Effect of regulated harmful matters from a heavy-duty diesel engine by H\textsubscript{2}/O\textsubscript{2} addition to the combustion chamber

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\section{1. Introduction}

Diesel engines have been widely used in heavy-duty buses, trucks, construction machines, and generators, because diesel engines have high fuel efficiency, power output, fuel economy and lower emissions of traditional pollutants such as hydrocarbons (HCs), nitrogen oxides (NO\textsubscript{x}) and carbon monoxide (CO) than gasoline engines\cite{1,2}. Although current diesel engines have higher NO\textsubscript{x} emissions than gasoline engines because of catalytic converters in gasoline engines, the problem of high NO\textsubscript{x} emissions from diesel engines can be mitigated by the use of low-temperature combustion\cite{3} and selective catalytic reduction\cite{4–8}. However, emissions of smoke, particulate matter, sulfur oxides, polycyclic aromatic hydrocarbons, and carbonyl compounds from the exhausts of a HDDE have always been a concern for the public and environmental researchers\cite{9–24}.

Alternative fuels such as biodiesels, alcohols, dimethyl ether (DME), compressed natural gas (CNG), liquefied petroleum gas (LPG), liquefied natural gas (LNG) and hydrogen are being widely discussed in many countries due to increasing environmental awareness and the rising price of diesel. Among these fuels, hydrogen is a generally acknowledged renewable, recyclable and non-polluting fuel. Compared to hydrocarbon fuel, hydrogen is the most significant being the absence of carbon\cite{25}. Additionally, hydrogen has wider flammability limits, higher flame speed and faster burning velocity than diesel fuel\cite{26}.

It is known that pollutant emissions from an HDDE under the US-HDD transient cycle test are representative because the engine is tested over a full range of load and speed conditions, including expressway, congested-urban, and uncongested-urban. However, heavy-duty diesel engines are always operating at low load in urban areas around humans indicating that pollutants are close to humans. The report from Taiwan MOTC indicates the mean speed of vehicles in Taiwan urban areas ranges from 28.7 to 45.4 km/h with average of 38.0 km/h\cite{27}. Therefore, a widely used diesel engine was tested at one low load steady-state condition, 24.5% of the max load (40 km/h), because that is how the engine is operating in urban areas around humans.

The main goal of the present study is to find H\textsubscript{2}/O\textsubscript{2} fuel for reducing emissions of regulated harmful matters (traditional pollutants) from HDDEs. Emissions of regulated harmful matters from the HDDE fueled with various H\textsubscript{2}/O\textsubscript{2} flow rate at 24.5% of the max load condition (40 km/h) were investigated.

\section{2. Experimental procedures}

\subsection{2.1. Test engine and hydrogen/oxygen fuels}

The heavy-duty diesel engine (non-catalyst) was used a Cummins B5.9-160 with the following characteristics: six-cylinders; four strokes; direct injection; fuel injection sequence 1–5–3–6–2–4; bore and stroke of 102 mm (Dia.) × 120 mm; total...
displacement of 5883 mL; compression ratio of 17.9:1, maximum horsepower of 118 kW at 2500 rpm; and maximum torque of 534 Nm at 1600 rpm. The experimental setup was shown in Fig. 1. In this study, an oxy-hydrogen generator machine (Epoch EP-560A) was used to electrolyze water and then get the mixture of hydrogen and oxygen (H₂/O₂). Then H₂/O₂ will be transported to the combustion chamber of the test diesel engine. The H₂/O₂ is then passed through a gas flow meter (the meters the flow of H₂/O₂ in terms of L/min) and two flame arrestors before it is transported to the engine via the air inlet manifold. A gas flow meter was used to measure the flow rate of H₂/O₂, and two flame arrestors were installed into the H₂/O₂ line for suppressing explosions in the experimental procedures. The properties of diesel and hydrogen were shown in Table 1.

2.2. Sample collection and analysis

The engine exhaust samples were collected in 10 L Tedlar bags through a full flow critical flow Venturi (CFV) type dilution tunnel, 350 mm in diameter. After passing through this tunnel, the exhaust was diluted with air simultaneously drawn into the tunnel, and mixed completely by a Spencer blower. The volume of sampling air varied with different venturi sizes of the CFV system. All the engine exhaust was introduced into the dilution system through a solid insulated pipe, 10 cm in diameter and 7.5 m in length. The engine was operated at a one load steady-state condition of 1600 rpm with torque and power outputs of 145 Nm (27.2% of max load) and 24.5 kW, respectively. In this condition, the measurement of the mixing ratio of the fuel (H₂/O₂/diesel) was first recorded without any induction of H₂/O₂ addition (neat diesel) into the engine. Then, seven flow rates of H₂/O₂ mixture were used by 10–70 L/min, interval 10 L/min. The sampling time was 20 min per test run.

For total hydrocarbon analysis, each sample was analyzed using a flame ionization detector (FID) (model 404, Rosemount, UK). For carbon monoxide/carbon dioxide analysis, each sample was analyzed using a non-dispersive infrared detector (NDIR) (model 880A, Rosemount, UK). For nitrogen oxides analysis, each sample was analyzed using a chemiluminescent detection (CLD) (model 955, Rosemount, UK).

3. Results and discussion

3.1. Brake thermal efficiency

Engine thermal efficiency is important on evaluating the engine economic and overall performance, and it also can be improved by optimizing the combustion system or fuel properties [28]. Fig. 2 displays the variation of brake thermal efficiency of the HDDE mixed with various H₂/O₂ flow rates. It sees from Fig. 2 that brake thermal efficiency is 31.1% for neat diesel, and increased with increasing addition of H₂/O₂ flow rate, from 31.4% for 10 L/min to 39.9% for 70 L/min. Higher brake thermal efficiency can be attributed to better mixing of hydrogen with air which results in better combustion. Similar results for the brake thermal efficiency of the Hydrogen addition were also found. Saravanan et al. [29] found that compared to diesel, the brake thermal efficiency was increased by 23.6–29.4% when running a diesel engine at 1500 rpm with 10 L/min hydrogen for intake port injection timing of 5ºC after top dead centre (ATDC) with injection duration of 90ºC crank angle (CA). Saravanan et al. [30] also found that the brake thermal efficiency was increased from 21.8% to 23.2% while running a diesel engine with 20 L/min hydrogen. Bari and Mohammad [26] found that the brake thermal efficiency was increased from 32.9% to 35.8% when running a diesel engine at 22 kW with 6.0% induction of H₂/O₂ mixture [26].

3.2. Brake specific fuel consumption

Fig. 3 depicts the variation of brake specific fuel consumption (BSFC) of the HDDE mixed with various H₂/O₂ flow rates. This study used neat diesel with H₂/O₂ as an additive, and so fuel
consumption is the sum of the diesel and diesel equivalent energy needed to produce the H2/O2 mixture. The BSFC of neat diesel was 254.74 g/kW h, and was 262.06 g/kW h, 262.75 g/kW h, 260.42 g/kW h, 263.80 g/kW h, 246.51 g/kW h, and 229.56 g/kW h for 10–70 L/min of H2/O2 mixture addition, respectively. For 10–40 L/min of H2/O2 mixture addition, the BSFC was higher than that of neat diesel. However, for 50, 60 and 70 L/min of H2/O2 mixture addition, the BSFC was lower than that of neat diesel by about 3.2%, 9.9% and 10.5%, respectively. This is due to better mixing of hydrogen with air resulting in complete combustion of fuel and hydrogen with higher flame speed than diesel. The results were similar to the findings of Saravanan et al. [30] in which the BSFC was reduced from 395.8 g/kW h to 372.6 g/kW h when running a diesel engine with 20 L/min hydrogen. The results were also quite similar to those of Bari and Mohammad Esmaeil [26] in which the value of BSFC was reduced from 256.1 g/kW h to 235.3 g/kW h when running a diesel engine at 22 kW with 6.0% induction of H2/O2 mixture.

3.3. Emissions of regulated harmful matters

Fig. 4 shows the concentrations of regulated harmful matters (traditional pollutants), including THC, CO, CO2 and NOx, in the exhausts of the HDDE mixed with various H2/O2 flow rates, as described in order below.

3.3.1. Total hydrocarbon emissions

Fig. 4a shows the variation of total hydrocarbon (THC) emission of the HDDE mixed with various H2/O2 flow rates. The THC concentration for neat diesel was 3.60 ppm, and THC decreased from 3.51 ppm for 10 L/min of H2/O2 mixture to 3.25 ppm for 70 L/min of H2/O2 addition. The reduction of THC is due to the higher flame velocity of hydrogen. Also, the absence of carbon in hydrogen fuel also tends to reduce the THC emissions.

3.3.2. Carbon monoxide emissions

Fig. 4b displays the variation of carbon monoxide (CO) concentration of the HDDE mixed with various H2/O2 flow rates. The CO concentration was 26.00 ppm for neat diesel, and was decreased to 24.00 ppm for 70 L/min of H2/O2 addition. This is because that the H2/O2 mixture does not contain carbon element and also because that the engine was operated at leaner equivalence ratio [31,32].

3.3.3. Carbon dioxide emissions

Figs. 4c shows the variation of carbon dioxide (CO2) concentration of the HDDE mixed with various H2/O2 flow rates. The CO2 concentration for neat diesel was 7906 ppm, and was decreased to 7893 ppm for 10 L/min of H2/O2 addition, and to 7523 ppm for 70 L/min of H2/O2 addition. The reduction of CO2 emission is due to less carbon element in the formed mixture of fuels than that in the neat diesel [26]. Also, the CO2 emission is reduced because
of the better combustion of hydrogen fuel and also due to the absence of carbon in hydrogen flame [25,33].

3.3.4. Nitrogen oxides emissions

Fig. 4d shows the variation of nitrogen oxides (NOx) concentration of the HDDE mixed with various H2/O2 flow rates. The NOx concentration was 60.05 ppm for neat diesel, and was increased from 60.49 ppm for 10 L/min of H2/O2 mixture to 67.22 ppm for 70 L/min of H2/O2 addition. The higher concentration of NOx is due to both higher temperature and more available oxygen in the formed mixture [30,34].

4. Conclusions

Experiments were conducted to study the performance and emission characteristics by introducing various amounts of H2/O2 mixture into a heavy-duty diesel engine. The results indicated that brake thermal efficiency is increased from 31.1% for neat diesel to 39.9% for 70 L/min of H2/O2 addition. For 10–40 L/min of H2/O2 mixture addition, the brake specific fuel consumption (BSFC) was higher than that of neat diesel. However, for 50, 60 and 70 L/min of H2/O2 mixture addition, the BSFC was lower than that of neat diesel by about 3.2%, 9.9% and 10.5%, respectively. The emission concentrations of THC, CO, and CO2 were reduced due to improved combustion and the absence of carbon in hydrogen fuel. The emission concentration of NOx was increased due to higher temperature and more available oxygen in the formed mixture.

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References