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Effect Of Addition Of Oxygen Enriched Hydrogen Gas Produces By Electrochemical Reaction In The Reduction Of Pollutants Coming Out From A DI Diesel Engine

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Abstract: The present investigation related with the enhancing of combustion phenomena of DI diesel using Oxygen Enriched Hydrogen Gas. Here the Oxygen enriched hydrogen gas was produced by the process of electrochemical reaction-electrolysis. The produced gas was aspirated into the combustion process of mineral diesel along with intake air, at the flow rate of 4.6 lpm. The results show that the fuel consumption gets decreased and simultaneously, engine-out pollutants come down by the addition of Oxygen enriched hydrogen gas with warm diesel fuel induction. When, the diesel fuel temperature was increased from 25^0C to 35^0C, total fuel consumption of the test engine decreased by 15.76%, unburned hydrocarbon emission decreased by 25.76%, smoke emission decreased by 33.33% and the NO_X emission increased by 19.52%.

Keywords: diesel engine; electrolysis; oxygen enriched hydrogen gas; pre heated diesel fuel.

INTRODUCTION

The increase in number of automotive vehicles in recent years has resulted in great demand for petroleum products. The scarcity of conventional fossil fuels, growing emissions of combustion generated pollutants push the researchers all over the world to find the alternative fuel sources. Hydrogen has more advantages compared to other alternative fuels since it is a non-carbon fuel, which results in the total elimination of HC, CO, and CO_2 emissions [1]. Comparing to mineral diesel, hydrogen has wider flammability limits, higher flame speed and fast burning velocity, which enable engines to run on very lean mixtures [2-3]. These features make hydrogen an excellent fuel to potentially meet the ever increasingly stringent environmental controls of exhaust emissions from combustion devices, including the reduction of green house gas emissions [4]. Hydrogen can be produced through thermal, electrolytic, or photolytic processes applied to fossil fuels, biomass, or water [5]. Properties of hydrogen are shown in Table 1[6].

Usage of hydrogen in the diesel engine has been researched by several peoples. Most of these researches concentrate on using pure hydrogen as a dual fuel, which requires heavier and bigger storage tanks. One of the reliable solutions to this problem is, to produce hydrogen on-board and use it immediately. Only process, which fulfills the on-board production of hydrogen is water electrolysis process. Water electrolysis is one of the most important industrial processes for hydrogen production today, and is expected to become even more important in the future [7].

Bade Shrestha et al. [8] conducted experiments on a turbocharged diesel engine. They used 3 units of hydrogen generation system (HGS) to evaluate, each having a capacity to produce hydrogen - oxygen mixture of 690 cm^3/min, by the process of water electrolysis. The result showed that there was an increase in combustion efficiency and reduction in exhaust emissions, when the hydrogen flow rate was increased. Particulate matter (PM) reduced up to 60%, CO reduced up to 30% and reduction in NO_X was up to 19% compared to the diesel combustion.

Bari and Mohammad Esmaeil [9] carried out their experimental work with the use of H_2/O_2 mixture produced by water electrolysis. Results show that the HC emission decreased from 192 ppm to 97 ppm by adding 30.6 l/min of H_2/O_2 mixture. At 22 Kw of load, NO_X emission was found to be increased from 232 ppm to 307 ppm and the minimum amount of CO_2 was achieved at 19 kW as 2.06 ppm with 31.75 l/min of H_2/O_2 induction. CO emission decreased from 0.24% to 0.012% at 22 kW.

Adrian Birtas and Radu Chiriac [10] did an experiment to find the effect of HRG (Hydrogen Rich Gas) produced by water electrolysis on diesel engine performance and emission. HRG was supplied at different flow rates to the engine intake manifold. Flow rate corresponding to 3.38% of H_2, led to an increase in the effective power by 3.8%, the maximum pressure by 11.3 %, the brake thermal efficiency by 1.92 %, the smoke emission decreased by 25%, CO emission by 17% and the NO_X emission increased by 24%.

When oxygen enriched hydrogen gas is used to enhance the combustion process of the diesel engine; due to the higher degree of constant volume combustion, higher flame speed associated with high diffusivity through the fuel-air mixture resulted in high-grade combustion. Increasing the temperature of diesel fuel resulted in, increased vaporizing rate of fuel droplets [11]. When the ignition is initiated by pilot mineral diesel, the combustion is of spontaneous nature. Due to spontaneous combustion, the pressure and the temperature of the combustion get increased. The atmosphere of high temperature and sufficient oxygen concentration present within the combustion chamber resulted in more thermal NO_X and reduction in all engine-out pollutants.

Preheating of fuel offers great advantage of easy conversion of the diesel engine to work on heavy fuels. It needs no modifications in the engine usage atmosphere. Engine with fuel preheating has indeed in principle superior characteristics to that of normal fuel operation [12]. Engine using preheated fuels resulted in, improved brake thermal efficiency and reduced smoke, particulate emissions [12-16].

When the pre heated diesel fuel is used in the engine, the engine fuel economy get increased [11] and the ignition delay period gets decreased. Ignition delay period can be defined as the time period between start of injection and start of combustion. During this delay period the fuel is atomized, vaporized, and mixes with air to form combustible mixture. When the warm diesel fuel is injected through the nozzle, results in fine atomized spray. Because of this fine spray, the fuel droplets mingle with air molecules in quick time and form the combustible mixture, which resulted in drop in delay period. When the ignition delay period gets decreased, the pre-mixed combustion phase gets reduced [17]; hence the NO_X emission gets decreased. All other engine-out pollutants like CO, UBHC and smoke also get decreased to some extent.

When analyzing the vast literature of hydrogen usage in diesel engine, significant work was not carried out in optimizing the effect of pre heated diesel fuel. Hence, an effort is made during this investigation to fill this void.

PROCESS OF ELECTROLYSIS

For producing an Oxygen Enriched Hydrogen gas by electrochemical reaction, need an electrolyser for the separation of water, which consists of the electrolysis chamber, an aqueous electrolytic solution comprising water and electrolyte. Here, the electrolyte used was Sodium hydroxide (NaOH). The aqueous electrolyte solution was filled in an electrolysis chamber such that, ¾th of the electrolysis chamber was filled with aqueous electrolyte solution and ¼th of the electrolysis chamber above the aqueous electrolyte solution was left as empty to use it as a gas collection chamber. The electrodes stack consists of two types of electrodes comprising anode electrodes and cathode electrodes; these electrodes were made of Stainless steel 316L material since, Stainless steel 316L material gives much more corrosion resistant than other electrode materials. In the electrolyser, the anode electrode and the cathode electrode were placed sequentially with a gap of 2 mm between them. Oxygen

Enriched Hydrogen gas production primarily depends on the gap between the electrodes and also directly proportional to the surface area of the anode and cathode electrodes, concentration of aqueous electrolyte solution and the potential difference applied between the anode and cathode electrodes. The electrodes stack was partially immersed in the aqueous electrolyte solution. When an electrical potential was applied across the electrodes of the electrolyser, water was directly transmuted into the Oxygen Enriched Hydrogen gas and was collected in the gas collection chamber and delivered through the flexible hose to the intake manifold of the diesel engine.

EXPERIMENTAL WORK

In the present method, the electrolyser decomposes distilled water into a new fuel composed of hydrogen, oxygen and their molecular and magnecular bonds [18-19], called oxygen enriched hydrogen gas. The produced gas was aspirated into the combustion process along with intake air, at the flow rate of 4.6 lpm with pre heated diesel fuel. The diesel fuel was pre heated by an in-house made heater. In this investigation diesel fuel was pre heated to 35^0C, which was more by 10^0C than normal injection temperature of diesel fuel. In this investigation, the combustion of mineral diesel with 25^0C was taken as a base reading, to compare the emission characteristics of a test engine operating under the influence of oxygen enriched hydrogen gas of flow rate of 4.6 lpm at different load ranges of the test engine.

TEST ENGINE SETUP

The present investigation of using oxygen enriched hydrogen gas with pre heated diesel fuel was carried out in a Kirloskar make SV1 model single cylinder, water-cooled, four stroke, DI diesel engine, developing the rated power of 5.9 kW at a speed of 1800 rpm and having a compression ratio of 17.5:1. The engine specification is given in Table 2. Eddy current dynamometer was used to load the engine. The oxygen enriched hydrogen gas was metered through a digital mass flow controller of Aalborg make for precision measurement. 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 with 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 engine-out pollutants such as CO_2, CO, UBHC, NO_X and Excess oxygen (O_2) available in exhaust were measured using Crypton 290 EN2 five gas analyzer. The smoke opacity was measured using AVL smoke meter in Hatridge Smoke Unit (HSU). The experimental setup is shown in figure 1.

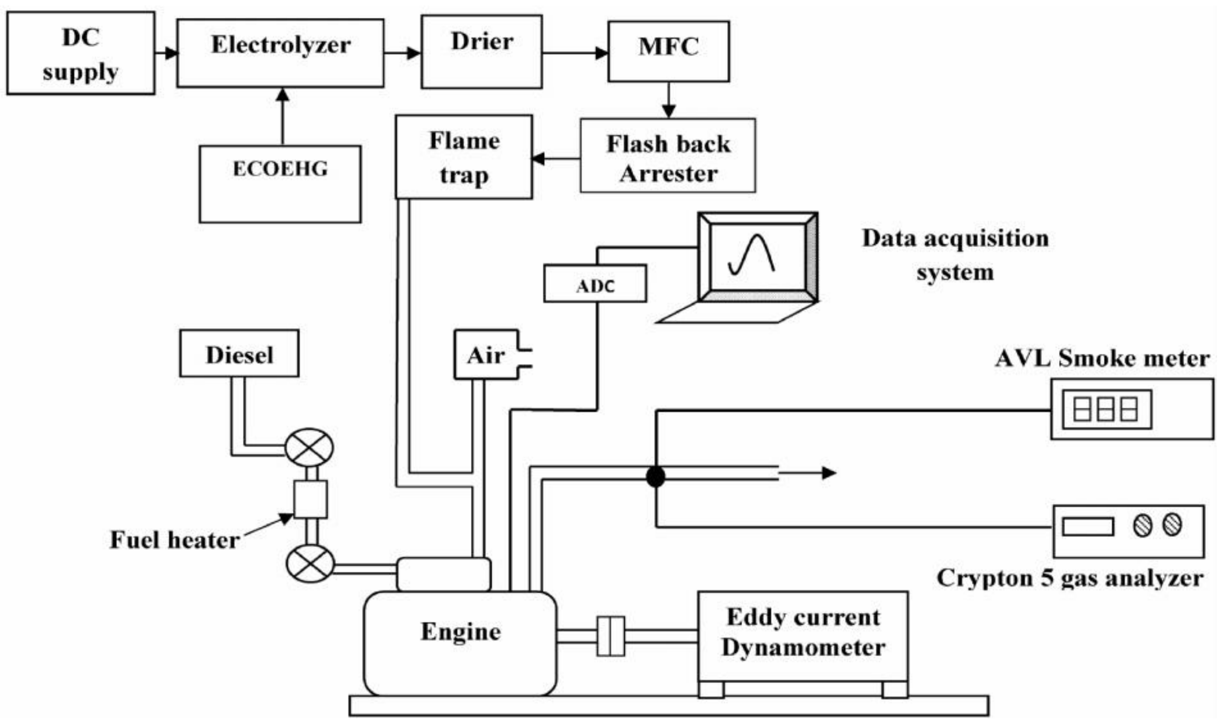

Fig. 1. Schematic arrangement of experimental setup.

Table 1. Important properties of hydrogen

Properties of hydrogen	
Limits of flammability in air	4–75% vol.
Minimum energy for ignition	0.02 mJ
Auto-ignition temperature	858 K
Quenching gap in NTP air	0.064 cm
Burning velocity in NTP air	265–325 cm/s
Diffusion coefficient in NTP air	0.61 cm^2/s
Heat of combustion (LCV)	119.93 MJ/kg

Table 2. Engine specifications

Specifications of test engine	
Make and Model	Kirloskar, SV1
General	4-Stroke / Vertical
Type	Compression Ignition
Number of Cylinder	One
Bore	87.5 mm
Stroke	110 mm
Cubic capacity	661 cc
Clearance Volume	37.8 cc
Compression Ratio	17.5: 1
Rated Output	5.9 kW
Rated Speed	1800 rpm
Combustion Chamber	Hemispherical Open
Type of Cooling	Water Cooled

RESULTS AND DISCUSSION

Carbon monoxide emission (CO)

The effectiveness of oxygen enriched hydrogen gas on Carbon monoxide (CO) emission of the test engine is represented by figure 2. This graph is made for 4.6 lpm of flow rate of oxygen enriched hydrogen gas with diesel fuel temperature of 25^0C (FT25) and 35^0C (FT35) at various load conditions of the test engine. When the combustion is not completed, carbon monoxide forms during the combustion process. When oxygen enriched hydrogen gas with warm diesel fuel is used in the engine, resulted in lower amount of carbon monoxide emission.

At the rated power of the test engine, 4.6 lpm of oxygen enriched hydrogen gas with diesel fuel temperature of FT25; the CO emission decreases from 0.13% vol. to 0.11% vol., by a decrease of 15.38% compared to mineral diesel combustion. When the temperature of the injected diesel fuel is FT35, for the same load condition of the engine, the CO emission decreases from 0.13% vol. to 0.10% vol., by a decrease of 23.08% compared to mineral diesel combustion. This decrease in CO emission is due to higher efficiency combustion of oxygen enriched hydrogen gas, and the faster oxidation reactions associated high-temperature atmosphere resulted due to increased vaporization rate of the fuel-air mixture [11] along with atomic hydrogen and oxygen present in the gas mixture, the surface area exposed by finely fractured fuel molecules is high, and when the combustion is initiated by the ignition of pilot diesel fuel, the combustion is intense, comparing to mineral 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 CO emission.

Carbon dioxide emission (CO_2)

The CO_2 emission of the test engine is displayed in figure 3, for 4.6 lpm of flow rate of oxygen enriched hydrogen gas with diesel fuel temperature of FT25 and FT35 at various load conditions of the test engine. If the degree of combustion of fuel and air mixture is high, the CO_2 emission will be more. Probably, the same thing happens during the combustion influenced by the oxygen enriched hydrogen gas with warm diesel fuel injection.

When oxygen enriched hydrogen gas of 4.6 lpm with FT35 is introduced, at the full rated load conditions of the engine, CO_2 emission increases from 3.3% vol. to 3.7% vol., by an increase of 12.12%. On the other hand, when the condition of the diesel fuel is FT25, for the same rated power of the test engine, CO_2 emission increases from 3.3% vol. to 3.6% vol., by an increase of 9.09%. The CO_2 emission increases because of the high degree of combustion obtained due to higher catalytic action of gas mixture. The high flame velocity of oxygen enriched hydrogen gas associated with high diffusing property and the high oxidation reactions initiated due to change in diesel fuel temperature makes the fuel-air mixture more homogeneous and resulting in more CO_2 emission, when the combustion is initiated by diesel combustion.

Oxides of nitrogen emission (NO_X)

The figure 4 represents the NO_X emission during combustion assisted by oxygen enriched hydrogen gas, supplied to the engine at 4.6 lpm of flow rate with diesel fuel temperature of FT25 and FT35 at various load conditions of the test engine. NO_X is formed in the combustion process, because of three factors; high combustion temperature; sufficient oxygen concentration and residence time. If these three factors present in a combustion process, the NO_X formation is more. By analyzing the figure 4, the NO_X emission increases when oxygen enriched hydrogen gas with warm diesel fuel is used in the combustion process.

When the flow rate of oxygen enriched hydrogen gas of 4.6 lpm with FT35 is inducted at full rated load conditions of the test engine, the NO_X emission increased from 420 ppm to 502 ppm comparing to mineral diesel combustion, results in, increase of 19.52%. When with FT25, the NO_X emission increased from 420 ppm to 491 ppm, results in an increase of 16.90%. This increase in NO_X emission is due to high temperature produced by increase in vaporization rate of fuel droplets due to change in diesel fuel temperature associated with high flame velocity of the hydrogen present in the gas mixture resulted in a spontaneous combustion, as a result of enhanced pre-mixed combustion phase of oxygen enriched hydrogen gas, when ignition is assisted by pilot diesel fuel.

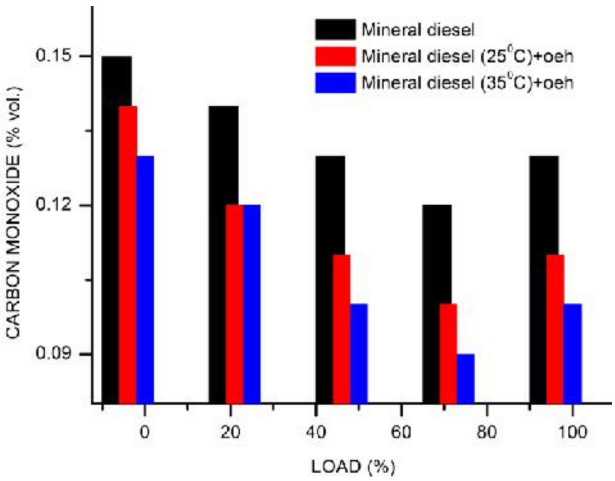

Fig. 2. Variation of carbon monoxide emission with varied load conditions.

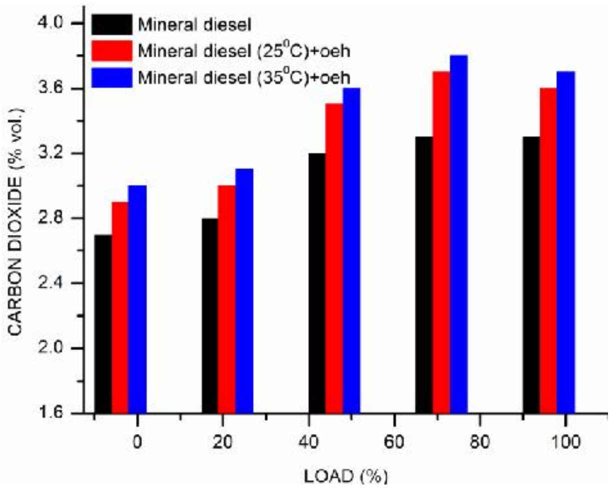

Fig. 3. Variation of carbon dioxide emission with varied load conditions.

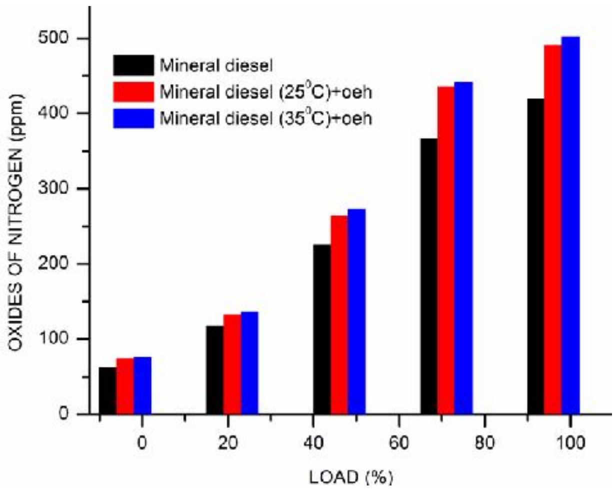

Fig. 4. Variation of oxides of nitrogen emission with varied load conditions.

Smoke emission

The figure 5 portraits the amount of smoke emitted by the test engine during its combustion, when mineral diesel was combusted and when mineral diesel with 4.6 lpm of flow rate of oxygen enriched hydrogen gas with diesel fuel temperature of FT25 and FT35 at various load conditions of the test engine.

When, oxygen enriched hydrogen gas with warm diesel fuel is inducted into the combustion process, the smoke reduces substantially. If the heavier structure of fuel molecules is fractured into lighter and smaller hydrocarbon structures in quick time, the homogeneous mixture can be formed. This is what probably happens; when oxygen enriched hydrogen gas is aspirated into the combustion process of the diesel engine. When oxygen enriched hydrogen gas of 4.6 lpm with FT25 is inducted at full rated load condition of the test engine, the smoke is 30 HSU compares to mineral diesel combustion of 42 HSU, by a decrease of 28.57%. When Oxygen enriched hydrogen gas with FT35 is aspirated into the combustion process, smoke emission decreases from 42 HSU to 28 HSU, by a decrease of 33.33%.

This decrease in smoke emission is due to availability of more homogeneous mixture and less heterogeneous mixture of fuel and air, high oxygen concentration presents in the overall fuel mixture and the high burning velocity causes rapid flame propagation in hydrogen. When the combustion is initiated by the ignition of pilot diesel fuel, the combustion is of higher grade and also more intense; which in turn decreases the smoke emission.

Unburned hydrocarbon emission (UBHC)

The graphical representation of the variation of UBHC emission is shown in figure 6, when the test engine was operated under the influence of oxygen enriched hydrogen gas of 4.6 lpm with diesel fuel temperature of FT25 and FT35 at various load conditions of the test engine. When, 4.6 lpm of gas mixture with FT35 is inducted into the combustion process, resulting in 49 ppm at a rated load condition of the engine, at the same time the mineral diesel combustion results, the UBHC emission of 66, by a reduction of 25.76%. When, 4.6 lpm of gas mixture with FT25 is inducted into the combustion process, resulted in the reduction of 19.70% of UBHC emission.

This decrease UBHC emission is due to; more oxygen concentration presents in the overall fuel mixture, the high burning velocity causes rapid flame propagation in hydrogen combustion engines resulting in an intense convection of the burning gas and a large heat transfer from the burning gas to the combustion chamber walls [20]. Least flame quenching distance of the hydrogen present in the gas mixture, the high fracturing capability of heavier hydrocarbon molecules by atomic hydrogen and oxygen present [19] in the gas mixture and increased vaporization rate of fuel; due to warm diesel fuel resulted in, high-grade combustion and less UBHC emission compared to mineral diesel combustion.

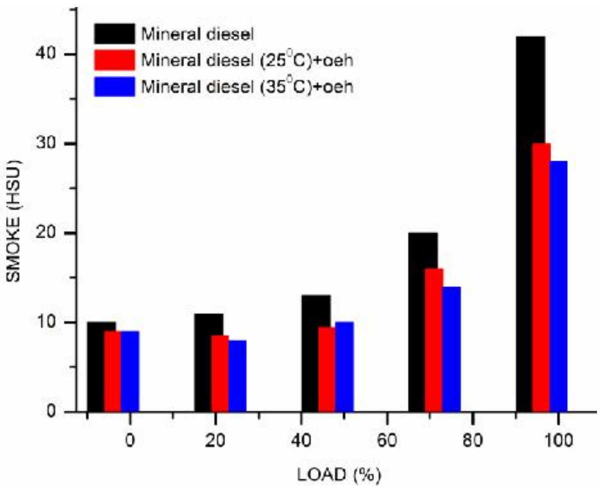

Fig. 5. Variation of smoke emission with varied load conditions.

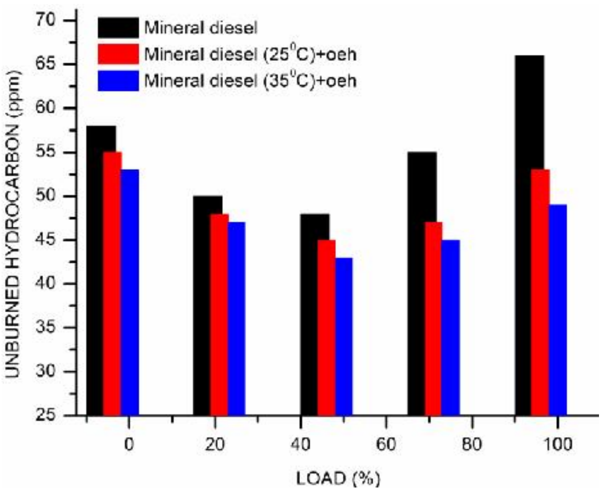

Fig. 6. Variation of unburned hydrocarbon emission with varied load conditions.

Excess oxygen (O_2)

The figure 7 shows the effect of oxygen enriched hydrogen gas addition on the excess oxygen present in the exhaust emission of a test engine at different load conditions and for the flow rate of 4.6 lpm of gas mixture with diesel fuel temperature of FT25 and FT35. It is evident from the graph, when 4.6 lpm of oxygen enriched hydrogen gas with warm diesel fuel is introduced in the combustion process, results in reduction in oxygen percentage in the exhaust of the diesel engine.

This is due to the strong oxidizing ability of oxygen enriched hydrogen gas associated with change in diesel fuel temperature. Overall high percentage of oxygen, high rate of fracturing capability of atomic hydrogen and oxygen present in the oxygen enriched hydrogen gas mixture and subsequent increase in the oxidation rate of diesel fuel molecules resulted in, high-temperature atmosphere in the combustion chamber.

When 4.6 lpm flow rate of oxygen enriched hydrogen gas with FT35 is aspirated into the combustion process, at the rated load condition of the test engine, the excess oxygen present in the exhaust is 16.68%, whereas the mineral diesel combustion results in 18.37%, by a reduction of 9.2%. At the same time, when oxygen enriched hydrogen gas with FT25 is introduced into a combustion process of mineral diesel results in, reduction in excess oxygen in the exhaust by 8.87%.

Total Energy Consumption (TEC)

The figure 8 represents the effectiveness of oxygen enriched hydrogen gas of 4.6 lpm of flow rate with diesel fuel temperature of FT25 and FT35 at various load conditions of the test engine on the total energy consumption (TEC). At full rated load of the test engine and for diesel fuel temperature of FT25, the total energy consumption decreases from 2.01 MJ/h to 1.73 MJ/h, when 4.6 lpm of Oxygen enriched hydrogen gas is introduced into the combustion of mineral diesel, decrease by 14.12% comparing to lone mineral diesel combustion. When, the diesel fuel temperature is FT35, for the same rated load condition of the engine, the TEC decreases by 15.76%, comparing to lone mineral diesel combustion.

When analyzing the graph of total energy consumption (TEC), it is clear that the total energy consumption decreases, when oxygen enriched hydrogen gas with FT25 and FT35 are used in the engine. This decrease in total energy consumption is due to combined effect of oxygen enriched hydrogen gas and the effect of warm diesel fuel temperature. When the diesel fuel temperature is increased, very fine size of fuel droplets are obtained at the exit of injector nozzle, which enhances the intimacy of fuel droplets with air molecules [11]. On the other hand, due to high heating value of the hydrogen present in the gas mixture, operation of the hydrogen-fueled engine at the leaner equivalence ratio [21] and also the rate of combustion is high due to faster chain reactions initiated by atomic hydrogen and oxygen present in the gas mixture after the start of diesel ignition resulted in decrease in TEC.

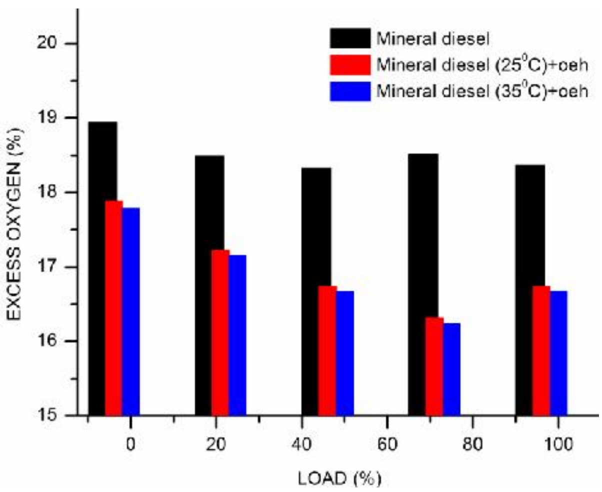

Fig. 7. Variation of excess oxygen in exhaust with varied load conditions.

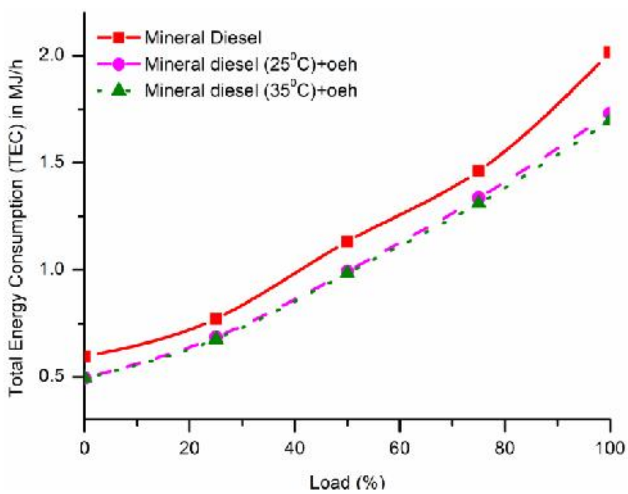

Fig. 8. Variation of total energy consumption with varied load conditions.

CONCLUSIONS

From the present experimental investigation of using oxygen enriched hydrogen gas of 4.6 lpm with warm diesel fuel in the combustion process of the DI diesel engine resulted in, decrease in the fuel consumption and reduction of all engine-out pollutants except oxides of nitrogen (NO_X). Since, when oxygen enriched hydrogen gas is used in the combustion process of mineral diesel, due to enhanced combustion phenomena, the pressure and the temperature developed during the combustion is more, resulting in more NO_X emission. When 4.6 lpm of oxygen enriched hydrogen gas is introduced in the combustion process along with FT35 results,

- The CO emission decreases from 0.13% vol. to 0.1% vol., by a decrease of 23.08%.
- The UBHC emission decreases from 66 ppm to 49 ppm, by a decrease of 25.76%, as a result of addition of oxygen enriched hydrogen gas.
- The NO_X emission increased by 19.52%, due to enhanced pre-mixed burning phase.
- The smoke emission reduced substantially by 33.33 %.

REFERENCES

1. Saravanan N. and Nagarajan G., Performance and emission studies on port injection of hydrogen with varied flow rates with Diesel as an ignition source, Appl. Energ., 2010, 87, 2218–2229.
2. Verhelst S. and Sierens R., Aspects concerning the optimisation of a hydrogen fueled engine, Int. J. Hydrogen Energ., 2001, 26, 981-985.
3. Ali Mohammadi, Masahiro Shioji, Yasuyuki Nakai, Wataru Ishikura and Eizo Tabo, Performance and combustion characteristics of a direct injection SI hydrogen engine, Int. J. Hydrogen Energ., 2007, 25, 296–304.
4. Karim G.A., Hydrogen as a spark ignition engine fuel, Journal of the Society of Chemical Industry, 2002, 56, 256-263.
5. Demirbas A. and Arin G., Hydrogen from biomass via pyrolysis: relationships between yield of hydrogen and temperature, Energy Sources, 2004, 26, 1061-1069.
6. Murari Mohon Roy, Eiji Tomita, Nobuyuki Kawahara, Yuji Harada and Atsushi Sakane, An experimental investigation on engine performance and emissions of a supercharged H_2-diesel dual-fuel engine, Int. J. Hydrogen Energ., 2010, 35, 844–853.
7. Momirlan M. and Veziroglu T.N., Current status of hydrogen energy, Renew. Sust. Energ. Rev., 2002, 6, 141–179.
8. Bade Shrestha S.O., LeBlanc G., Balan G. and De Souza M., A Before Treatment Method for Reduction of Emissions in Diesel Engines, SAE Technical Paper, 2000, 2000-01-2791.
9. Bari S. and Mohammad Esmaeil M., Effect of H_2/O_2 addition in increasing the thermal efficiency of a diesel engine, Fuel, 2010, 89, 378–383.
10. Adrian Birtas and Radu Chiriac, A Study of injection timing for a diesel engine operating with gasoil and HRG gas, U.P.B. Sci. Bull., Series D, 2011, 73, 65-78.
11. Clarence R. Shepherd, Diesel engine fuel preheating system, United States Patent, US 4343283, 1982 August 10.
12. Nwafor O.M.I, The effect of elevated fuel inlet temperature on performance of diesel engine running on the neat vegetable oil at constant speed conditions, Renew. Energ., 2003, 28, 171–181.
13. Naga Prasad C.S., Vijaya Kumar Reddy K, Kumar B.S.P., Ramjee E, Hebbel O.D and Nivendgi M.C., Performance and emission characteristics of a diesel engine with castor oil, Indian Journal of Science and Technology, 2009, 2, 25-31.
14. Murat Karabektas,Gokhan Ergen and Murat Hosoz, The effects of preheated cottonseed oil methyl ester on the performance and exhaust emissions of a diesel engine, Appl. Therm. Eng., 2008, 28, 2136–2143.
15. Hanbey Hazar and Hüseyin Aydin, Performance and emission evaluation of a CI engine fueled with preheated raw rapeseed oil (RRO)–diesel blends, Appl. Energ., 87, 786–790.
16. Pugazhvadivu M. and Jeyachandran K., Investigations on the performance and exhaust emissions of a diesel engine using preheated waste frying oil as fuel, Renew. Energ., 2005, 30, 2189–2202.
17. Ali Mohammadi, Masahiro Shioji, Yasuyuki Nakai, Wataru Ishikura and Eizo Tabo, Performance and combustion characteristics of a direct injection SI hydrogen engine, Int. J. Hydrogen Energ., 2007, 32, 296-304.

18. Klein Dennis J. and Ruggero Maria Santilli, Apparatus and method for the conversion of water into a new gaseous and combustible form and the combustible gas formed thereby, United States Patent, US 20060075683 A1 2006 April 13.
19. Ruggero Maria Santilli, A new gaseous and combustible form of water, Int. J. Hydrogen Energ., 2006, 31, 1113–1128.
20. Shudo T., Nabetani S. and Nakajima Y., Analysis of the degree of constant volume and cooling loss in a spark ignition engine fuelled with hydrogen, Int. J. Engine Res., 2001, 2, 81-92.
21. Saravanan N, Nagarajan G, Kalaiselvan K.M. and Dhanasekaran C., An experimental investigation on hydrogen as a dual fuel for diesel engine system with exhaust gas recirculation technique, Renew. Energ., 2008, 33, 422–427.

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