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Effect of H_2/O_2 addition in increasing the thermal efficiency of a diesel engine

S. Bari *, M. Mohammad Esmaeil

Sustainable Energy Centre, School of Advanced Manufacturing and Mechanical Engineering, University of South Australia, Mawson Lakes, SA 5095, Australia

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ABSTRACT

Using hydrogen as an additive to enhance the conventional diesel engine performance has been investigated by several researchers and the outcomes are very promising. However, the problems associated with the production and storage of pure hydrogen currently limits the application of pure hydrogen in diesel engine operation. On-board hydrogen–oxygen generator, which produces H_2/O_2 mixture through electrolysis of water, has significant potential to overcome these problems. This paper focuses on evaluating the performance enhancement of a conventional diesel engine through the addition of H_2/O_2 mixture, generated through water electrolysis. The experimental works were carried out under constant speed with varying load and amount of H_2/O_2 mixture. Results show that by using 4.84%, 6.06%, and 6.12% total diesel equivalent of H_2/O_2 mixture the brake thermal efficiency increased from 32.0% to 34.6%, 32.9% to 35.8% and 34.7% to 36.3% at 19 kW, 22 kW and 28 kW, respectively. These resulted in 15.07%, 15.16% and 14.96% fuel savings. The emissions of HC, CO_2 and CO decreased, whereas the NO_x emission increased.

1. Introduction

Due to the depletion of fossil fuels and ever increasing oil prices, engine manufacturers worldwide are currently encouraged to find out alternative approaches to increase fuel economy and reduce harmful emissions from internal combustion engines. One of the possible ways to increase the performance of diesel engines is to use an additive as complementary fuel along with diesel, leading to reduced fuel consumption and toxic gas emissions. However, detail investigation on the availability of the additives and the required percentage for optimum engine performance needs to be carried out in selecting any particular additive. Researchers worldwide have investigated the effect of adding several additives to diesel fuel on the performance of diesel engines [1–3]. Forson et al. [1] used jatropha as an additive to diesel and examined the engine performance by using different blends of jatropha oil and diesel (2.6/97.4%, 20/80%, and 50/50%). Using a dynamometer the engine was loaded under a variety of load conditions between 2 kg and 10 kg. They found that by increasing the amount of jatropha oil in the blend, brake thermal efficiency and brake power increased under all load conditions. Among examined blends, the mixture consisting of 2.6% jatropha oil and 97.4% conventional diesel fuel was found to give the maximum brake thermal efficiency and brake power. Using this blend, the brake thermal efficiency was increased to 19.7% from 15.5% when running on diesel and the brake power was also increased to 1.32 kW from 1.07 kW, when the torque was 9.2 N-m for both cases. With this mixture proportion, the specific fuel consumption was also reduced to 440 g/kWh from 560 g/kWh.

Yanfeng et al. [4] evaluated the use of 2-methoxyethyl acetate (MEA), which is an oxygenated additive to diesel fuel, in a diesel engine with several fuel blends containing 10%, 15%, and 20% of MEA. Using MEA10, MEA15, and MEA20 at 2000 rpm, indicated thermal efficiency increased by 2.5%, 5.7%, and 7.1%, respectively. However, the engine's power reduced due to the lower heating value of the mixture by approximately 3.9%, 5.7%, and 8.1% when fuelled with MEA10, MEA15, and MEA20, respectively. To maintain the same power as diesel, higher quantities of cyclically delivered fuel blends were required.

Among many additives, hydrogen with its unique criteria seems to be the most promising additive which can significantly reduce fuel consumption and harmful emissions in conventional diesel engines. Compared to diesel, hydrogen has wider flammability limits, higher flame speed and faster burning velocity [5] which enable engines running on very lean mixtures [6–8]. Unlike other additives, hydrogen is a renewable and clean burning fuel [9–11] and addition of hydrogen to hydrocarbon-based fuels does not increase any threat in increasing the toxic gas emissions. Moreover, generation of hydrogen is possible from a variety of sources such as fossil fuels, biomass, water and some industrial waste chemicals [12,13]. Due to the unique combustion nature of hydrogen, addition of hydrogen to the fuels with low level of burning rate can improve the combustion rate of the formed mixture [10].

The use of hydrogen as an additive to diesel has been investigated in several studies [2,10,14,15]. Senthil et al. [10] evaluated

* Corresponding author. Tel.: +61 8 8302 3439; fax: +61 8 8302 3380.
E-mail address: saiful.bari@unisa.edu.au (S. Bari).

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the performance of a diesel engine by adding different proportions of hydrogen into biodiesel and diesel, and found an increase in the brake thermal efficiency at higher power outputs of the engine. In addition, significant reductions in exhaust emissions were also observed. Tomita et al. [2] has also reported similar outcome in reducing exhaust emissions using hydrogen as an additive to diesel fuel. Saravanan et al. [14,15] used hydrogen as a supplementary fuel under constant flow rate of 10 l/min and 20 l/min, respectively and studied the performance parameters of a diesel engine with/without exhaust gas recirculation (EGR) system. They also found an increase in brake thermal efficiency with corresponding reduction in specific fuel consumption.

Most of these works focused on the use of pure hydrogen as an additive which brings on-board storage problem of hydrogen into consideration. Hydrogen has a high specific energy and very low density entailing high storage volume unless it is compressed (typically 70 MPa) or combined chemically with a metal alloy. To store hydrogen on-board in forms of a compressed gas, a cryogenic liquid or a gas dissolved in metal hydrides, a large amount of hydrogen is required to be stored and carried which leads to increase in the overall weight of the vehicle [16]. Alternatively, in terms of liquid hydrogen storage, not only the cost of onboard cryogenic containers is high, but also a high level of energy is required to convert the gaseous hydrogen into liquid [17]. Therefore, the use of small and light hydrogen containers are respected which need to be filled in short distances of driving. However, hydrogen supply infrastructures are not still available and need to be developed in the near future [18,19]. In addition, the wide flammability range of hydrogen makes it a hazardous fuel to be stored which can be combusted at atmosphere pressure at concentrations from 4% to 74.2% by volume [20].

One of the viable solutions to this problem is to generate hydrogen on-board through electrolysis of water and use it in the form of hydrogen–oxygen (H_2/O_2) mixture. However, no significant work has been carried out in testing diesel engine with the addition of H_2/O_2 mixture. The aim of this study is to investigate the impacts of adding H_2/O_2 mixture on the performance parameters of a diesel engine coupled to a generator producing electricity. The engine was tested at a constant speed of 1500 rpm with the addition of varying amount of H_2/O_2 mixture (1–6%) under three different load levels of 19 kW, 22 kW, and 28 kW.

2. Experimental setup and procedure

A Hino WO4D, four-cylinder, direct injection, and water cooled diesel engine was used in this experiment. The detail of the engine is listed in Table 1 and the properties of diesel and hydrogen is listed in Table 2 [10]. The engine was mounted to an electrical generator and the generator was then connected to an adjustable load cell to put load on the engine. A schematic diagram of the experimental setup is shown in Fig. 1. The mixture of H_2/O_2 was generated by electrolysing water using an oxy-hydrogen generator machine, Epoch EP-500. In order to simplify the setup, the H_2/O_2 mixture was generated using 24 V external power supply. But in reality it will be produced from the battery/alternator arrangement of the engine. The power needed to produce the H_2/O_2 mixture is included as an input energy to the engine. The generated mixture is then passed through a drier container and a flow meter before it is introduced to the engine via the air inlet manifold. The flow line of H_2/O_2 mixture was connected to the ground using a normal wire to prevent concentration of static electricity which may cause explosion. Two flame arrestors were installed into the H_2/O_2 line for suppressing explosions anywhere in the line.

Table 1
The engine specifications.

Combustion system type	Direct injection type 4 cylinder, in-line, overhead valve
Bore × stroke	104 × 118 mm
Piston displacement	4.009 l
Compression ratio	17.9
Maximum output power	38 kW at 1500 rpm

Table 2
Properties of diesel and hydrogen [10].

Properties	Diesel	Hydrogen
Density (kg/m^3)	840	0.082
Calorific value (MJ/kg)	42.7	119.81
Flame velocity (m/s)	0.3	2.70
Auto ignition temp. (°C)	280	585
Carbon residue (%)	0.1	0.0

A Dwyer model RMC gas flow meter was used to measure the H_2/O_2 mixture flow rate flowing into the engine with an accuracy of ±0.5 l/min. Also, a nozzle mounted to the air inlet duct of the engine was used to measure the air-flow rate. The pressure difference across the nozzle was measured with an accuracy of ±0.01 kPa using a U tube manometer. To enable measuring the diesel fuel, a digital weighting scale with an accuracy of ±1 g and a stop watch were used. The CO and CO_2 emissions were measured by non-dispersive infrared (NDIR) gas analyser with an accuracy of ±0.1%. The chemiluminescence's method was used for the detection of oxides of nitrogen (NO_x) with an accuracy of ±1 ppm. The flame ionization detection (FID) methodology was used to measure HC emission with an accuracy of ±1 ppm. Engine speed was measured with an accuracy of ±1 rpm using a digital tachometer.

The engine was operated at a constant speed of 1500 rpm with three different power levels of 19 kW, 22 kW, and 28 kW applied by a load cell. Under each load condition, the flow rate of diesel fuel and other parameters were first recorded without any induction of H_2/O_2 mixture into the engine. Then, with no change in the experimental conditions, a small amount of H_2/O_2 mixture was introduced to the engine. The impacts of the induction of H_2/O_2 mixture on the engine performance parameters such as output power, diesel fuel consumption, exhaust temperature, air-flow rate, H_2/O_2 mixture flow rate, engine speed and emissions were recorded. Then, the flow rate of H_2/O_2 mixture was increased and the required data were collected until the optimum fuel saving was achieved.

3. Results and discussion

In this investigation, the performance and emission characteristics of a diesel engine were studied using H_2/O_2 mixture enrichment at a constant speed of 1500 rpm. The flow rate of H_2/O_2 mixture was varied to obtain optimum performance and the engine was tested at three different powers of 19 kW, 22 kW, and 28 kW. In this experiment, the H_2/O_2 mixture was generated using 24 V external power supply and the power needed to produce the H_2/O_2 mixture is included in the input energy of the engine.

3.1. Brake thermal efficiency

The variation of brake thermal efficiency at different% H_2/O_2 mixture is presented in Fig. 2. It can be observed from the figure that, regardless of the level of load, increasing the % induction of H_2/O_2 mixture the break thermal efficiency of the engine increases.

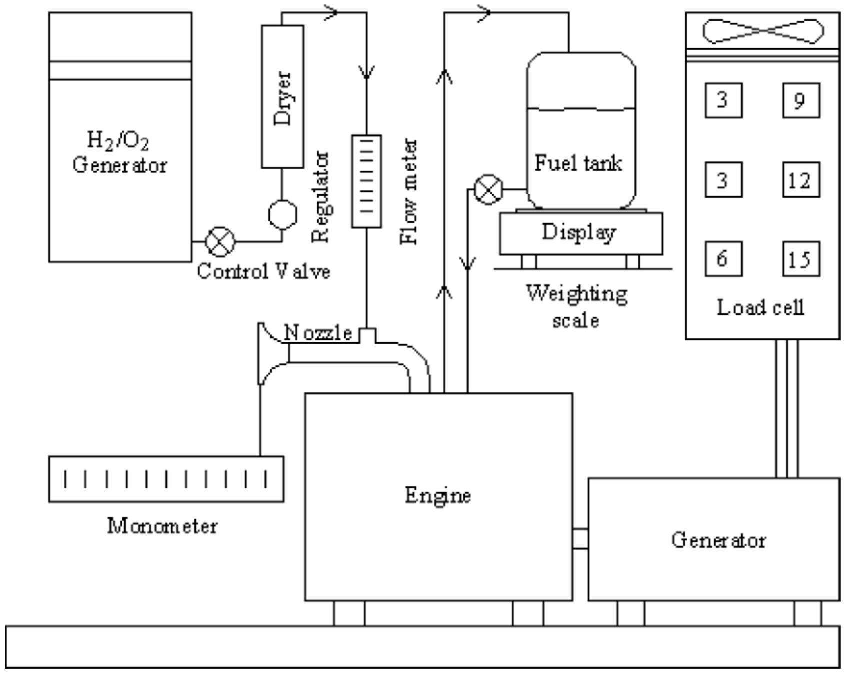

Fig. 1. Experimental setup.

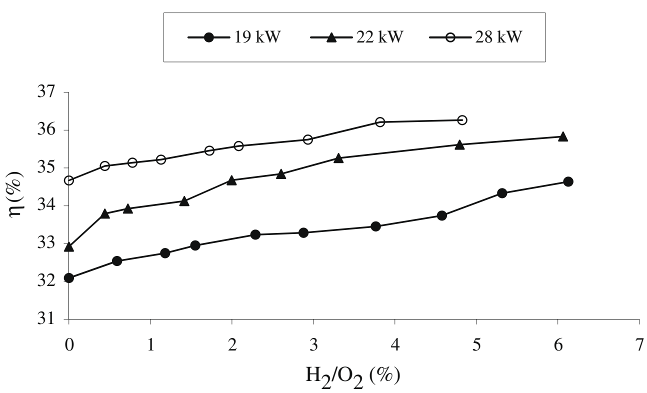

Fig. 2. Variation of brake thermal efficiency with H_2/O_2 percentage.

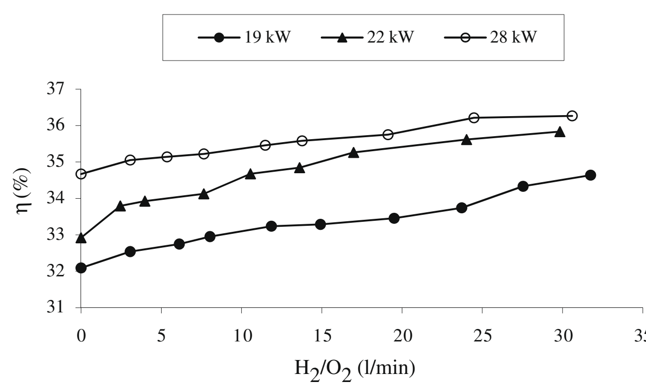

Fig. 3. Variation of brake thermal efficiency with H_2/O_2 flow rate.

The flame speed of hydrogen is nine times faster than the flame speed of diesel [5,10]. Therefore, burning diesel in the presence of hydrogen will result in overall faster and more complete combustion. This will result in higher peak pressure closer to TDC and therefore, will produce a higher effective pressure to do work. These have contributed to improve the efficiency. However, the increase in efficiency diminishes after 5% total diesel equivalent of H_2/O_2 mixture (flow rate of 25 l/min), and therefore, the flow rate of H_2/O_2 mixture were kept to a maximum of 6% total diesel equivalent of H_2/O_2 mixture (30 l/min). At 19 kW, the maximum brake thermal efficiency increased to 34.6% from 32.0% when running on diesel. Similarly, the brake thermal efficiency increased to 35.8% from 32.9% at 22 kW, and at 28 kW, the efficiency increased to 36.3% from 34.7%. Fig. 3 shows the actual flow rate of H_2/O_2 mixture needed to produce those increases in efficiency, which were 30.6 l/min, 29.8 l/min, and 31.7 l/min corresponding to 4.84%, 6.06%, and 6.12% of the total diesel equivalent flow rate at 19 kW, 22 kW, and 28 kW, respectively.

These low percentages of H_2/O_2 mixture acted as an additive to improve the combustion process which is the result of higher flame speed of hydrogen compared to diesel. The outcome of this study follows the logic of the experimental study of Senthil Kumar [10,14,15]. Their study was carried out with diesel as the main fuel and pure hydrogen as an additive injected into the air intake port during the intake stroke. The study undertaken by Saravanan et al. [14] shows that compared to diesel, the brake thermal efficiency of a diesel engine at 1500 rpm with 10 l/min hydrogen enrichment is increased to 29.4% from 23.6% for intake port injection timing of 5° after top dead centre (ATDC) and with injection duration of 90° crank angle (CA). However, the maximum brake thermal efficiency was found at port injection timing of 15° ATDC with 60° crank angle duration as 31.7%, but knocking was observed at this condition. In another study, Saravanan et al. [15] found that the brake thermal efficiency increases from 21.75% to 23.1% when running a diesel engine at 1500 rpm with 20 l/min hydrogen enrichment. Senthil Kumar [10] also found an increase in brake thermal efficiency from 30.3% to 32% while running a diesel engine at 1500 rpm and full load condition with 7% hydrogen mass share addition. Though their studies used pure hydrogen as an additive and this study used H_2/O_2 mixture as an additive, but the results showed similar improvement as it is the hydrogen which acted as additive to improve the performance.

3.2. Brake specific fuel consumption and fuel saving

Fig. 4 shows the variation of brake specific fuel consumption (bsfc) with the percentage of H_2/O_2 mixture. The fuel consumption is the sum of diesel, diesel equivalent hydrogen flow rate and diesel equivalent energy needed to produce the H_2/O_2 mixture. The figure reveals that addition of a small amount of H_2/O_2 into the air intake to enhance diesel combustion decreases the bsfc regardless of the level of load. This is due to uniformity in hydrogen mixture formation with air resulting in better combustion and also hydrogen with higher flame speed than diesel assists to have more complete combustion and peak pressure closer to TDC producing more work. By inducting approximately 6.1% H_2/O_2 mixture into diesel, bsfc reduced from 262.7 g/kWh to 243.4 g/kWh at 19 kW, from 256.1 g/kWh to 235.3 g/kWh at 22 kW with 6.0% H_2/O_2 induction and from 243.2 g/kWh to 232.4 g/kWh at 28 kW with 4.8% induction of H_2/O_2 mixture. The results coordinate with the study of Saravanan et al. [15] in which the value of bsfc is reduced from 395.8 g/kWh to 372.6 g/kWh with 20 l/min hydrogen enrichment to diesel.

Fig. 5 illustrates the variation of the total mass flow rate of fuel with the percentage of H_2/O_2 mixture. The total rate of fuel consumption is calculated as the sum of diesel, the diesel equivalent flow rate of hydrogen and the diesel equivalent energy needed to produce H_2/O_2 mixture. As expected, the induction of H_2/O_2 reduces the total fuel consumption rate of the engine under all applied load conditions. The decrease in the total fuel consumption is due to the better combustion of the formed mixture owing to higher flame speed of hydrogen and overall leaner mixture (as shown later). At 19 kW the total fuel consumption decreased by 9.3% (from 1.39 g/s to 1.26 g/s) with 6.1% total diesel equivalent H_2/O_2 mixture. At 28 kW load, the decrease in total fuel consumption is found to be 6.8% (from 1.91 g/s to 1.78 g/s). Among the load conditions applied, at 22 kW, the reduction in total fuel consumption rate reaches its highest value as 10.25% (from 1.56 g/s to 1.40 g/s).

Fig. 6 shows the percentage saving of diesel fuel versus the percentage of inducted H_2/O_2 mixture. Though the graph has some overlapping nature, but it is clear from the graph that with the increase in inducted mixture the diesel fuel consumption decreased or the percentage of fuel saving increased for all loads. By inducting H_2/O_2 into the diesel engine the maximum fuel savings were recorded as approximately 15% (15.07%, 15.16%, and 14.96% at 19 kW, 22 kW, and 25 kW, respectively). However, the rate of increase in fuel saving starts to decline with addition of more than 4% H_2/O_2 mixture and no significant gain in fuel savings were observed beyond 5% addition of H_2/O_2 mixture. This indicates that beyond 5% induction, H_2/O_2 mixture acts as a fuel rather than an additive.

3.3. Air–fuel ratio

Fig. 7 depicts the variation of air–fuel ratio with H_2/O_2 percentage. As the H_2/O_2 mixture is inducted through the intake air the mixture replaces some air that could result in reduced air–fuel ratio. Instead, the figure shows that the air–fuel ratio increases with increasing H_2/O_2. This is due to the fact that the inducted mixture contains oxygen as well. This increase in air–fuel ratio improves the combustion resulting lower fuel consumption and better efficiency as described earlier. The increases in air–fuel ratio at the maximum flow rate of H_2/O_2 mixture were from 95.5 to

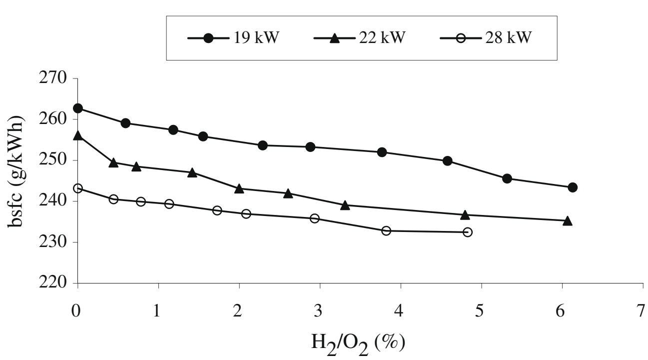

Fig. 4. Variation of brake specific fuel consumption (bsfc) with H_2/O_2 percentage.

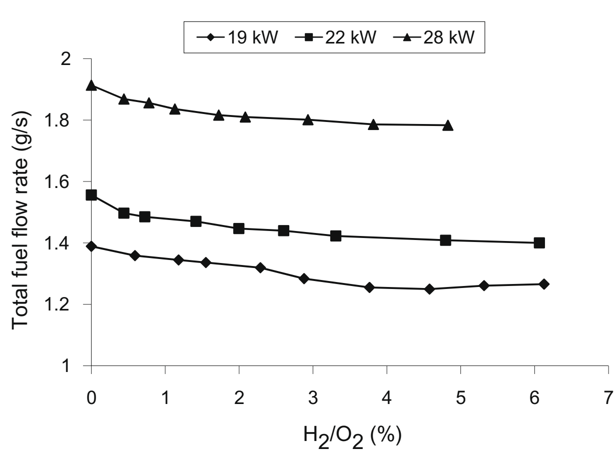

Fig. 5. Variation of total fuel flow rate with H_2/O_2 percentage.

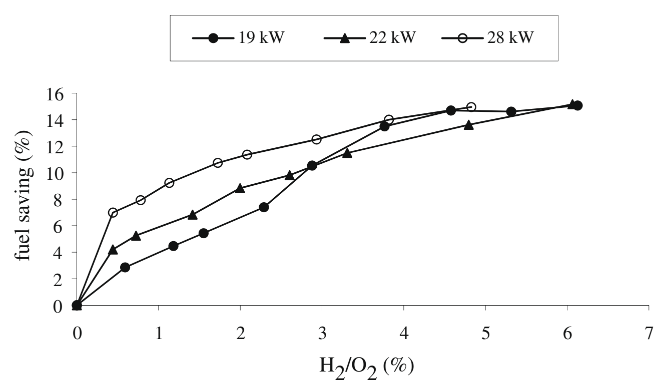

Fig. 6. Variation of fuel saving with H_2/O_2 percentage.

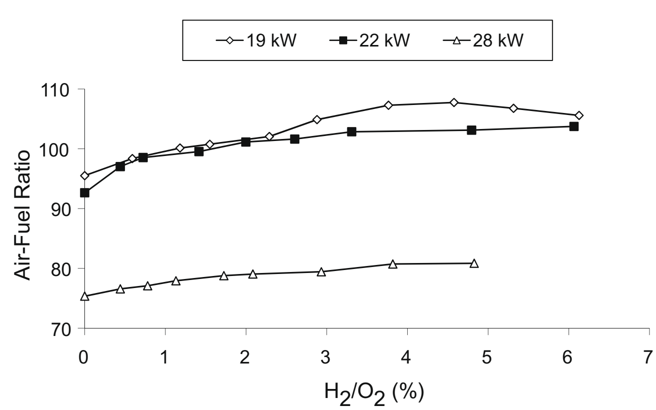

Fig. 7. Variation of air–fuel ratio with equivalent H_2/O_2 percentage.

105.5, from 92.6 to 103.7 and from 75.3 to 80.8 at 19 kW, 22 kW, and 28 kW, respectively.

3.4. Hydrocarbon

Fig. 8 depicts the variation of hydrocarbon (HC) with % of H_2/O_2 under different load conditions. Though the graph shows some overlapping, but regardless of the load level, by introducing H_2/O_2 to diesel the HC emission reduced. The reduction of HC emissions is due to the absence of carbon in hydrogen fuel and also due to better combustion of diesel fuel with the aid of hydrogen which has a higher flame speed. At 19 kW the HC emission dropped from 187 ppm to 85 ppm with 31.75 l/min induction of H_2/O_2. At 22 kW and 28 kW the HC emission decreased from 189 ppm to 93 ppm by adding 29.84 l/min and from 192 ppm to 97 ppm by adding 30.6 l/min of H_2/O_2, respectively.

3.5. Oxides of nitrogen (NO_x)

The variation of NO_x emission with percentage of H_2/O_2 is shown in Fig. 9. At all load levels, induction of H_2/O_2 resulted in increase in the amount of NO_x emission. Higher air–fuel ratio coupled with better combustion due to higher flame speed of hydrogen might have caused the peak pressure and temperature to rise. Both high temperature and more available oxygen in the formed mixture might have caused NO_x emission to rise [21]. The NO_x emission is found to be increased from 220 ppm to 280 ppm, 232 ppm to 307 ppm, and 270 ppm to 339 ppm at 19 kW, 22 kW, and 28 kW of load, respectively.

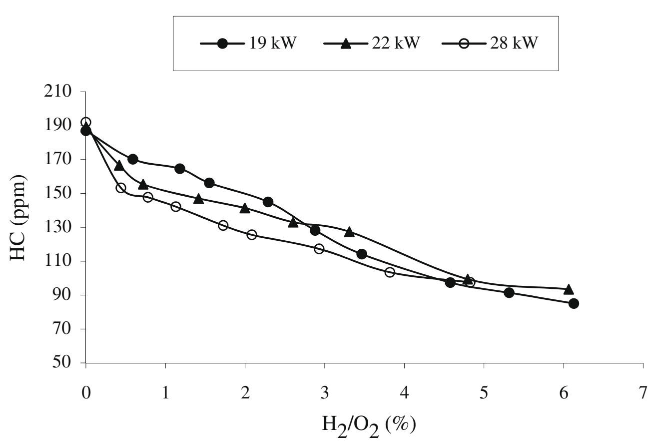

Fig. 8. Variation of HC emission with H_2/O_2 percentage.

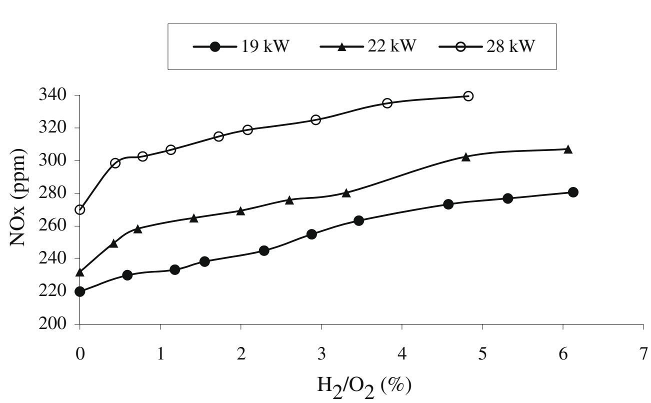

Fig. 9. Variation of NO_x with H_2/O_2 percentage.

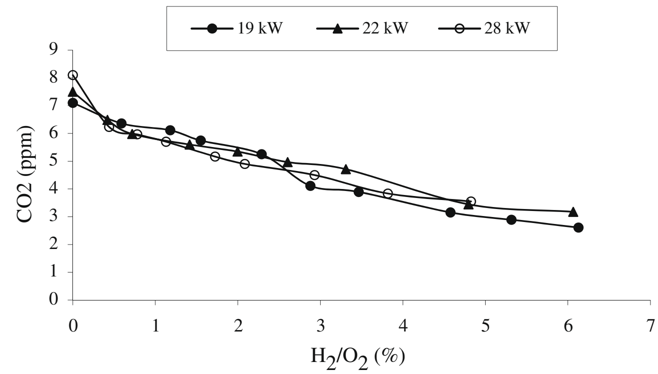

Fig. 10. Variation of CO_2 with H_2/O_2 percentage.

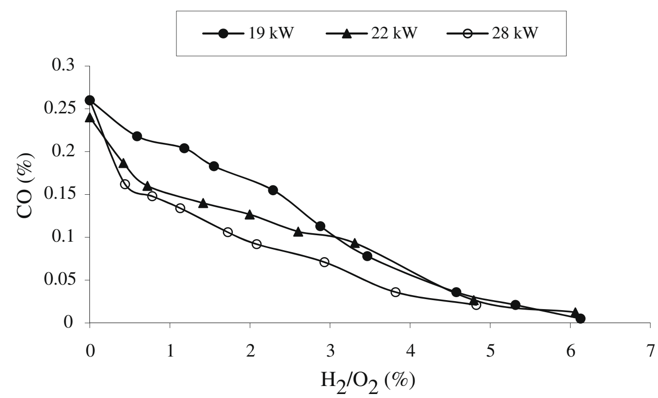

Fig. 11. Variation of the CO with H_2/O_2 percentage.

3.6. Carbon dioxide

Fig. 10 shows the variation of carbon dioxide (CO_2) with the % of H_2/O_2. Again, the figure shows some overlapping. However, as observed from the figure, at all load levels CO_2 is reduced. The reduction in CO_2 is due to less carbon concentration in the formed mixture of fuels. Hydrogen is a carbon less fuel and when substituted to diesel the formed mixture produces less carbon dioxide. The reduction of CO_2 is achieved at all load conditions. The minimum amount of CO_2 was achieved at 19 kW as 2.06 ppm with 31.75 l/min of H_2/O_2 induction. For the other load conditions, the trend is almost similar and the lowest CO_2 level was found as 3.17 ppm and 3.54 ppm at 22 kW and 28 kW, respectively.

3.7. Carbon monoxide

Fig. 11 depicts the variation of carbon monoxide (CO) with the percentage of H_2/O_2. Although the CO values for neat diesel operation is relatively lower, by inducting H_2/O_2 into diesel the CO amount is further reduced. This is due to the absence of carbon in the hydrogen fuel and also operation at leaner mixture (higher air–fuel ratio). CO is reduced from 0.26% to 0.005% at 19 kW, from 0.24% to 0.012% at 22 kW and from 0.26% to 0.021% at 28 kW.

4. Conclusion

The impacts of using a small amount of H_2/O_2 mixture as an additive on the performance of a four-cylinder diesel engine were evaluated. The required amount of the mixture was generated using electrolysis of water considering on-board production of H_2/O_2 mixture. Hydrogen which has about nine times higher flame speed than diesel has the ability to enhance overall combustion generating higher peak pressure closer to TDC resulting in more work. The experimental results showed that with the introduction of 6.1% total diesel equivalent H_2/O_2 mixture into diesel, the brake thermal efficiency increased by 2.6% at 19 kW, 2.9% at 22 kW, and 1.6% at 28 kW. The brake specific fuel consumption of the engine reduced by 7.3%, 8.1%, and 4.8% at 19 kW, 22 kW, and 28 kW, respectively. However, adding H_2/O_2 beyond 5% does not have significant effect in enhancing the engine performance. The emissions of HC, CO_2 and CO were found to be reduced due to better combustion while NO_x increased due to the higher temperature reached during the combustion.

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