly high combustion temperatures, supported further by the combustion of the Hydrogen in the overall fuel supplied to the engine, the nitrogen present in the air reacts with oxygen to form NO_x. A recent study [3] showed that hydrogen fuel supplement can be used in diesel engine with hydrogen to diesel ratio of 34% calculated based on amount of energy in the fuel (which represent 19% as mass ratio between hydrogen to diesel).

This study addresses the advantage of using hydrogen supplement in diesel engine while at the same time pointing the effect of hydrogen on emission. The hydrogen is introduced through the air-intake manifold at atmosphere condition to assure minimal retrofit to current diesel engine. The supplement hydrogen can be produced using renewable source of energy such as solar energy with water electrolysis.

Utilizing dual fuel configuration, this study reports the effect of hydrogen supplement fuel that is injected to the air-intake manifold of a compression ignition engine and co-combusted in the presence of diesel fuel where diesel is combusted as the main fuel. The hydrogen supplement is used to replace a portion of the diesel fuel required to produce the engine output power. The study reports the effect of hydrogen supplement fuel on the engine efficiency, specific fuel consumption, exhaust temperature, NO_x emission and PM emission.

2. Experimental setup

A schematic diagram of the engine with instrumentations is show in Fig. 1. The test is conducted using a Ricardo E6 research engine which is a single cylinder compression ignition engine. The engine is fully equipped with instrumentation for measurements of all engine operating parameters. The engine is modified to work with hydrogen in the dual fuel mode where hydrogen is injected into the air-intake manifold as shown in Fig. 1. The engine is loaded by an electrical dynamometer rated at 22 kW and 420 V. The torque of the engine is measured through force transducer that is connected to the electrical dynamometer which has uncertainty of ±0.1 N. The liquid fuel flow rate is measured digitally by a multi-function microprocessor-based fuel system. The engine specifications are shown in Table 1. The chemical characteristics of the primary fuel (diesel) and the supplement fuel (hydrogen) are listed in Table 2.

As shown in Fig. 1, hydrogen gas is injected into the air-intake manifold at atmosphere pressure. A pressure regulator, a volumetric rotameter and a throttle value are used to control the hydrogen flow rate. The uncertainty of the hydrogen flow meter is ±0.5 LPM. The flow rate of air is measured using a calibrated orifice meter with pressure transducer arrangement. The pressure transducer has uncertainty of ±0.1 Pa. The diesel flow rate is measured by recording the required time to consume a fixed volume of diesel with uncertainty of ±0.1 ml/s. The measurement of combustion pressure, engine speed, engine output torque, and crank angle are collected using a high speed data acquisition system. A labVIEW interface program has been written to collect the data at a rate of 50,000 points per second and to store the data.

The main objective of the conducted experiments is to understand the effect of hydrogen supplement on the performance of a dual fuel single cylinder diesel engine under different conditions, hence three sets of tests have been conducted which are as follow:

1) Test the effect of 4 LPM hydrogen when combusted with diesel engine in dual mode while varying engine speed from 1080 RPM to 1800 RPM.
2) Test the effect of variable hydrogen flow rate at fixed engine speed. The hydrogen flow rate is varied from 0 to 8 LPM insteps of 2 LPM for fixed engine speed of 1260 RPM.
3) Test the effect of varying injection timing while engine is running in dual mode with hydrogen flow rate of 4 LPM, at fixed engine speed of 1260 RPM.

The engine efficiency and specific fuel consumption are calculated using equations (1) and (2) respectively:

$$\eta = \frac{\dot{W}_{out}}{\dot{Q}_{in}} = \frac{T \cdot \omega}{(\dot{m} \times LHV)_{Diesel} + (\dot{m} \times LHV)_{H_2}} \quad (1)$$

$$sfc = \frac{\dot{m}_{fuel}}{\dot{W}_{out}} \quad (2)$$

$$\dot{m}_{fuel} = (\dot{m})_{Diesel} + (\dot{m})_{H_2} \quad (3)$$

The lower heating value is used in equation (1) for the efficiency calculation since no vapor is condensed during the experiment. The density of hydrogen is calculated at the air-intake condition; namely at atmosphere pressure and room temperature.

The exhaust emission is measured using VARIO plus SE instrumentation manufactured by MRU Instruments, Inc. The analyzer