Reducing oxides of nitrogen engineering essay

Engineering

SR. Premkartikkumar*, K. Annamalai, A. R. PradeepkumarDepartment of Automobile Engineering, MIT Campus, Anna University, Chennai, India*Corresponding author. Tel: +91-44-22234809 Fax: +91-44-22475070Email address: premthermal46@gmail. com

Reducing oxides of nitrogen (NOX) and improving thermal efficiency of a DI diesel engine using oxygen enriched hydrogen gas

Abstract

Automotives give out more pollutants. These pollutants become a big threat to our environment. This study concerns reducing the engine-out emissions of a DI diesel engine using oxygen enriched hydrogen gas. In the present investigation, the oxygen enriched hydrogen gas was produced by the process of water electrolysis. The produced gas of 4. 6 litre per minute (lpm) was aspirated into the cylinder along with intake air at varied injection timing of diesel fuel. Here the injection times selected were 230BTDC (Before Top Dead Centre) and 190BTDC. The 230BTDC is the engine manufacturer recommended standard injection time and the 190BTDC is the retarded injection time. When oxygen enriched hydrogen gas was inducted at 100% rated load of the engine and at the retarded injection time of 190BTDC resulted in, increasing brake thermal efficiency by an average of 12. 21%, decreasing Carbon monoxide (CO) emissions by an average of 15. 38%, Unburned hydrocarbon (UBHC) emissions by an average of 12. 12%, Oxides of nitrogen (NOX) emissions by an average of 9. 04% and smoke emissions by an average of 19. 04% compared to standard injection time pure diesel combustion. The above data very clearly show that the engine-out emissions

can be reduced effectively by using oxygen enriched hydrogen gas in the combustion process of diesel engine. Keywords: diesel engine; electrolysis; oxygen enriched hydrogen gas; retarded injection time; engine-out emissions

Introduction

Recent increase in price of petroleum fuels and stringent environmental norms are main reasons to search for the alternative fuels. Alternative fuels are clean fuels compared to diesel fuel and gasoline fuel in engine combustion process [1]. Hydrogen is emerging as one of the favorite alternative fuel and as an energy carrier. It has very good properties as an automotive fuel. The properties of hydrogen which push to use it as an automotive fuel are low ignition energy, low density, wide flammability limit, high diffusivity and high flame speed [2]. Due to its wider flammability limit, it can burn lean mixtures comfortably, resulting less amount of exhaust emissions. Nowadays, hydrogen is mostly produced by steam reforming or by partial oxidation of hydrocarbons [3]. However, for small hydrogen quantities and or when high-purity hydrogen is required, processes such as water electrolysis, ammonia decomposition or methanol reforming are also used [4]. Hydrogen can be produced by splitting the water. Various processes used to split the water are electrolysis, plasmolysis, magnetolysis, thermal approach, use of light, bio-catalytic decomposition of water and radiolysis [5]. When hydrogen is added into the combustion process, the in-cylinder pressure and the thermal efficiency get increased [6]. This improvement in combustion is due to the faster and cleaner-burning characteristics of hydrogen in comparison to conventional fuels [7].

Increased flame speed of hydrogen reduces the engine-out emissions of the internal-combustion engines [8]. Many studies have been reported on hydrogen combustion in diesel engines, in very different conditions. Combustion process can be considerably enhanced in internal - combustion engines, by adding a small amount of hydrogen to the main fuel [7]. Rev. W. Cecil explained about, how to use the energy of hydrogen to power an engine and how the hydrogen engine could be built in 1820 itself. Probably, this is the earliest invention made in hydrogen-fueled engines [9]. Properties of hydrogen are given in Table 1.

Some of the past researches in hydrogen-fueled engines

As a sole fuel or dual-fuel

Some researchers tried to use hydrogen as a sole fuel in the diesel engine. As the self-ignition temperature of hydrogen is about 858K, it is impossible to ignite hydrogen, just by heat of compression [10]. It needs an ignition starter to start its combustion. Wong used ceramic glow plug as an ignition starter and obtained some valid results [11]. The diesel-hydrogen dual fuel engine can be operated with less fuel than neat diesel operations; resulting in lower smoke level [12]. This hydrogen enriched method of operation enables the realisation of higher brake thermal efficiency and also reduction in specific energy consumption. Masood et al. made their investigation in a Kirloskar AV-1, single cylinder direct injection, water-cooled diesel engine with a nozzle hole size of 0. 15 mm. Experiments were conducted at a constant speed of 1400 rpm. The engine was modified to work on the different compression ratio. When the substitution percentage of hydrogen was varied from 10% to 90%, for the compression ratios of 24. 5 and 18. 35, NOX emission increased by 38% and 27%, respectively. This increase was due to high heating value of hydrogen and high operating temperatures. For the compression ratio of 22, the particulate matter (PM) reduced by 82. 6% and when the compression ratio was changed from 16. 35 to 24. 5, the percentage change in PM was 16%. The percentage reduction in the HC value was 93. 63% for the compression ratio of 24. 5, and for compression ratio of 18. 35; the reduction percentage was 82. 57%. When the compression ratio was changed from 16. 35 to 24. 5, the change in percentage of reduction in HC was by 17% [12]. Varde and Frame made some early researches in hydrogen, to use it in the internal-combustion engines. They found that when the flow rate of hydrogen introduced into the engine was 0. 65 kJ/s, the resulting thermal efficiency was lower than the pure petroleum diesel operation by 2%. On the other hand, increasing the flow rate to 1. 65 kJ/s resulted in increase in the thermal efficiency by 10%. Under optimum condition of 10% and 15% of the total energy, the smoke was reduced by an average of 50% [13]. Liew et al. used a turbocharged 1999 Cummins diesel engine with a rated power of 370 hp, 6-cylinder-diesel engine with the addition of 6% H2 into the intake air. The combustion efficiency of H2 observed was 97. 9%. With advanced phasing of 1. 5 crank angle degree (CAD), the peak cylinder pressure increased from 106. 4 bar to 120. 5 bar and also the peak heat release rate increased from 0. 25 kJ/CAD to 0. 53 kJ/CAD compared to diesel operation [14]. Bibhuti et al. investigated the effect of syngas on the performance, combustion and emission characteristics of a diesel engine. Three different volumetric compositions of syngas fuels were examined in dual fuel mode. The syngas of 100% H2 composition showed an improved engine performance and higher NOx emissions. The NOx emissions were reduced when 25% and 50% CO was added. At 100% H2 syngas mode and at best efficiency loading of 80%, the maximum diesel replacement was found as 72. 3%. At 50% H2 syngas mode with 80% load range of the engine, thermal efficiency was found to be 16. 1%. At higher loads, the 50% and 75% H2 content syngas modes showed a remarkable performance to that of 100% H2 mode. Higher CO and HC emissions were observed at 25% and 50% syngas modes. This was due to their CO content in the fuel compositions. At part load operations, all syngas modes resulted in a poor performance and higher emission levels [15].

Cooled or hot exhaust gas recirculation (EGR) has been used to control NOX emissions from diesel engines, but its application has been limited by low thermal efficiency and high unburned hydrocarbon emissions. Buomsik Shin et al. introduced hydrogen into a diesel engine in a dual-fuel mode with EGR. The energy content of the introduced hydrogen was varied from an equivalent of 2% to 10% of total fuel’s lower heating value. A test engine was operated at a constant diesel fuel injection rate and engine speed. At an EGR ratio of 31%, when the hydrogen equivalent to 10% of total fuel’s lower heating value was supplied, the specific NOX was lowered by 25% and there was a slight increase in a brake thermal efficiency [16]. Horng Wen Wu and Zhan Yi Wu tested a modified single-cylinder diesel engine, into a natural gas direct-injection with EGR, at various engine loads. In their test 0% to 40% EGR ratios were used. The hydrogen-energy-share was used in the ratio of 0% to 20%. It was found that the smoke emission decreased by 37. 6% and the NOX emission was reduced by 59. 5% for a 60% load, 40% EGR ratio and 20% added hydrogen. At 60% rated load, the peak pressure for diesel was 58. 8 bar and in 20% hydrogen without EGR it was 61. 6 bar. When diesel was mixed with 20% hydrogen, the efficiency increased by 3. 2% compared with pure diesel [17].

Used with change in injection timings

Injection timing plays an important role in reducing the engine-out emissions. Therefore, number of studies has been taken by several researchers indicates its significance. Abu-Jrai et al. investigated the influence of reformatted exhaust gas (REGR) consisting of hydrogen (H2), carbon monoxide (CO) and diluents on the combustion and emission characteristics of a single-cylinder diesel engine with a rated power of 7. 5 kW. The addition of REGR at moderate engine load substantially enhanced the premixed combustion phase and dramatically reduces the combustion duration. On the other hand, the addition of REGR at low load was demonstrated to retard the combustion phasing and prolong the combustion duration, which reduced the thermal efficiency of the engine. The increased engine-out emissions might also be an evidence of the deteriorated combustion at low load operation [18]. Saravanan et al. did an experimental investigation on the combustion analysis of a direct injection diesel engine. They used hydrogen and diethyl ether (DEE) as an ignition source. Hydrogen was inducted through an intake port, diethyl ether was inducted through an intake manifold and the diesel was injected in a conventional method. They optimized Injection time of hydrogen and DEE based on the performance, combustion and emission characteristics of the engine. The best time found for injection of hydrogen was 50CA before the gas exchange top dead centre (BGTDC) and for DEE it was 400CA after the gas exchange top dead centre (AGTDC). From their study, it was observed that hydrogen with diesel resulted in increased brake thermal efficiency by 20% and NOX emissions by 13% compared to diesel. In hydrogen-DEE operation, brake thermal efficiency increased by 30% and NOX emissions decreased by 97% compared to diesel operation [19]. Ali Mohammadi et al. investigated on the effect of hydrogen addition on injection timing of a single-cylinder test engine. Three modes of injection time were selected for investigation; during the intake stroke, at compression stroke and later stage of compression stroke. The results showed that in-cylinder injection of hydrogen, during the intake stroke prevented backfire. However, due to reduction in volumetric efficiency, thermal efficiency and output power get reduced. Hydrogen injected at the compression stroke prevented knock and increased thermal efficiency and maximum output power. Hydrogen injection at later stage of compression stroke achieved the thermal efficiency higher than 38. 9% and the brake mean effective pressure of 0. 95 MPa. Under high engine output conditions, late injection of hydrogen offered a great reduction in NOX emission due to lean operation [20]. Li jing-ding et al. conducted an experiment on a diesel engine at different speeds of 2600 and 3000 rpm, with injection timing advance of 21. 50CA and 200CA, respectively. The results showed that smoke in dual fuel operation of diesel with hydrogen at the peak load was less than the diesel operated engine [21]. Yang Zhenzhong et al. used 3-dimensional computational fluid dynamics (CFD) simulations in a two-stroke hydrogen-fueled engine, to investigate the formation rule of hydrogen–air mixture and improve the mixture quality. The simulation results showed that when hydrogen-injection began at 2600 CA, the forming quality of the mixture was better than other two injection timings of 2650 CA and 2700 CA. They concluded that with early injection, the injected hydrogen has enough time to mix with the air inside the combustion chamber and form a homogeneous mixture, while in late injection, there is not enough time for mixing, resulting in inferior performance of the engine [22].

Hydrogen produced especially by the water electrolysis process

Water electrolysis is one of the important industrial process used for production of hydrogen and will become more important process in the future [23]. An oxygen-enrichment of a fuel-air mixture also improves thermal efficiency and reduces especially particulate, carbon monoxide and unburned hydrocarbon emissions in exhaust [7]. Ruggero Maria Santilli in his investigation gave various measurements on a mixture of hydrogen and oxygen gas produced via an electrolyser. This mixture was appreciably different from other known gases [24]. Bari and Mohammad Esmaeil did their experimental work in a four-cylinder, direct injection, water-cooled diesel engine with constant speed with varying load and with H2/O2 mixture produced by water electrolysis. Result showed that at 19 kW of load, the brake thermal efficiency increased from 32. 0% to 34. 6%, HC emission decreased from 187 ppm to 85 ppm and least amount of CO2 of 2. 06 ppm was also observed. However, NOX emission increased from 220 ppm to 280 ppm [25]. Bade Shrestha et al. conducted experiments on a Chevrolet Silverado 6. 5 L turbocharged V8 diesel engine. A hydrogen generation system (HGS), which produces hydrogen and oxygen by water electrolysis was used as a hydrogen supply source. They used 3 units of HGS and each had capacity of producing hydrogen - oxygen mixture of 690 cm3/min. The results showed that there was an enhancement in combustion process and reduction in exhaust emissions as the amount of hydrogen flow rate increased by switching on more HGS units. The reduction in particulate matter (PM) was up to 60%, reduction in CO was up to 30% and reduction in NOX was up to 19% compared to the pure diesel combustion [7]. Adrian Birtas et al. carried out a test on a naturally aspirated direct injection, tractor diesel engine with four cylinders in-line having the total capacity of 3759 cm3, nominal power of 50 kW at 2400 rpm, maximum torque of 228 Nm at 1400 rpm, and the compression ratio of 17. 5: 1. The HRG (Hydrogen Rich Gas) produced by the water electrolysis process was aspirated along with the air stream inducted into the cylinder. The result showed that by adding HRG, smoke reduced up to 30%, while NOX concentrations increased up to 14% compared to pure diesel operation [26]. Recently, Hsin-Kai Wang et al. investigated the effects of introducing a hydrogen and oxygen mixture (H2/O2) to a heavy-duty diesel engine (HDDE) to check the performance, fuel consumption and emission characteristics. HDDE was tested at one low load steady-state condition of 24. 5% of the max load, using pure petroleum diesel and H2/O2 mixtures of 10 to 70 lpm. The results showed that brake thermal efficiency increased from 31. 1% for pure petroleum diesel to 39. 9% for 70 lpm of H2/O2 mixture. Brake specific fuel consumption (BSFC) was higher than that of pure petroleum diesel when the flow rate of H2/O2 mixture was 10 to 40 lpm. However, when flow rate was 50 to 70 lpm, the BSFC was lower than that of pure petroleum diesel by an average of about 7. 2%. Due to improved combustion phenomena, UBHC emissions, CO emission and CO2 emission were reduced, while the nitrogen oxides were increased. The NOX concentration was 60. 05 ppm for pure petroleum diesel, and was increased to 60. 49 ppm for 10 lpm of H2/O2 mixture and 67. 22 ppm for 70 lpm of H2/O2 addition [27]. When going through the vast literature of hydrogen usage in diesel engine, significant work was not carried out in optimizing the injection parameters, in particular, the injection timing. Hence, an attempt is made in this investigation to fill this void.

Experimental method

The present method of investigation provides a feasible solution for onboard production of hydrogen, which avoids the storing of hydrogen in heavy pressurised tanks. In the present process, the hydrogen was produced on-board along with oxygen at the desired rate by the process of water electrolysis. An electrolyser, which decomposes distilled water into a new fuel composed of hydrogen, oxygen and their molecular and magnecular bonds called oxygen enriched hydrogen gas [28]. The produced gas was aspirated into the cylinder along with intake air, at the flow rate of 4. 6 lpm at varied injection timing of diesel fuel. Thereby, the influence of oxygen enriched hydrogen gas on emission and performance characteristics of the engine was determined at various load ranges of a test engine.

Test Engine setup

The present investigation was conducted in a Kirloskar SV1 make single cylinder, water-cooled, four stroke, DI diesel engine, developing a rated power of 5. 9 kW at a speed of 1800 rpm and having a compression ratio of 17. 5: 1. The detailed specification of the engine is given in Table 2. For loading the engine, eddy current dynamometer was coupled to the engine. The oxygen enriched hydrogen gas was metered out through a digital mass flow controller of Aalborg make for precision measurement of gas flow. The engine in-cylinder pressure was measured using a Kistler make piezoelectric pressure transducer with an in-line charge amplifier. The amplified signals were correlated to the signal from crank angle encoder having an accuracy of 0. 1 degrees crank angle. The data obtained were stored on a personal computer for analysis. Cooling water temperature, inlet air temperature and exhaust gas temperature were measured using K type thermocouples. The exhaust gas emissions such as Carbon dioxide (CO2), Carbon monoxide (CO), Unburned hydrocarbon (UBHC), Oxides of nitrogen (NOX) and Excess oxygen (O2) available in exhaust were measured by Crypton 290 EN2 five gas analyzer. The smoke was measured by AVL smoke meter in terms of Hatridge Smoke Unit (HSU). The experimental setup is shown in the fig-1.

Experimental procedure

When DC power supply is switched on, in this study 12V was supplied. The potential difference across the anode electrodes and the cathode electrodes along with the aqueous electrolyte solution of NaOH present in the electrolyser produces oxygen enriched hydrogen gas by the process of water electrolysis. The produced gas was then passed through a drier, flashback arrestor and flame trap before enriching with inlet air. Drier was used to remove the moisture content present in the gas. Flashback arrestor and flame trap were used to suppress the flame if a back-fire from the engine occurred. The injection time of diesel fuel was varied to find out the effectiveness of oxygen enriched hydrogen gas on the combustion phenomena of a test engine. In the present experimental work, the two injection timings were selected; one is the standard injection time of 230BTDC recommended by the engine manufacturer, and another one is retarded injection time of 190BTDC. The injection time of the diesel fuel was varied by varying the shim thickness at the connection point between the pump and the engine. In this experiment, pure petroleum diesel combustion with standard injection time of 230BTDC was taken as a base line, to compare various performance and emission characteristics of a test engine at varied injection timing of diesel fuel operating under the influence of oxygen enriched hydrogen gas of flow rate of 4. 6 lpm at various load ranges of the test engine. All experimental data were collected, after the engine reached the steady state.

Results and Discussion

Carbon monoxide (CO)

Fig-2 shows the influence of oxygen enriched hydrogen gas on Carbon monoxide (CO) emission of the test engine under various load ranges of the engine for standard injection timing of 230BTDC and retarded injection timing of 190BTDC. CO is formed in a combustion process when the carbon molecules are not oxidized fully and converted to carbon dioxide. When oxygen enriched hydrogen gas is used in the combustion process, the CO emission is less because of good combustion assisted by high flame speed of hydrogen and its high diffusing property through the air-fuel mixture results in less CO emission. Increasing the engine load reduces CO emission gradually. When the load on engine increases, combustion temperature begins to increase and resulting in reduction in CO emission [29]. When oxygen enriched hydrogen gas of 4. 6 lpm is used as a combustion catalyst in diesel fuel combustion at full rated load of the engine, CO emission decreases from 0. 13% vol. to 0. 10% vol., by 23. 07% at standard injection timing of 230BTDC. This result confirms the resulted obtained by Bade Shrestha et al. [7]. At the same time, when the injection time is retarded, the CO emission decreases from 0. 13% vol. to 0. 11% vol., by 15. 38% compared to pure petroleum diesel combustion. On the other hand, at 25% rated load of the engine, the CO emission decreases from 0. 14% vol. to 0. 12% vol., by 14. 28% at standard injection timing of 230BTDC. When the injection time is retarded, CO emission decreases from 0. 14% vol. to 0. 13% vol., by 7. 14% compared to pure petroleum diesel combustion. This decrease in CO emission is due to more homogeneous mixing of fuel and air. Because of catalytic action of oxygen enriched hydrogen gas. The surface area exposed by fractured fuel hydrocarbon structures is more. When the combustion is initiated by the ignition of pilot diesel fuel, the combustion is of higher rate and intense compared to pure diesel combustion, which in turn extracts more energy from the diesel fuel and there by decreases the consumption of diesel fuel for producing the same amount of work and also decreases the carbon monoxide emission.

Unburned hydrocarbon (UBHC)

Fig-3 represents the variation of UBHC emission, when the test engine was operated with the assistance of oxygen enriched hydrogen gas at various load ranges of the engine for standard injection timing of 230BTDC and retarded injection timing of 190BTDC. When 4. 6 lpm of oxygen enriched hydrogen gas is introduced into the cylinder at full rated load of the engine and at standard injection timing of 230BTDC, UBHC emission decreases from 66 ppm to 53 ppm, by 19. 69%. This result confirms the result obtained by Bari and Mohammad Esmaeil [25]. When the injection time is retarded, the

UBHC emission decreases from 66 ppm to 58 ppm, by 12. 12% compared to pure petroleum diesel combustion. When oxygen enriched hydrogen gas is aspirated into the combustion process of diesel at 25% rated load of the engine, the UBHC emission decreases from 50 ppm to 48 ppm by 4%. When the standard injection time is retarded to 190BTDC, UBHC emission decreases from 50 ppm to 49 ppm by 2% compared to pure petroleum diesel combustion. This decrease in UBHC emission is due to the increase in oxygen percentage presents in the overall fuel mixture. The high catalytic action of atomic hydrogen and oxygen present in the oxygen enriched hydrogen gas, fracture heavier diesel fuel molecules and initiate high oxidation reaction which increases the rate of combustion [24]. Also, low flame quenching distance of oxygen enriched hydrogen gas combust major part of the fuel-air mixture before the flame reaches the cylinder wall resulting in, less UBHC emission in the exhaust.

Oxides of nitrogen (NOX)

NOX is formed during combustion because of three factors; high temperature; high oxygen concentration and residence time. Fig-4 represents the NOX emission during the combustion under the influence of oxygen enriched hydrogen gas at various load ranges of the engine for standard injection timing of 230BTDC and retarded injection timing of 190BTDC. Fig-4 clearly shows that NOX emission depends upon the injection timing of diesel fuel and loading condition of the test engine. The NOX emission is high, when oxygen enriched hydrogen gas of flow rate of 4. 6 lpm is added to the combustion of diesel fuel at standard injection timing of 230BTDC at all load conditions of the engine. At 100% of rated load of the engine, the NOX emission is 491 ppm whereas; the pure petroleum diesel combustion results in 420 ppm, by an increase of 16. 9%. This confirms the result obtained by Hsin-Kai Wanga et al. [27]. This increase in NOX emission is due to the high temperature produced by an instantaneous combustion of oxygen enriched hydrogen gas. When ignition is initiated by pilot diesel fuel, improved pre-mixed combustion phase and faster combustion rates were observed, resulting in higher NOX concentration. However, when the oxygen enriched hydrogen gas is introduced at retarded injection timing of 190BTDC at 100% rated load condition of the test engine results in a NOX emission of 382 ppm, which is a 9. 04% decrease when compared to pure petroleum diesel combustion. This decrease in NOX emission is due to reduced pre mixed combustion phase as a result of retarded injection time. When injection time of diesel fuel is retarded, the fuel is introduced into the cylinder at relatively higher pressure and temperature atmosphere; which decreases the ignition delay period and the pre mixed combustion phase. When comparing the quantities of NOX produced during the combustion influenced by oxygen enriched hydrogen gas, the retarded injection time shows a 22. 19% reduction in NOX than standard injection time of diesel fuel.

Smoke Emission

Fig-5 compares the amount of smoke emission by the test engine during its combustion, when oxygen enriched hydrogen gas at 4. 6 lpm is added as an additive to the combustion process of diesel at various load ranges of the engine for standard injection timing of 230BTDC and retarded injection timing of 190BTDC. When oxygen enriched hydrogen gas is inducted into the combustion process, the smoke reduces substantially. The smoke is emitted from the engine due to the incomplete combustion of the fuel-air mixture as a result of lesser oxidation reactions. When oxygen enriched hydrogen gas of 4. 6 lpm is inducted at 100% rated load of the engine at standard injection timing of diesel fuel of 230BTDC results, the smoke emission of 30 HSU, whereas in pure petroleum diesel combustion, the smoke emission is 42 HSU, by a reduction of 28. 57%, which was also proved earlier by Adrian Birtas et al. in his HRG investigation [26]. At the same time, when injection time of diesel fuel is retarded, resulted in smoke emission of 34 HSU, by a reduction of 19. 04% compared to pure petroleum diesel combustion. If heavier hydrocarbon fuel molecule structure is fractured into lighter and smaller hydrocarbon structure in less time, a homogeneous mixture can be formed. This happens when oxygen enriched hydrogen gas is inducted into the combustion process of the diesel engine. When comparing the smoke emitted during combustion of oxygen enriched hydrogen gas of 4. 6 lpm at standard injection time of diesel fuel of 230BTDC and retarded injection time of 190BTDC, resulting in 13. 33% increase as a result of retarded injection time of diesel fuel. During retarded injection time of diesel fuel, lesser oxidation reaction is observed which in turn increases the smoke emission. when combustion is initiated, thereby increasing the smoke emission.

Excess oxygen (O2)

Fig-6 shows the effect of oxygen enriched hydrogen gas at 4. 6 lpm of flow rate at various load ranges of the engine on the excess oxygen present in the exhaust emission of the test engine for standard injection timing of 230BTDC and retarded injection timing of 190BTDC. When oxygen enriched hydrogen gas was used with petroleum diesel a reduction in exhaust excess oxygen percentage with load rate was observed. This is due to the strong oxidizing ability of oxygen enriched hydrogen gas, high fracturing capability of gas mixture and subsequent increase in oxidation rate of lighter hydrocarbons resulting in an increased rate of combustion reaction. When 4. 6 lpm flow rate of oxygen enriched hydrogen gas is aspirated along with air by the engine, at 100% rated load, the excess oxygen present in the exhaust is 16. 23%. Whereas, the pure petroleum diesel combustion results in 18. 37% of excess oxygen in the exhaust, which is a reduction by 11. 64% as a result of oxygen enriched hydrogen gas addition to the combustion process of a diesel engine at the standard injection timing of diesel fuel of 230BTDC. This result confirms the result obtained by Vamshi K. Avadhanula et al. [30]. When the injection time of diesel fuel is retarded, the excess oxygen percentage in the exhaust is 16. 94% at same rated load of the engine, which is a reduction by 7. 78% as a result of oxygen enriched hydrogen gas addition. When comparing the reduction percentage of excess oxygen concentration in engine exhaust, the standard injection time combustion reduces more oxygen content in the exhaust than the retarded time combustion. This is because in standard injection time combustion, the rate of combustion is high as more homogeneous mixture is taking part in the combustion process due to high reactive rate of oxygen enriched hydrogen gas. This enhances the overall combustion phenomena. The inherent qualities of hydrogen such as high flame speed, high diffusivity and least quenching distance results in a higher combustion grade leading to lesser excess oxygen concentration in the exhaust.

Brake thermal efficiency

Brake thermal efficiency is the real indication of the efficiency, with which the chemical energy available in the form of fuel is converted into useful work. The graphical representation of effectiveness of oxygen enriched hydrogen gas on the brake thermal efficiency of the engine at different rated load conditions of a test engine for standard injection timing of 230BTDC and retarded injection timing of 190BTDC are shown in fig-7. When oxygen enriched hydrogen gas is used as a combustion catalyst in pure petroleum diesel combustion, the rate of increase in brake thermal efficiency is higher than pure petroleum diesel combustion. Under the influence of oxygen enriched hydrogen gas at 100% rated load of the engine, the brake thermal efficiency increases from 24. 32% to 28. 32%, by 16. 44% for standard injection timing of 230BTDC. At the same time, when the injection time is retarded to 190BTDC the brake thermal efficiency increases from 24. 32% to 27. 29%, by 12. 21% when compared to pure petroleum diesel combustion. This increase in brake thermal efficiency is due to higher heat content of a hydrogen present in the gas mixture, its high flame velocity and also due to the atomic hydrogen and oxygen [24] present in the gas, as they are very energetic and very reactive than their dual molecule counterparts; because of this intrinsic characteristic, when the ignition of oxygen enriched hydrogen gas is initiated by petroleum diesel, they immediately start to fracture the heavier hydrocarbon molecules of diesel fuel and initiated the chain reaction, which resulted in high-efficiency combustion. When the test engine is operated in retarded injection timing of 190BTDC and under the influence of oxygen enriched hydrogen gas of 4. 6 lpm at 100% rated load, resulting in 3. 63% decrease in brake thermal efficiency when compared to standard injection time. This decrease in brake thermal efficiency is due to low temperature atmosphere prevailing in the combustion chamber. As a result of retarded injection time, less time is available to form homogeneous mixture during the ignition delay period which results in a drop in the combustion temperature. On the other hand, at 25% rated load of the engine, the brake thermal efficiency increases from 15. 86% to 17. 86%, by 12. 61% for standard injection time and increases from 15. 86% to 18. 01%, by 13. 56% for the retarded injection time. This increase in brake thermal efficiency is due to the decrease in the compression work caused by differences in mixture gas properties and charge mass with retarded injection time [31].

Brake specific energy consumption (BSEC)

The effectiveness of oxygen enriched hydrogen gas on the brake specific energy consumption of the engine at various load conditions of a test engine for standard injection timing of 230BTDC and retarded injection timing of 190BTDC are shown in fig-8. The brake specific energy consumption decreases when oxygen enriched hydrogen gas is used in the combustion process of diesel because of the higher-energy content of hydrogen, higher oxidation reactions induced by atomic hydrogen, oxygen present in the mixture and higher temperature developed due to high grade combustion. For the standard injection timing of 230BTDC at 100% rated load of the engine, the brake specific energy consumption decreases from 14. 8 MJ/kWh to 12. 71 MJ/kWh, by 14. 12% due to higher catalytic action of oxygen enriched hydrogen gas. When oxygen enriched hydrogen gas is introduced into the combustion process of the diesel engine, the heavier hydrocarbon structures of fuel molecules are fractured into smaller and lighter hydro carbon structures and there by increases the surface to volume ratio, resulting in more homogeneous mixture of fuel and air. At the same time, when the injection time is retarded the brake specific energy consumption decreases from 14. 8 MJ/kWh to 13. 19 MJ/kWh, by 10. 88% when compared to pure petroleum diesel combustion. The above data clearly show that when the engine is operated in retarded injection time mode, the brake specific energy consumption increases by 3. 77% compared to standard injection time mode. This increase in brake specific energy consumption is due to an unfavorable mixture formation which results in inferior quality combustion and subsequent reduction in combustion temperature. On the other hand, for the standard injection timing of 230BTDC and at 25% rated load of the engine, the brake specific energy consumption decreases from 22. 69 MJ/kWh to 20. 15 MJ/kWh, by 11. 19%. At the same time, when the injection time is retarded, the brake specific energy consumption decreases from 22. 69 MJ/kWh to 19. 98 MJ/kWh, by 11. 94% when compared to pure petroleum diesel combustion. This decrease in brake specific energy consumption is due to the decrease in the compression work when the engine is operated in retarded injection mode [31].

In-cylinder pressure

The Fig-9 compares the in-cylinder pressure developed during the introduction of oxygen enriched hydrogen gas assisted petroleum diesel combustion at the standard injection timing of 230BTDC and retarded injection timing of 190BTDC. When oxygen enriched hydrogen gas is introduced into the combustion process of petroleum diesel at 4. 6 lpm at standard injection timing of 230BTDC, the ignition delay is more by 10, than pure petroleum diesel combustion. As the self-ignition temperature of oxygen enriched hydrogen gas is more than the petroleum diesel, it needs an assistance to start its combustion. When oxygen enriched hydrogen gas is assisted by the ignition of petroleum diesel, the combustion is instantaneous and creates high pressure and high temperature in the combustion chamber. The pressure of 74 bar was seen, when oxygen enriched hydrogen gas at 4. 6 lpm is inducted into the combustion process of pure petroleum diesel, where as the peak pressure resulted in pure petroleum diesel combustion was 70 bar. The rate of pressure rise is also higher as a result of instantaneous combustion of oxygen enriched hydrogen gas addition. When the injection time is retarded, the in-cylinder pressure developed during the combustion process is 68 bar, as the pre mixed combustion phase gets reduced due to retarded injection time [20]. During retarded injection of diesel fuel, the fuel is introduced into the combustion chamber at relatively high pressure and high-temperature atmosphere resulting in shorter ignition delay periods. Hence there is a possibility of decrease in homogeneous mixing, in-cylinder pressure and combustion efficiency.

Conclusions

From the results we can conclude that the DI diesel engine can be operated effectively by inducting oxygen enriched hydrogen gas of 4. 6 lpm in the combustion process of petroleum diesel. When going through the results analytically, it is very clear that when the engine is operated in standard injection mode the brake thermal efficiency increases by 16. 44% and the NOX emissions by 16. 9% and all other engine-out emissions like CO, UBHC and Smoke reduce by 23. 07%, 19. 69% and 28. 57% respectively compared to pure diesel combustion. In retarded injection mode the brake thermal efficiency increases by 12. 21% and all other engine-out emissions like CO, UBHC, NOX and Smoke reduces by 15. 38%, 12. 12%, 9. 04% and 19. 04% respectively. Above data show that when DI diesel engine is operated in a retarded injection mode our objective of increasing the brake thermal efficiency and simultaneous reduction of NOX emissions can be achieved concretely.