University of
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Report

on

ENHANCEMENT OF DIESEL ENGINE PERFORMANCE AND REDUCTIONS OF EMISSIONS BY ON-BOARD PRODUCED HYDROGEN INJECTION

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Executive Summary

The internal combustion (IC) diesel engine which is a highly efficient and powerful type of engine is extensively utilized throughout the world today in various applications from road transport, marine propulsion, railway transport, mechanical drives through to and including power generation. While being highly efficient and already widely utilized, the diesel engine due its continued growth is an ever-growing consumer of petroleum diesel fuel while also being a major source of air pollutions around the world, which is harmful to both humans and the environment. An emerging fuel that has potential to address these issues is hydrogen due to its wide abundance. The use of pure hydrogen or hydrogen/oxygen (H_2/O_2) gas mixture is being researched and investigated as a likely alternative or additive in diesel engines to reduce the global demand for petroleum diesel fuels and produced harmful emissions. In this project, the use of H_2/O_2 mixture added to a diesel engine via the inlet air is investigated. The aim of the experimental research project is to investigate the impact on the performance and exhaust emissions of a diesel engine with the use of H_2/O_2 mixture as an additive.

Experimental research was conducted on a Cummins 6BT5.9-G2, in-line 6-cylinder, direct-injection, turbocharged, water-cooled diesel engine powered generator set, which has a capacity of 100 KVA (kilovolt-ampere). The generator set was connected to a portable variable resistive load bank which would allow varying step loads to be applied to the generator and as such to the diesel engine. The H_2/O_2 gas mixture was generated and supplied by a HYDI unit, which uses electrolysis of demineralized water to produce the required H_2/O_2 mixture. The H_2/O_2 mixture production rate was varied by the current passed to the HYDI unit and it was powered by the diesel engines battery/alternator. Experiments were conducted at varying loads of 20 kilowatt (kW), 40 kW, 60 kW, 65 kW, 70 kW and 75 kW with H_2/O_2 mixture flowrates of 0.42 LPM, 0.84 LPM and 1.25 LPM. The diesel engine was fitted with the necessary instrumentation and equipment in order to measure and record its performance parameters. Also, specialist calibrated exhaust emission equipment was utilized to accurately measure the exhaust emissions of oxygen (O_2), carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), nitric oxide (NO), nitrogen dioxide (NO_2) and particulate matter (PM).

It was found that through the addition of the H_2/O_2 mixture via the inlet air, there were significant reductions in the exhaust emissions of PM concentrations. The average reductions in PM concentrations were 10.34%, 24.77% and 41.05% across the load range at H_2/O_2 mixture flow rates of 0.42 LPM, 0.84 LPM and 1.25 LPM, respectively. The maximum reduction in exhaust emission PM concentrations was 56% at the 75 kW load and with a H_2/O_2 mixture flow rate of 1.25 LPM. It was also found that there were slight reductions in the exhaust emission of CO. The average reduction in CO emissions were 5.50%, 3.40% and 2.32% across the load range at H_2/O_2 mixture flow rates of 0.42 LPM, 0.84 LPM and 1.25 LPM, respectively. Also, there was very little to no change in the produced NO_x exhaust emissions at any of the H_2/O_2 mixture flow rates. However, when the diesel engine performance was investigated with the addition of the H_2/O_2 mixture there was no evidence to indicate or support that there was any impact by way of improvement or reduction to the performance parameters of thermal efficiency and brake specific fuel consumption (bsfc). The water needed for 24-hours operation were 0.325 L, 0.649 L and 0.874 L at H_2/O_2 mixture flow rates of 0.42 LPM, 0.84 LPM and 1.25 LPM, respectively.

1. INTRODUCTION

The use, demand and dependence of petroleum-derived fuels throughout the world is continuing to grow at an ever-increasing rate. The subsequent detrimental environmental effects caused due to harmful emissions from the combustion of these fuels in Internal Combustion (IC) engines also continue to grow at a similar escalating rate, impacting the global and local environments [1, 2]. According to the World Health Organization (WHO), outdoor air pollution is a significant environmental health problem which does not discriminate and affects all people in low-, middle-, and high-income countries around the world [3]. Outdoor air pollution was estimated to be the cause of approximately 4.2 million premature deaths around the world in 2016 [3]. The cause of this high mortality is primarily attributed to the exposure of Particulate Matter (PM) emissions released from IC engines, which cause cardiovascular, respiratory disease and cancers [3]. The 2005 WHO Air Quality Guidelines indicate that by reducing global PM emissions by approximately 71% would potentially cut air pollution related deaths by approximately 15% globally [2]. Currently, petroleum-derived fuels have serious issues with high emissions of carbon dioxide (CO_2) and emitting other toxic emissions such as nitrogen oxide (NO_X), carbon monoxide (CO), hydrocarbon (HC) and particulate matter (PM) [4]. Diesel engines produce more PM emissions than gasoline engines due to their heterogenous mixture of air and fuel within the engine's combustion chamber. Through various studies, it has been reported that the addition of either pure hydrogen (H_2) gas or a mixture of produced hydrogen/oxygen (H_2/O_2) gas into diesel engines has resulted in significant reductions in HC, CO, CO_2 and PM emissions by as much as over 50%. There has also been observed with high hydrogen flow rates a significant increase in diesel engine's thermal efficiency. Although due to the increased in-cylinder temperatures from the higher energy content of hydrogen an increase in NO_X emissions is observed particularly under high load conditions [5]. As gasoline and diesel are the main conventional petroleum-derived fuels for IC engines, many countries have implemented strict exhaust emission regulations [6]. This has led researchers to progressively explore alternative methods and clean energy sources to meet the ever-increasing stringent emission regulations.

A significant aspect of hydrogen that makes it very attractive as an alternative fuel is its large specific energy content [7]. It is known that among commonly used fuels in IC engines hydrogen energy density is amongst the highest. Being that for 1 kg of hydrogen, approximately three times more energy can be provided than that of diesel or gasoline fuels [5]. Hydrogen has a very high auto-ignition temperature and a very high-octane number due to the presence of oxygen. These aspects allow the opportunity for the engine compression ratios to be increased and therefore, the potential for the increase in an engine's efficiency [8]. The low ignition energy value and associated wide flammability range of hydrogen will also allow engines to run on very lean air/fuel mixtures. Additionally, hydrogen properties show a very high flame speed and high diffusivity, allowing for greatly improved mixture uniformity and rapid combustion once ignited [7].

Although using only hydrogen fuel in a compression ignition (CI) engine is somewhat difficult due to the auto-ignition temperature of hydrogen being much higher than that of diesel (diesel 257˚C and hydrogen 585˚C) [9]. To achieve auto-ignition of hydrogen a compression ratio of over 20 would be required, otherwise a supplementary spark ignition source is needed for combustion to occur. The other option to achieve the required high temperature conditions would be to have intake air charge heating [10]. However, this can potentially cause preignition and backfire situations due to the wide flammability limit of hydrogen. Therefore, to use hydrogen in a conventional CI engine as a fuel without the associated disadvantages and risks, other ignition sources must be developed or identified. This has led researchers to look at hydrogen as an additive to enhance conventional CI engines running on diesel fuel, that can significantly reduce harmful combustion emissions as well as reducing diesel fuel consumption while maintaining the CI engines performance [11].

Putrasari et al. [12] evaluated the performance of a 0.667 Litre (L) single cylinder diesel engine with H_2 being added at a constant fixed flow rate of 10 LPM via the air intake manifold and without H_2 being added at varying engine loads and found that there was an increase of thermal efficiency at higher engine speeds when H_2 was added. It was also observed that at low loads and high engine speed exhaust NO_X and smoke emission were significantly reduced with the addition of H_2. Cernat et al. [13] through their research also identified and reported similar results of improved brake thermal efficiency at mid-engine loads of between 40% and 70% load. They also observed reductions in exhaust emissions of NO_X, CO_2 and smoke at varying flow rates of H_2 from 9 LPM to 40 LPM injected into the air intake manifold of a 10.34 L diesel engine. The observed smoke reductions were more evident at higher loads and was attributed to the addition of H_2 which improved combustion due to the lower carbon content of the combustion chamber air-fuel mixture. Sharma et al. [14] used H_2 energy substitution (HES) of 0%, 5%, 10%, and 20% of diesel fuel and studied the effects on a 0.661 L single cylinder diesel engine performance parameters as well as the produced exhaust emissions at engine loads of 25%, 50% and 75%. At higher load of 75% and with 20% HES, they observed a slight decrease in brake thermal efficiency along with reductions in CO and CO_2 emissions although there was an observed increase in NO_X emission. It was suggested that the increase in NO_X emission was due to the higher in-cylinder combustion temperatures.

Pure hydrogen gas has a very low density and high specific energy meaning that very large storage volumes would be required for storage unless it is compressed to very high pressures or combined chemically with a metal alloy [11]. Currently the common storage methods of H_2 are hybrid and liquid storage. Both storage methods have comparable volumetric storage capabilities, but both methods require approximately 10 times the space of that required to store an equivalent energy content of liquid gasoline or diesel fuel [15].

The challenge and associated safety concerns with on-board storage of hydrogen when used as either a single source of fuel or as a fuel additive in transport applications have become significant challenges to be addressed and overcome. The current storage methods of hydrogen within the transportation industries are classified according to the state of the hydrogen being either gaseous or liquid storage. The method of storing hydrogen in its liquid state requires cryogenic temperatures where the hydrogen gas is reduced to a temperature of -253°C. At this temperature hydrogen will remain in its liquid state at one atmosphere pressure [16]. Therefore, to maintain the cryogenic temperatures of liquid hydrogen within a storage vessel requires special insulation designs that minimize the effect of heat losses [17]. As there is no insulation design that can perfectly insulate from the effect of heat losses, the liquid hydrogen in the storage vessel will eventually change back to gaseous state over time thus significantly increasing the pressure inside the storage vessel. Since the storage vessel is designed to only one atmosphere pressure rating, to prevent excessive pressure build up within the storage vessel the vaporized gaseous hydrogen is discharged to the surrounding atmosphere through a pressure-reducing valve (PRV) or pressure safety valve (PSV), this results in slow depletion of liquid hydrogen in the storage vessel [18-20]. To minimize the effect of heat losses through the storage vessel, large cryogenic hydrogen storage vessels are usually designed to be spherical in shape and surrounded by some heavy insulation material [21].

White et al. [21] studied a cryogenic compressed storage vessel chamber that could be used for mobile transport applications. The system was operated at a temperature of between -233˚C and -193˚C (40-80 K) and a pressure of 300 bar. Due to high pressure storage being used, the vaporization of liquid hydrogen was inhibited to some extent. Ahluwalia et al. [22] reported that this method of liquid hydrogen storage prevented any loss of liquid hydrogen for more than 7 days when filling to only 85% of the storage vessels capacity. This method of cryogenic compression storage of liquid hydrogen still requires high strength materials to withstand the high pressures and uses vacuum insulation to prevent heat losses. The materials used for the manufacture of the storage vessel are usually very rare and the cryogenic temperatures of the liquid hydrogen are extremely hazardous [23]. Therefore, the associated cost of using this cryogenic compression storage method is expected to be in the vicinity of \$390/ kg of H_2 [21].

The compressed hydrogen gas storage method is currently the dominant choice in industry and the most developed hydrogen storage technology. The Society of Automotive Engineers has developed a standard SAE J2600 [24] which was specifically developed for onboard ground transportation vehicle applications using compressed hydrogen gas. However, even if a commercial technical standard has been established, the actual performance of the product may vary depending on the production process.

According to Züttel [25], the weight of high-pressure hydrogen cylinders is 13 wt% of the total weight of the gas and cylinder at a pressure of 800 bar. However, according to Toyota Motor Corporation (TMC), in 2017 they produced tanks with a weight of 5.7 wt% at 700 bar [26]. The process of compressing hydrogen gas requires a lot of energy, such that compressing hydrogen gas from 20 bar to 700 bar requires at least 1.36 kWh/kg of H_2[27]. Since, hydrogen gas is unavoidably heated during the high compression process, an additional 0.15 kWh/kg of H_2 for the pre-cooling of the hydrogen gas to -40°C is required to prevent the storage vessel from overheating during refuelling process [27]. From a safety point of view, the extremely high hydrogen gas pressures of 700-800 bar presents a significant potential hazard in transportation applications and the associated complex refuelling process also increases the potential risk of a significant safety hazard [28].

In an effort to address the issues surrounding the storage of large enough quantities of H_2 for the prolonged operation of engines, a number of researchers came up with a solution to generate the required hydrogen on-board by the way of water electrolysis, using an on-board electrolyser to produce a mixture of hydrogen and oxygen gases in stoichiometric quantities, commonly known as H_2/O_2 gas, HHO gas or hydroxy gas and is fed into the engine as required without the need to store and carry large quantities of H_2 gasonboard.

Gad et al. investigated by experimentation the effect of adding H_2/O_2 gas mixture at a constant flow rate of 0.42 LPM from a dry cell electrolyser with NaOH alkaline solution, via the intake manifold on the performance and emissions of a 0.824 L, single cylinder diesel engine at various loads. It was found that when using the H_2/O_2 gas mixture, there was an improvement in the diesel engine performance such that thermal efficiency improved by about 15% and a corresponding equal reduction in specific fuel consumption. Along with the engine performance improvements there were observed improvements in the exhaust emissions such that hydrocarbon and CO emissions were reduced across the load range. Although there was an observed increase of 8% in the NO_X emission across the load range as compared with diesel only operation. Rimkus et al. [29] investigated the performance and emissions of a 1.9 L, four-cylinder diesel engine by using H_2/O_2 gas mixture at a constant flow rate of 3 LPM as an additive from an on-board electrolyser with KOH alkaline solution, via the intake manifold. The primary experimentation consisted of the engine being operated at a constant speed of 1900 rpm and four loads of 25%, 50%, 75% and 100% being applied. It was reported that as the load on the engine was increased the H_2 energy concentrations in the fuel mixture reduced from approximately 1.1% at 25% load to 0.4% at 100% load. At the load of 25% they observed that the H_2/O_2 gas mixture increased the indicated specific fuel consumption and reduced the indicated engine efficiency. Although as the load on the engine increased and the resulting reduction in hydrogen energy concentrations in the fuel mixture, the subsequent effects of the H_2/O_2 gas mixture on the engine's performance were reduced to the point of having very little impact at 100% load. Whereas for the exhaust emissions the observed effect of the H_2/O_2 gas mixture improved the combustion process and reduced the concentrations of incomplete combustion products such that CO, HC concentration and smoke levels decreased for all applied loads. Although there was also observed increases in the exhaust CO_2 and NO_X emissions across all applied loads. Liu et al. [30] also reported very similar results in the produced exhaust emissions of a 0.406 L single cylinder diesel engine using H_2/O_2 gas mixture as an additive. This research also reported that the addition of H_2/O_2 gas mixture at a flow rate of 2 LPM via the intake manifold had the greatest effect on the produced exhaust PM emissions, such that a decrease in the exhaust PM emissions was observed. In fact, it was reported that at greatest reduction in gross particle mass in produced PM emissions was at the highest engine load conditions. Subramanian et al. [31] used both pure H_2 gas and H_2/O_2 gas mixture as separate supplementary fuels via the intake manifold. The diesel engine performance and emissions were analysed at six different incremental of H_2/O_2 gas mixture and H_2 gas flow rates starting from 6 LPM through to 36 LPM and at five different loads for each of these flow rates. They reported that the brake thermal efficiency of the diesel engine reduced for all flow rates of the H_2 gas and H_2/O_2 gas mixture except at 6 LPM of H_2/O_2 gas mixture. This was attributed to the better utilization of excess air. It was also reported that there was a reduction in the CO_2 and smoke emissions for all flow rates and loads due to the reduction in carbon content in the combustion chamber. Unburnt HC were also reported to reduce although only at the higher flow rates and at higher loads. Whereas produced NOx emissions were lower when compared with diesel only emissions at the lower H_2 gas and H_2/O_2 gas mixture flow rates although at the higher loads NO_X emission increased. Rodriguez et al. [32] investigated only the performance of a stationary diesel engine with the addition of H_2/O_2 gas mixture produced on-board. Mixed results were reported from this investigation. The H_2/O_2 gas mixture had a positive impact with increases in both produced power and torque. There was also an observed increase in exhaust gas temperatures that was attributed to H_2 gas combustion.

The above-mentioned research studies focused on the use H_2 as supplementary fuel or H_2/O_2 gas mixture produced via an electrolyser with some form of alkaline solution, as an additive for IC engine powered equipment and the subsequent effects on engine performance and produced exhaust emissions. The higher amount of H_2 or H_2/O_2 gas mixture increased the performance and reduced the exhaust emissions. However, to achieve this a large volume of H_2 gas or water would need to be carried which could potentially add significant weight and take up a large volume of space which could be an issue to effecting vehicle's performance. Keeping these issues in mind, this research focuses to use limited amounts of water for electrolysis via an on-board electrolyser to produce the required H_2/O_2 gas mixture using the engines battery/alternator to be added to the engine's intake air. Another objective is to reduce the engines produced PM emissions as global reductions of 71% could reduce associated deaths by approximately by 15% globally [2]. There was only one study that assessed the impact of adding H_2/O_2 gas mixture and its effect on the exhaust PM emissions produced [30]. Therefore, findings from this research would strengthen the phenomena of using H_2/O_2 mixture produced by on-board electrolysis using power from the IC engines battery/alternator to reduce the produced PM exhaust emissions. The quantity of water needed to store will be evaluated and finally, the performances and other emissions of the engine will be assessed as well.

2. EXPERIMENTAL SETUP

The experimental set-up consists of a Cummins 6BT5.9-G2, in-line 6-cylinder direct-injection, turbocharged, water-cooled diesel engine powered generator set, which has a capacity of 100 kVA. The specifications of the diesel engine are shown in Table 1. The diesel engine is connected to an electrical generator with a rated speed of 1550 RPM for prime power application of 100 kVA (80 kW) continuous power output with a power factor of 0.8. The generator is connected to a portable variable resistive load bank with varying loads to be applied to the diesel engine. Experiments are conducted using load steps of 20 kW, 40 kW, 60 kW, 65 kW, 70 kW and 75 kW. A schematic diagram of the experimental setup is shown in Fig. 1. A digital scale and a stopwatch are used to measure the fuel mass flow rate. The HYDI unit generates and provides the H_2/O_2 mixture, which uses the power from the battery/alternator of the engine to electrolyse water to produce the required H_2/O_2 mixture. The H_2/O_2 mixture is varied by the current passed through the HYDI unit. This produced H_2/O_2 mixture is drawn off by the HYDI unit and then, fed via a flow line connected to the engine's air inlet just prior to the turbocharger inlet. Experiments are conducted with H_2/O_2 gas mixture flow rates of 0.41 LPM, 0.82 LPM and 1.25 LPM and the required currents are 10 A, 20 A and 30 A, respectively which are applied across the electrolysis cell.

Table 1. Diesel Engine Specifications.

Cummins 6BT5.9-G2 Diesel Engine for Generator Set	
Technical Specifications	**Value/Type**
Bore	102.1 mm
Stroke	119.9 mm
Number of cylinders	6 Cylinder, In-line
Compression ratio	17.3: 1
Rated Engine speed	1550 rpm
Engine displacement	5900 cc (5.9 L)
Aspiration	Turbocharged
Fuel System	Direct Injection
Governor	Electronic
Cooling	Liquid Coolant

A digital weather station is used to measure the barometric pressure and humidity of the surrounding environmental conditions at each experimental step. The temperatures of inlet air, exhaust gas and the H_2/O_2 mixture are measured by using K-type thermocouples which are connected to digital displays with an accuracy of ±0.1˚C. A bell mouth shaped velocity nozzle is mounted on the air inlet duct of the engine with an inclined tube manometer. The pressure differential across the inlet nozzle with an accuracy of ±0.01 kPa is used to calculate the airflow rate.

The diesel engine exhaust emissions are sampled and measured using a calibrated Testo 340 emissions analyser with emissions measurement accuracy of ±10 ppm for CO and NO_2, ±5 ppm for NO and NO_X and ±0.2% volume for O_2 and CO_2. A TSI Nanoparticle emission tester, Model 3795 is used to measures the solid-particle number-concentration with a particle concentration accuracy of ±10%. It measures the solid particle concentrations by evaporating and oxidizing the volatile components and particles from the diluted sample.

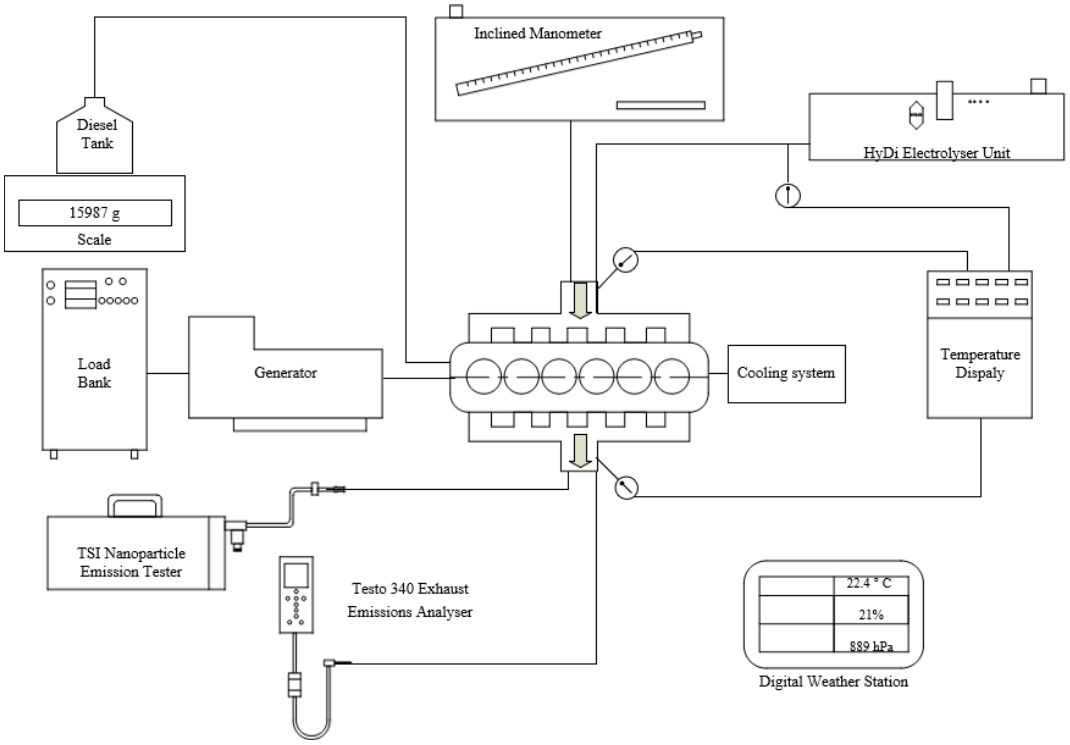

Figure 1. Experimental setup

The generator set diesel engine is operated at an isochronous governed speed of 1550±5 rpm with 6 different independent loads of 20 kW, 40 kW, 60 kW, 65 kW, 70 kW and 75 kW applied by the load bank to the generator set. The engine performance parameters and operating conditions such as engine load, inlet air differential pressure, inlet air temperature, exhaust gas temperature, engine speed, humidity, barometric pressure and exhaust emissions are measured and recorded without any addition of H_2/O_2 mixture. The emissions of CO, CO_2, O_2, NO, NO_2, NO_X and Particulate Matter (PM) are also recorded. Following the same procedure, the experiments are conducted with minimum applied load through to the maximum load with 0.42 LPM, 0.84 LPM and 1.25 LPM of H_2/O_2 mixture, and measure and record the engine performance and emission parameters and operating conditions. Then, the whole experiments are repeated with the maximum load to no-load with the highest H_2/O_2 mixture to minimum H_2/O_2 mixture and measure and record the engine performance and emission parameters and operating conditions. The duration of each set of experiments was around 3 hours.

3. ANALYSIS OF EXPERIMENTAL RESULTS

This section analyses the effect of the addition of the H_2/O_2 gas mixture at flow rates of 0.42 LPM, 0.84 LPM and 1.25 LPM via the inlet air on a diesel engine performance and exhaust emissions as compared to diesel fuel only operation. The aim of this section is to provide some analysis into the collected and calculated experimental results of whether the addition of the H_2/O_2 gas mixture and at which of the three flow rates have the greatest impact in enhancing the diesel engines performance and reducing the exhaust emissions.

3.1 Performance of the Engine

In this section the diesel engine performance is analysed by a number of performance parameters measured and calculated to identify if there are any significant changes or impacts to either exhaust temperatures, thermal efficiency, air fuel ratio, air mass flow rate, fuel mass flow rate and brake specific fuel consumption due to the addition of the H_2/O_2 gas mixture as compared with diesel fuel only operation.

3.11 Exhaust Temperature

Exhaust gas temperatures generally increase at a linear rate with increasing engine speed or load and is relative to the air-fuel ratio (AFR). In diesel engines load is controlled by varying the AFR. In this research, at lower loads the exhaust gas temperatures are found to be around 550 K and at higher load around 900 K as can be seen in Fig. 2. This is due to the AFR and the amount of fuel injected, because at low loads the AFR is very lean meaning that there is a relatively small amount of fuel being injected into the combustion chamber as compared to the air going into the combustion chamber. The low exhaust gas temperature is a result of the fuel combustion thermal energy having to heat the excess air in the combustion chamber. However, as the load increases the amount of fuel being injected into the combustion chamber increases, which decreases the AFR moving towards lower AFR but remaining still lean mixture. Therefore, when combustion occurs there is far more thermal energy released as compared to lower load. Therefore, more of the thermal energy is used in generating power, which results in higher exhaust temperatures. The addition of the H_2/O_2 gas mixtures at any of the three flow rates was observed to have minimal impact on the direct measured exhaust temperatures across the load range as shown in Fig. 2.

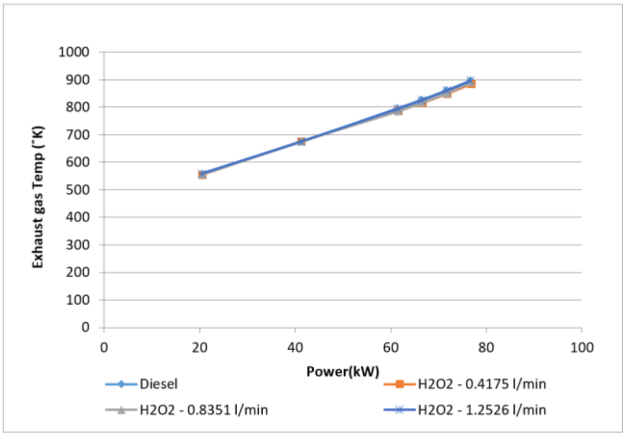

Figure 1. Exhaust Gas Temperature vs. Power

At the higher flow rate of H_2/O_2 mixture, the observed reduction in measured exhaust temperature as compared with diesel across the load range is 0.05%. With the middle flow rate of H_2/O_2 mixture the observed reduction in measured exhaust temperatures across the load range is 0.83%. Whereas with the lowest flow rate of H_2/O_2 mixture the observed reduction in measured exhaust gas temperature across the load range is 1.03%. It is also noted that at 65 kW load point, the reduction in measured exhaust temperature is 1.49%, in fact at all H_2/O_2 mixture flow rates the greatest reduction in measured exhaust temperatures is at the 65 kW load point. This could be the result of the addition of H_2/O_2 mixture, as hydrogen is a very fast burning fuel (265-365 m/s) being approximately 10 times faster than that of diesel fuel (30 m/s) [9, 11, 33]. This means during the main combustion period; it burns more hydrocarbon fuel leaving lower unburnt hydrocarbon fuel during the expansion and exhaust strokes which would continue to burn otherwise during these strokes causing lower exhaust temperatures than pure diesel operation. This is evident from PM emissions as shown in later which is lower with H_2/O_2 mixture than pure diesel operation.

3.12 Thermal Efficiency

The calculated brake thermal efficiency of the diesel engine is shown in Fig. 2. This is the ratio of brake work produced per unit time to the amount of fuel chemical energy supplied per unit time that is released in the combustion process. From Fig. 2, it can be observed that there are marginal changes in the thermal efficiency of the engine across the load range for any of the H_2/O_2 mixture flow rates. In fact, the average change in thermal efficiency for the 0.42 LPM H_2/O_2 mixture is an increase of 0.72%, for the 0.84 LPM H_2/O_2 mixture an increase of 0.28% and for the 1.25 LPM H_2/O_2 mixture an increase of only 0.16% as compared with the diesel only operation.

At lower loads, the thermal efficiency is low despite approximately 95%-98% of the injected diesel fuel being combusted due there being sufficient available air in the combustion chamber [34]. As described earlier, the excess air at lower loads is very high meaning this air is needed to be heated by the combustion thermal energy resulting in lower combustion temperature and lower cylinder pressures (i.e., lower power output) which results in lower thermal efficiency. As the load on the engine increases the AFR decreases meaning that there is less excess air in the cylinder having to be heated by the combustion thermal energy. Therefore, more of the combustion thermal energy is used in producing higher combustion temperatures resulting in higher cylinder pressures (i.e., more power output) resulting in higher thermal efficiency. The maximum thermal efficiency observed for diesel fuel only operation is 31.19% at the 65 kW load point. With the addition of the H_2/O_2 mixture at the flow rates of 0.84 LPM and 1.25 LPM the peak thermal efficiency is also observed at the 65 kW load point with 31.42% and 31.24% an increase of 0.74% and 0.14% respectively, over diesel only operation. Whereas for the 0.42 LPM H_2/O_2 mixture flow rate the maximum thermal efficiency is achieved at the 70 kW load point with 31.69% an increase of 2.84% over diesel only operation at the same load point. The observed improvements in the brake thermal efficiency with H_2/O_2 mixture can be attributed to the oxygen molecule present with the H_2/O_2 mixture.

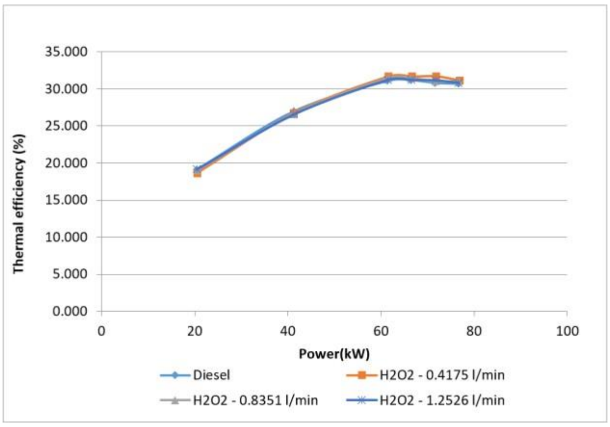

Figure 2. **Thermal Efficiency vs. Power**

Beyond the points of maximum achieved thermal efficiency, the AFR continues to decrease tending towards stoichiometry AFR. Therefore, there is less available air for complete combustion to occur specially at core of the fuel injected region. As a result, the thermal efficiency starts to decrease slightly for the higher load points of 70 kW and 75 kW for diesel only operation. With the addition of H_2/O_2 mixture a very slight decrease in thermal efficiency is also observed although not as great as the diesel only operation. For all H_2/O_2 mixture flow rates at the higher loads the thermal efficiency is maintained at around 31% for the 70 kW and 75 kW load points being an average improvement of 1.28% over diesel only operation. This is attributed to the presence of additional O_2 from the H_2/O_2 mixture being added.

3.13 Air Fuel Ratio

Air Fuel Ratio (AFR) is the ratio of the measured intake air mass flow rate to the measured fuel mass flow rate being consumed by the engine for combustion. Ideal combustion occurs at stoichiometric AFR which is when the fuel and air are in theoretically correct proportions so that when the combustion in the cylinder has completed there is no fuel or oxygen remaining. Figure 3 shows the calculated AFR for diesel only operation and for each of the H_2/O_2 mixture flow rates over the load range.

As can be seen in Fig. 3, at lower load the AFR is high meaning that it is a very lean fuel mixture but as the load increases the AFR gradually decreases at an almost linear rate to the maximum applied load of 75 kW. Although at the maximum load point, the AFR is still a lean mixture as compared to the stoichiometric AFR of diesel fuel being 14.5:1 with the calculated experimental AFR for diesel only operation being 16.2:1. With the addition of the H_2/O_2 mixture the calculated AFR is in between 17:1 and 16.5:1 at the maximum load point of 75 kW. At maximum load with the addition of the H_2/O_2 mixture there is an observed slight increase in AFR of 2.12% for 0.41 LPM flow rate of H_2/O_2 mixture, 1.74% for 0.82 LPM flow rate of H_2/O_2 mixture and 0.49% for 1.25 LPM flow rate of H_2/O_2 mixture. It is also observed that across the load range with the addition of H_2/O_2 mixture for all flow rates of 0.41 LPM, 0.82 LPM and 1.25 LPM there are corresponding average increase in the AFR of 1.64%, 1.54% and 0.49%, respectively. As shown later, as the H_2/O_2 mixture increases into the engine the diesel flow rate decreases which makes the AFR with H_2/O_2 mixture higher or leaner than diesel only operation. Therefore, due to the addition of the H_2/O_2 mixture the AFR is slightly leaner than that of diesel only operation.

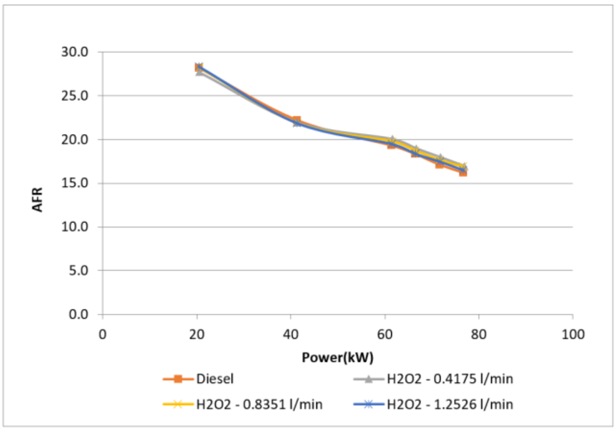

Figure 3. Air Fuel Ratio vs. Power

3.14 Air Mass Flow Rate

Air mass-flow rate is the mass of air in kilograms taken in by the engine per second of time. Figure 4 shows that as the load on the engine increases the air mass-flow rate also increases at a linear rate corresponding to the increase in the fuel mass flow rate to produce the power required. As can be seen at lower load there is very little change in air mass flow rate at any of the H_2/O_2 mixture flow rates as compared to diesel fuel only operation. Whereas at higher loads from 60 kW to 75 kW the air mass flow rate increases with the addition of the H_2/O_2 mixture. The average increases observed with the addition of the H_2/O_2 mixture are 2.34% at 0.41 LPM, 2.10% at 0.82 LPM and 0.54% at 1.25 LPM. The inlet temperatures of H_2/O_2 mixtures are lower than the inlet temperatures of air as shown in Fig. 5. This lower temperature decreases the inlet air temperature to some degree which increases the air density and as such increases the airflow rate. This corresponds to the observed increase in AFR as discussed previously.

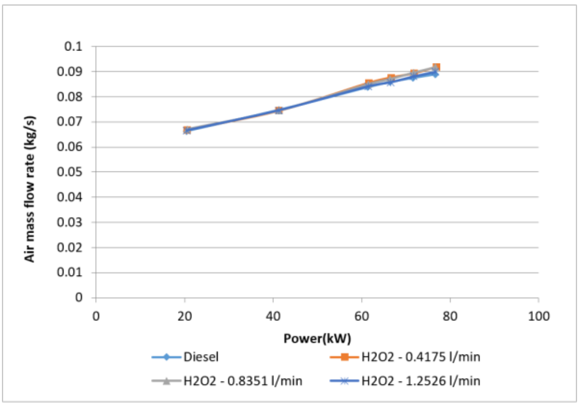

Figure 4. Air Mass Flow Rate vs. Power

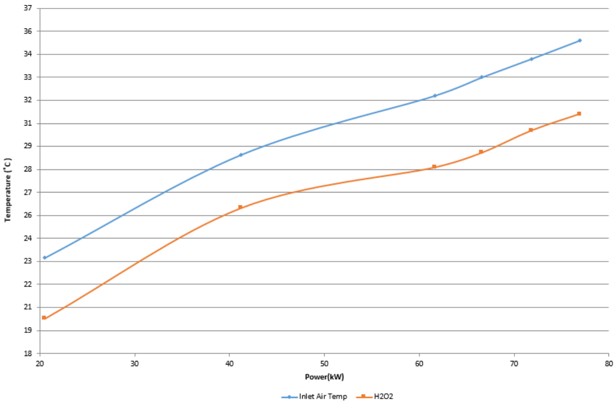

Figure 5. Inlet Air Temperature vs. Power

3.15 Brake Specific Fuel Consumption (bsfc)

Figure 7 shows the brake specific fuel consumption (bsfc) which is the fuel mass flow rate per unit of power output from the engine. This performance parameter is independent of engine size and measures how efficiently an engine uses the fuel supplied to produce work at a specific operating condition. The desired results are low bsfc values across the load range. It is generally accepted that, for petroleum fuels the bsfc is inversely proportional to the thermal efficiency. This can be clearly seen when comparing Fig. 7 to Fig. 2. From inspection of Fig. 7, it is shown that there is marginal change in the bsfc of the engine across the load range with the addition of any of the H_2/O_2 mixture flow rates. In fact, the average change across the load range in bsfc for 0.42 LPM H_2/O_2 mixture flow rate is a decrease of 0.68%, for the 0.84 LPM H_2/O_2 mixture flow rate a decrease of 0.27% and for the 1.25 LPM, H_2/O_2 mixture flow rate a decrease of only 0.15% as compared with diesel only operation. The minimum bsfc for diesel fuel operation is 253.2 g/kWh at 65 kW load point. At lower loads, the bsfc is high due to higher AFR. Even though approx. 95% -98% of the fuel injected is combusted due to there being enough available air [34]. The remaining excess air is heated by the combustion thermal energy resulting in lower combustion temperatures and lower cylinder pressure (i.e., less power output). As the load is increased the AFR decreases meaning lower excess air to be heated. Therefore, more of the thermal energy is used in producing higher combustion temperatures resulting in higher cylinder pressures and lower bsfc (i.e., more power output). Beyond the minimum bsfc point, the AFR continues to decrease, as a result there is not enough air for complete combustion especially in local fuel-rich region which increases the bsfc. This is due to more fuel being required to produce power to carry the applied load. With this increase in bsfc there is a corresponding decrease in the thermal efficiency as well.

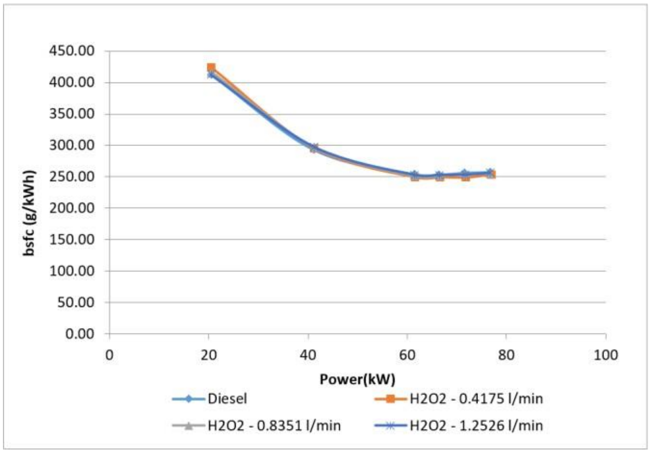

Figure 6. Brake Specific Fuel Consumption vs. Power

3.2 Emissions from the Engine

In this section, the effect of the addition of the H_2/O_2 mixture had on the produced and measured exhaust emissions results are analysed. As the current practises to reduce the harmful combustion emissions produced from diesel engines is by two primary methods being developed and used. The first is to improve engine and fuel technology so that better combustion occurs, and therefore, fewer combustion exhaust emissions such as CO, NOx and PM are produced. The second method is by aftertreatment or filtration of the combustion exhaust emissions. This is achieved by using thermal converters or catalytic converters that assist in promoting chemical reactions in the exhaust emissions flow. These chemical reactions convert the harmful exhaust emissions to acceptable emissions of CO_2, H_2O and N_2. The filtration method is by diesel particulate filtration (DPF) where the filter fitted to the diesel engines exhaust is designed to capture and then burn off the accumulated PM either through the use of a catalyst or by active means such as a fuel burner which heats the filter element to PM combustion temperatures.

3.2.1 Oxygen

Oxygen in the exhaust typically comes from the intake air. Most of the oxygen taken in by the engine is consumed during the combustion process, but there is always a bit of oxygen left over in the exhaust stream. The percentage by volume of oxygen present in the exhaust emissions is a good indicator of the air fuel ratio in the engine's combustion chamber. Figure 8 clearly shows that at lower load the percentage by volume of oxygen in the exhaust stream is very high at around 15% and as the load increases the percentage by volume of oxygen decreases at a linear rate to around 9% at higher load. This shows that the percentage by volume of oxygen in the exhaust stream is proportional to the AFR as shown in Fig. 3 previously.

With the addition of the produced H_2/O_2 mixture at any of the flow rates of 0.41 LPM, 0.82 LPM and 1.25 LPM it is observed that there are marginal effect on the percentage by volume of oxygen in the exhaust stream which can be clearly seen in Fig. 8. The effect of the addition of the H_2/O_2 mixture flow rates across the load range show average reductions of 0.44% at 0.41 LPM, 0.31% at 0.82 LPM and 0.07% at 1.25 LPM as compared to diesel fuel only operation. This shows that the additional oxygen being introduced into the combustion chamber is being consumed for better combustion, as unburnt hydrocarbon in the fuel-rich region could burn with oxygen presence with the air fuel mixture better than the diesel only operation. The PM measurements confirm this fact as shown later.

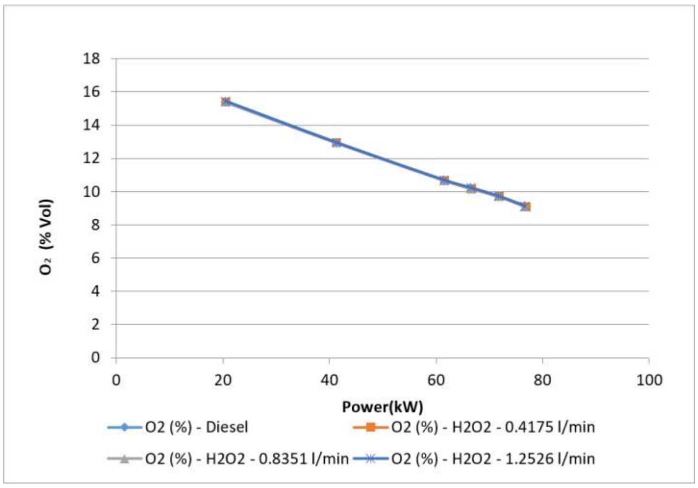

Figure 8. Exhaust Oxygen % Volume vs. Power

3.2.2 Carbon Dioxide

Carbon dioxide is a direct by-product of the combustion process by way of oxidising carbon from the fuel and produces carbon dioxide inside the combustion chamber with the oxygen present in the cylinder. The percentage by volume of carbon dioxide present in the exhaust is proportional to fuel injected. As shown in Fig. 9, at lower load the percentage by volume of carbon dioxide in the exhaust stream is low at around 4% and as the applied load increases the percentage by volume of carbon dioxide in the exhaust stream increases at a linear rate to where at higher load the carbon dioxide percentage by volume in the exhaust stream is around 8.8%. This clearly shows that as the applied load increases the fuel mass flow increases means that there is more carbon to increase the carbon dioxide emission in the exhaust. The effect of the addition of the H_2/O_2 mixture flow rates across the load range find average changes of -0.16% at 0.42 LPM, +0.01% at 0.84 LPM and -0.31% at 1.25 LPM, respectively as compared to diesel fuel only operation. These results show that the addition of the H_2/O_2 mixtures have no significant impact on the carbon dioxide emissions from the engine.

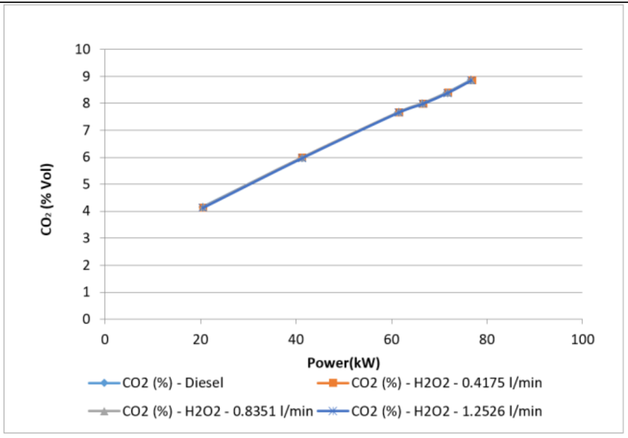

Figure 9. Carbon Dioxide % Volume vs. Power

3.2.3 Carbon Monoxide

Carbon monoxide is also a by-product of the combustion process but is viewed as incomplete production of carbon dioxide from the carbon present in diesel fuel. The CO emissions in diesel engines exhaust streams are heavily influenced by the air fuel ratio. Such that at very lean AFR and lower loads, the carbon monoxide level is stable, but decreases as the load increases due to higher combustion temperature. But as the load increases and the engines AFR moves closer towards stoichiometric operation, the oxygen content in the combustion chamber is less and therefore, the production of carbon monoxide increases dramatically. Figure 10 shows the changes in exhaust emissions of CO parts per million (ppm) with the engine load. With the addition of the H_2/O_2 mixture into the air inlet the produced CO in the exhaust emissions are seen to be slightly lower than that of diesel fuel only due to the presence of additional oxygen in H_2/O_2 mixture. It is observed that the exhaust emissions of carbon monoxide are reduced by an average of 5.50%, 3.40% and 2.32% across the load range at H_2/O_2 mixture flow rates of 0.42 LPM, 0.84 LPM and 1.25 LPM, respectively.

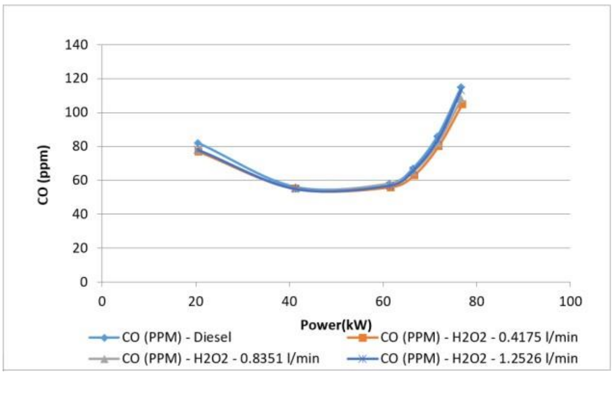

Figure 10. Carbon Monoxide PPM vs. Power

3.2.4 Nitrogen Oxides

Figure 11 shows the nitrogen oxides (NOx) exhaust emission, which are composed primarily of nitric oxide (NO) as shown in Fig. 12 with a small percentage being comprised of nitrogen dioxide (NO_2) as shown in Fig. 13. The

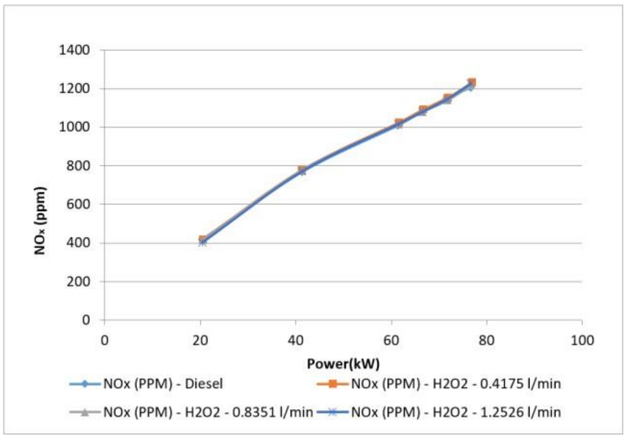

Figure 11. Nitrogen Oxides vs. Power

nitrogen oxides exhaust emissions are formed within the combustion chamber during the combustion process at high temperature regions. Nitrogen which is an inert gas that is stable and non-reactive, existing naturally in the inlet air in its diatomic form. The high temperatures during combustion cause the diatomic nitrogen to dissociate into individual nitrogen atoms making it free to react with the oxygen present in the combustion chamber. The nitrogen atoms quickly react with the oxygen present which forms NO. The downside to NO being formed from the individual nitrogen atoms is that it is also readily and quickly oxidized into nitrogen dioxide (NO_2) with any residual oxygen within the combustion chamber. Figure 11 shows the changes in exhaust emissions of NOx parts per million (ppm) with engine load. At higher load, more fuel is combusted in the combustion chamber resulting in higher temperature causing more NO_X emissions than at lower loads. With the addition of the H_2/O_2 mixture the produced NOx in the exhaust emissions are very similar to that of diesel only operation. It is observed that the exhaust emissions of NOx change very little, by an average of +1.03%, +0.04% and -0.23% across the load range at the H_2/O_2 mixture flow rates of 0.42 LPM, 0.84 LPM and 1.25 LPM, respectively.

3.2.5 Nitric Oxide

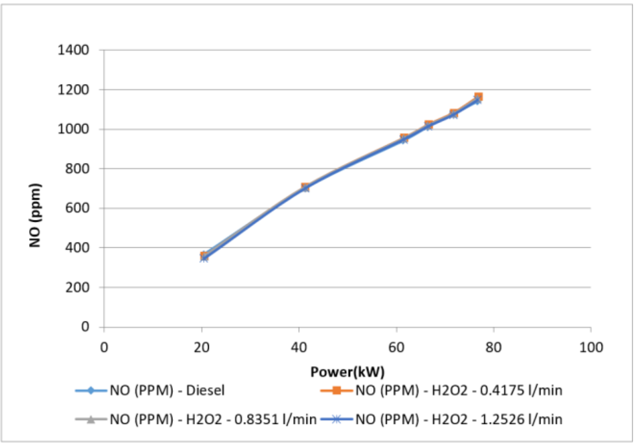

Figure 12. Nitric Oxide vs. Power

Figure 12 shows the changes in the exhaust emissions of NO parts per million (ppm) with engine load. With the addition of the H_2/O_2 mixture the produced NO in the exhaust emissions are again very similar to that of diesel only operation. It is observed that the exhaust emissions of NO change very little, by an average of +0.53%, +0.12% and -0.86% across the load range at H_2/O_2 mixture flow rates of 0.42 LPM, 0.84 LPM and 1.25 LPM, respectively.

3.2.6 Nitrogen Dioxide

Figure 13 shows the changes in the exhaust emissions of NO_2 parts per million (ppm) with the engine load. With the addition of the H_2/O_2 mixture the produced NO_2 in the exhaust emissions increased across the applied load range and for all H_2/O_2 mixture flow rates as compared to that of diesel only operation. It is observed that the exhaust emissions of NO_2 increase, by an average of 1.82%, 4.62% and 5.91% across the load range at H_2/O_2 mixture flow rates of 0.42 LPM, 0.84 LPM and 1.25 LPM, respectively. This increase can be attributed to the additional oxygen present in the combustion chamber reacting with the individual nitrogen atoms and NO from the addition of the H_2/O_2 mixture. As the nitrogen dioxide emissions only make up a very small proportion of the overall nitrogen oxides emission the observed small increase in nitrogen dioxide emissions of approximately 1-5 ppm count across the load range for all H_2/O_2 mixture flow rates has very little impact on the total nitrogen oxides emissions.

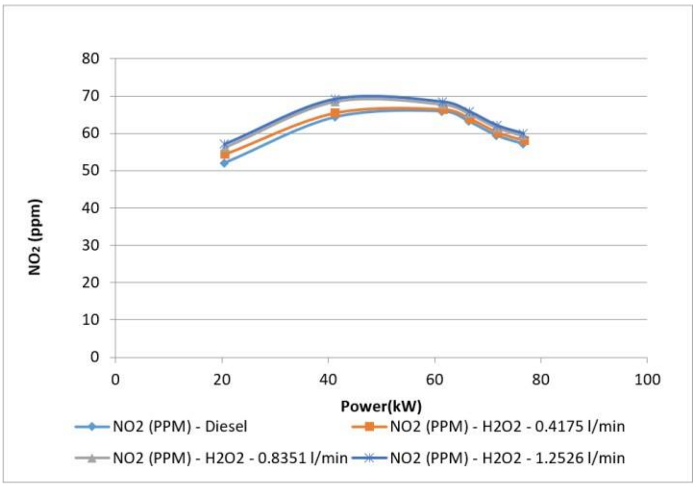

Figure 13. **Nitrogen Dioxide PPM vs. Power**

3.2.7 Particulate Matter Concentration

The exhaust of compression ignition or diesel engines contains carbon soot particles or particulate matter (PM). Figure 14 shows the exhaust emissions of PM number concentration (Million/cm^3) with the engine load. Particulates in the exhaust of diesel engines contains solid carbon soot particles and are generated in the cylinder combustion chamber during combustion in the fuel rich zones. With the addition of the H_2/O_2 mixture into the air inlet the produced PM number concentration in the exhaust emissions are observed to be significantly lower than that of diesel only operation. The benefit of these observed PM number concentration reductions is that the effect due to diesel engine PM emissions on human health conditions as well environmental issues could be significantly reduced. In addition diesel engine performance can be explored further due to them currently being smoke limited [35]. Therefore, this significant reduction of exhaust PM emissions through the addition of the H_2/O_2 mixture, diesel engines with their overall greater efficiencies over spark ignition engines will be able to be developed and utilized to their full potential.

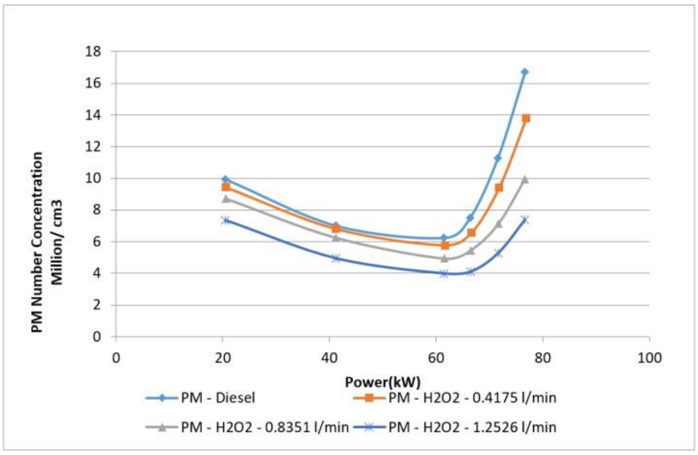

Figure 14. **Particulate Matter Number Concentration vs. Power**

The PM in the exhaust is generated in the fuel rich regions within the combustion chamber during combustion. Figure 15 shows the soot formation as black region and turbulent flame as yellow region. At lower loads and lower combustion temperatures along with insufficient mixing of fuel and air, creates fuel rich regions within the combustion chamber and therefore, moderate exhaust PM concentrations are generated as shown in Fig. 14. As the load increases turbulence within the combustion chamber increases improving mixing of fuel and air so the PM carbon particles find enough oxygen to further react and are consumed to form CO_2. As such the PM number concentration decreases up to the rated load point of 65 kW. Also, as more fuel is injected reducing the AFR the combustion temperature is higher which assists to burn off carbon. The maximum exhaust PM number concentrations occur beyond the rated load of 65 kW this is when there is excess fuel and the AFR tends closer towards stoichiometric conditions meaning there is not enough oxygen present in the combustion chamber to form CO_2.

Figure 15. Soot formation at fuel-rich region [36]

In Figure 14, it is clear that the observed exhaust emissions of PM number concentration reduce with the addition of the H_2/O_2 mixture, by an average of 10.34%, 24.77% and 41.05% across the load range at H_2/O_2 mixture flow rates of 0.42 LPM, 0.84 LPM and 1.25 LPM, respectively. In fact, at the peak engine load point of 75 kW and with a H_2/O_2 mixture flow rates of 1.25 LPM, the exhaust emission PM number concentration is reduced by 56% as compared with the diesel only operation. This is due to more oxygen from the H_2/O_2 mixture which could help to combust the carbon in the fuel-rich region.

3.3 Water and Power Consumption of H_2/O_2 mixture

The H_2/O_2 mixtures were produced at three different flow rates of 0.42 LPM, 0.84 LPM and 1.25 LPM which consumed 10 A, 20 A and 30 A current, respectively. Figure 15 shows the flowrates of O_2, H_2 and H_2/O_2 mixture against the consumption of current and Fig. 16 shows the water consumption. The water consumptions for 0.42 LPM, 0.84 LPM and 1.25 LPM H_2/O_2 mixture flow rates were 0.013523 L/hr, 0.027047 L/hr and 0.04057 L/hr, respectively.

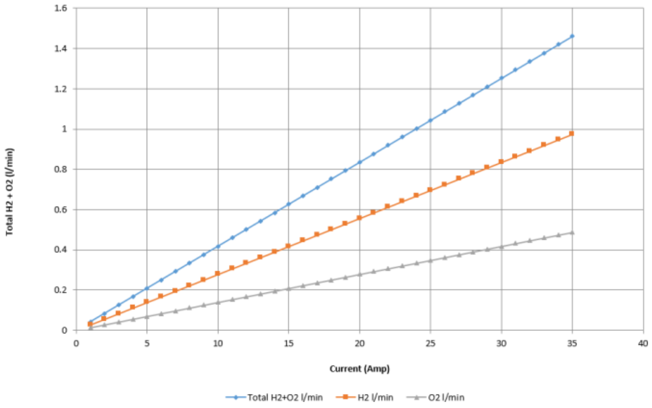

Figure 15. H2/O2 flow rates vs. Current

The water needed for 24-hours operation are 0.325 L, 0.649 L and 0.974 L at H_2/O_2 mixture flow rates of 0.42 LPM, 0.84 LPM and 1.25 LPM, respectively.

At rated power, the amount of diesel needed for 24 hours operation is 492 L. The Cummins 6BT5.9-G2 generator used in this study has a fuel tank of 290 L. Therefore, for 24-hours operation at rated load, the fuel tank needed to fill up 1.7 times or approximately twice per day. For 24-hours operation, the amount of demineralized water needed is only 0.974 L for 30 A operation. The H_2/O_2 mixture is produced by electrolysis using power from the battery/alternator. During the whole operations, the battery did not die and there was no issue with starting the diesel engine when the engine was shut down during the night-time.

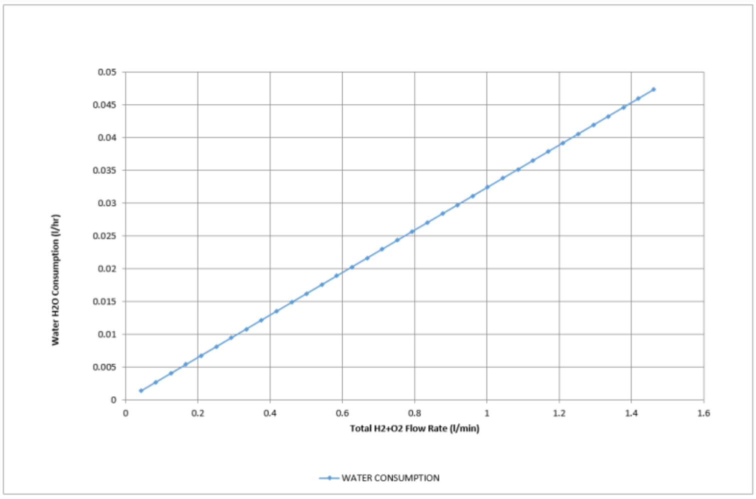

Figure 16. **Water consumption vs. H2/O2 flow rates**

Previous studies done by various researchers as described in section 1 used 9 to 40 LPM of H_2 and 0.42 to 6 LPM of H_2/O_2 mixture to improve the performance and reduce the emissions of diesel engines. However, the water needed for 24-hours operation will be 86 L and 4.2 L per day for 40 LPM of H_2 and 6 LPM of H_2/O_2 mixture, respectively.

The findings are encouraging though the amount of water needed to carry could be a serious issue. For stationary power applications, the space for water tank needed to produce H_2 or H_2/O_2 mixture might be able to fit, however, for mobile applications this could be a serious problem.

4. CONCLUSIONS

This experimental research investigated the effects of the addition of on-board production of H_2/O_2 mixture to a direct fuel injection diesel engine. The main findings and conclusions from this research are summarised below:

- The addition of the H_2/O_2 mixture is extremely effective in the reduction of combustion PM emissions with results indicating up to a maximum of 56% PM emission reduction at peak load and an average of 41% PM emission reduction across the load range for a H_2/O_2 mixture flow rate of 1.25 LPM.
- There is no evidence to indicate that there was any impact to the diesel engines performance parameters of thermal efficiency and bsfc by the addition of the H_2/O_2 mixture. This is a positive aspect as this indicates that the diesel engine is not experiencing any additional pressures or stresses that could impact on the reliability of the diesel engine.
- It is positive to see that with the addition of the H_2/O_2 mixture there is a slight overall reduction of 5.50%, 3.40% and 2.32% for the H_2/O_2 mixture flow rates of 0.42 LPM, 0.84 LPM and 1.25 LPM, respectively in the produced CO emissions. Also, very little to no change in the produced NOx emissions were observed.
- The water consumption at 0.42 LPM, 0.84 LPM and 1.25 LPM of H_2/O_2 mixture were found to be 0.013523 L/hr, 0.027047 L/hr and 0.04057 L/hr, respectively and for 24-hours operation with diesel generator at rated power the total water needed is only 0.974 L.
- Overall, the addition of H_2/O_2 mixture to a diesel engine is a possible technique to significantly reduce PM emissions with minimal effect on the overall engine performance and other produced exhaust emissions.

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