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Reducing pollutant emissions from a heavy-duty diesel engine by using hydrogen additions

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HIGHLIGHTS

- The hydrogen supplement enhances diesel engine thermal efficiency.
- The hydrogen produced from water electrolysis can reduce the fuel consumption.
- H_2 addition reduces the traditional pollutants at idling condition.
- A great improvement on CO, CO_2 emissions was observed with hydrogen addition.
- An important reduction on NOx was achieved with H_2 addition at low loads.

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ABSTRACT

This study aimed to investigate the effect of conventional diesel engine through the addition of H_2 mixture, generated through water electrolysis. In this work, three different ratios of diesel–hydrogen blends, 0%, 0.6% and 1.2% hydrogen by volume used, respectively. The experiments were carried out at the idling condition under constant speed from the low to high engine load with the different amount of H_2 mixture. The results showed that the brake thermal efficiency (BTE) increased as the brake specific fuel consumption (BSFC) decreased with an increasing amount of hydrogen. The hydrogen addition leads to reduce the emissions of carbon dioxide (CO_2) and carbon monoxide (CO). At the high operation load, the reduction in emissions was the most significant, but the total hydrocarbon (THC) emissions increased 4.94% and 13.1% on average with the low level of hydrogen addition (0.6% and 1.2% by volume). Nevertheless, the addition of hydrogen lowered nitrogen oxide (NOx) emissions at the idling and low load conditions, but increased at the high load, since the thermal NOx dominated at the higher temperature. Consequently, the addition of low level hydrogen decreased CO and CO_2 emissions, whereas the THC and NOx emissions increased at the high engine load.

1. Introduction

Both rapid depletion of global fossil fuel reserves and rapidly increasing demand for energy around the world have led to a sharp rise in fuel prices since the turn of the century. Thus, there is a growing need to develop and apply alternative fuels. Moreover, fossil fuels are the primary source of greenhouse gases, which are responsible for the accelerating trend of global warming. Recent study focused on developing fuels that burn cleanly and had less emission, especially in urban environments. Many studies on clean combustion examine alternative fuels such as alcohols, dimethyl ether (DME), biodiesels, compressed natural gas (CNG), liquefied petroleum gas (LPG), liquefied natural gas (LNG) and hydrogen, and these are seen as direct replacements for petroleum-based fuels in many situations [1–3].

Diesel engines are widely used in both on-road and off-road vehicles. Previous research tried using edible vegetable oils from various sources, such as rapeseed, cottonseed, coconut, palm and soybean, as the replacement fuel for diesel engines. Unfortunately, a major and unwarranted, side-effect of using edible oil as engine fuel is that the price of edible oil has skyrocketed due to the sharp

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increase in demand. As the edible oil becomes more expensive due to higher demand, this also causes food prices to increase, which can cause serious problems for low-income people [4,5]. Hydrogen is a non-toxic, odorless, renewable and recyclable alternative fuel. The only combustion product of hydrogen is water, thus it can potentially and significantly improve the quality of air. In short, hydrogen is a promising candidate as the next generation clean energy source for both compression-ignition and spark-ignition engines. Moreover, hydrogen fuel has the benefits of long-term, continuous availability, unlike petroleum or other fossil fuels that are found in depleting reserves [6–13].

Many investigations have been conducted to examine the effects of hydrogen addition on the performance and emissions characteristics of diesel engines. Sandalcı and Karagoz [14] showed that adding hydrogen (higher than 20%) to diesel can lower the thermal efficiency, smoke, carbon monoxide and carbon dioxide emissions but increase the fuel consumption and NOx emissions. Saravanan and Nagarajan [15] demonstrated that the brake thermal efficiency increased, while smoke and NOX decreased, under lean burn conditions when hydrogen was added through the intake port of a single-cylinder direct injection diesel engine. Shirk et al. [9] experimented with hydrogen–diesel fuel blends in a light-duty diesel vehicle operated under the EPA Urban Dynamometer Driving Schedule (UDDS) cycle. They found that such blends could be used in current diesel vehicles with no adverse effects on engine performance and emissions. Gatts et al. [16] also found that hydrogen addition enhances both combustion efficiency and brake thermal efficiency when the engine is placed under high-load operations.

Studies have also been undertaken to examine the effects of hydrogen addition on engine performance and unregulated pollutants such as hydrocarbons, carbon monoxide and carbon dioxide. Wang et al. [17] reported that hydrogen, generally speaking, can reduce the emissions of carbonyl compounds. Zhou et al. [18] also concluded that hydrogen can improve engine performance at medium to high load operations, and efficiently reduce carbon monoxide, carbon dioxide and seven other kinds of unregulated emissions, except for the formaldehyde. Gomes-Antunes et al. [19] reported a higher power to weight ratio when using hydrogen blended diesel in a direct injection diesel engine. The result showed that a significantly higher peak in-cylinder gas pressure was also observed, the exhaust of carbon monoxide, carbon dioxide, NOx and smoke were all reduced.

There are no safe and efficient methods of distributing and storing a large amount of hydrogen that can meet the market demand and thus completely replace petroleum-based fuels. Moreover, the current urban infrastructure is not built for using hydrogen as the primary energy source. One of the long-term goals in research on hydrogen fuel is to produce it in an affordable and robust manner through water and sunlight [20]. Hydrogen can be stored in several ways, either as a cryogenic liquid, compressed gas or as a gas dissolved in metal hydrides. However, all of these methods will increase the overall weight of the vehicle [21]. Moreover, there are several issues with storing and carrying hydrogen in vehicles. Most cryogenic containers are expensive, and the cost of producing liquefied hydrogen is very high [22], while smaller containers are infeasible due to the need for frequent refilling and insufficient urban infrastructure for the hydrogen distribution [23,24]. In addition, the hydrogen can be ignited easily, and this makes it dangerous to be stored in large quantities and carried around since it can be combusted at the atmosphere pressure at concentrations from 4% to 74.2% by volume [25]. To overcome issues with the onboard storage, one approach is to produce the hydrogen onboard by the electrolysis of water [12]. Although some researchers studied about the hydrogen production via the water electrolysis, there isn't enough study in the literature using the water electrolysis method directly in internal combustion engines. The goal of this study is to investigate the impacts of hydrogen addition (using de-ionized as the hydrogen source) on the engine performance coupled to a generator producing electricity and the pollutant emission characteristics. The experiments are carried out at the idling condition under constant speed from the low to high engine load, with the addition of 0%, 0.6% and 1.2% hydrogen by volume, respectively.

2. Experiment section

2.1. Experimental setups

The engine tests in this study were conducted in the Refining and Manufacturing Research Center for heavy-duty diesel engine operation at the Chinese Petroleum Corporation. A Cummins B5.9-160 engine, which was a six-cylinder, direct-injection, non-catalyst heavy duty diesel engine was used in this study. Fig. 1 shows the engine specifications and schematic of the experimental setup. The physical and chemical properties of both diesel fuel and hydrogen are shown in Table 1. Engine tests were completed using a Schenck GS-350 dynamometer under several loading conditions, and at steady-state conditions. A GOC HGMS-1000 hydrogen generator was used to produce a continuous stream of hydrogen, then simultaneously inducted into the combustion chamber with the diesel fuel. A gas flow meter was installed to regulate the hydrogen stream. A flame arrestor was installed in the hydrogen line to suppress immature explosions before the hydrogen–diesel mixture reached the engine combustion chamber through the air inlet manifold.

2.2. Sample collection and analysis

Engine emissions were analyzed with an HORIBA MEXA-7400LE analyzer. Both carbon monoxide and carbon dioxide were measured by the non-dispersive infrared method (NDIR) (model 880A, Rosemount, UK). The total hydrocarbon was detected by the flame ionization detection (FID) (model 404, Rosemount, UK). Meanwhile, NOx was detected by chemiluminescence detection (CLD) (model 955, Rosemount, UK). The engine exhausts were sampled through a Critical Flow Venturi (CFV) type dilution tunnel, 350 mm in diameter. The exhaust gas was diluted with the air before being drawn into the tunnel. A Spencer blower was then used to mix the various components. It was later being pulled into an insulated pipe that 0.1 m in diameter and 7.5 m in length. A non-touch type HBM torque meter was used to measure the engine speed and engine load simultaneously. The K-Type thermal couple was used to measure exhaust temperature. The apparatus of measurements are given in Table 2.

The effect of hydrogen addition on engine performance under different loading conditions was investigated. Engine tests were conducted according to the test conditions listed in Table 3. Different amounts of hydrogen were added to commercially available diesel fuel according to the hydrogen volume fraction, as defined in Eq. (1) [16],

$$\mathrm{H_2\ volume\ fraction}\ (\%) = \frac{V_{H_2}}{(V_{H_2} + V_{air})} \times 100\% \qquad (1)$$

where V_{H_2} and V_{air} are the measured volumetric flow rates of hydrogen and air at normal conditions, respectively. Each operating test condition of engine was repeated for three times in order to obtain the reliable data.