EFFECTIVENESS OF OXYGEN ENRICHED HYDROGEN-HHO GAS ADDITION ON DIRECT INJECTION DIESEL ENGINE PERFORMANCE, EMISSION AND COMBUSTION CHARACTERISTICS

by

Premkartikkumar SELVI RAJARAM *, ***Annamalai KANDASAMY, and Pradeepkumar AROKIASAMY REMIGIOUS***

Department of Automobile Engineering, Madras Institute of Technology, Anna University, Chennai, India

Original scientific paper
DOI: 10.2298/TSCI121014078P

Nowadays, more researches focus on protecting the environment. Present investigation concern with the effectiveness of oxygen enriched hydrogen-HHO gas addition on performance, emission and combustion characteristics of a direct injection diesel engine. Here the oxygen enriched hydrogen-HHO gas was produced by the process of water electrolysis. When potential difference is applied across the anode and cathode electrodes of the electrolyzer, water is transmuted into oxygen enriched hydrogen-HHO gas. The produced gas was aspirated into the cylinder along with intake air at the flow rates of 1 lpm and 3.3 lpm. The results show that when oxygen enriched hydrogen-HHO gas was inducted, the brake thermal efficiency of the engine increased by 11.06%, carbon monoxide decreased by 15.38%, unburned hydrocarbon decreased by 18.18%, carbon dioxide increased by 6.06%, however, the NO_x *emission increased by 11.19%.*

Key words: *diesel engine, electrolysis, oxygen enriched hydrogen-HHO gas, emission characteristics*

Introduction

Faster rate of depletion of fossil fuel, day to day increase of automotive vehicles and stringent emission norms created a thirst to the researchers to find out an alternative that can be used in the compression ignition engines, with less modification or without any modification. Few alternative fuels which are under research are vegetable oil, biomass, biogas, primary alcohols (*i. e.* methanol, ethanol) and hydrogen. Alternative fuels are clean and environment friendly fuels compared to diesel fuel and gasoline fuel [1, 2]. Among these alternative fuels hydrogen attracts the researchers because of its simple reaction with oxygen into water as a clean method for energy conversion, the high-energy density, the wider flammability limits, the high burning velocities and also their significant structure of non-content of carbon atoms.

Today, hydrogen is mostly produced by steam reforming or partial oxidation of hydrocarbons (76% from natural gas and 23% from light or heavy oil distillates) [3]. However, for small hydrogen quantities, or when high-purity hydrogen is required, processes such as water electrolysis, ammonia decomposition or methanol reforming are also used [4]. 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 [5]. Water can be split by the number of

* Corresponding author; e-mail: premthermal46@gmail.com

ways. Bockris *et al*. [6] explained some of the processes, which can be used to split water are: electrolysis, plasmolysis, magnetolysis, thermal approach (direct, catalytic, cyclic decomposition of water and magmalysis), use of light (photo-sensitized decomposition using dyes, plasma-induced photolysis, photo-electrolysis, photo-aided electrolysis, the indirect path towards hydrogen by photo-electrolysis: the photo-electrochemical reduction of CO_2 and photovoltaic electrolysis), bio-catalytic decomposition of water and radiolysis. Because of its characteristics, hydrogen can be used in current conventional internal-combustion gasoline or diesel engines by dual fuel operation without important modifications, in the transition period before hydrogen becomes the sole fuel [7].

Many studies have been carried out on hydrogen combustion in diesel engines in very different conditions. Some of the researchers used hydrogen in a dual-fuel mode [8-12], some of the researchers used hydrogen with EGR of hot or cooled [13-16], even tried with superchargers [17] and also some of the researchers tried with hydrogen-rich gases like hydrogen rich gas (HRG) and hydrogen/oxygen mixture produced by water electrolysis [18-21].

Cecil [22] explained about, how to use the energy of hydrogen to power an engine and how the hydrogen engine could be built in 1820 itself. Presumably, this is the earliest invention made in hydrogen-fueled engines. Properties of hydrogen are given in tab. 1.

Table 1. Important properties of hydrogen [17]

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

Wong [23] tested the diesel engine with hydrogen as a sole fuel. As the self-ignition temperature of hydrogen is about 858 K [17], it is impossible to ignite hydrogen, just by heat of compression. It needs an ignition starter to start its combustion. So he used ceramic glow plug as an ignition starter and obtained valid results.

Varde and Frame [24] made some early research in hydrogen in dual fuel mode. They found, when the rate flow of hydrogen inducted into the engine was 0.65 kJ/s, the resulting efficiency was consistently lower than the pure diesel combustion. When the flow rate of hydrogen is increased to1.65 kJ/s, resulted in higher thermal efficiency. Under optimum condition of 10% and 15% of the total energy, the smoke reduction was found to be as much as 50% lower at part load operation.

Yi *et al*. [25] used port injection and in-cylinder injection to supply hydrogen to the engine. Their result shows that the thermal efficiency of the engine is higher in port injection than in-cylinder method of injection at all equivalence ratios.

Senthil Kumar *et al.* [26] made an investigation on the effect of hydrogen addition to the combustion process of a small single-cylinder diesel engine fueled with vegetable oil. The addition of hydrogen resulted in an increase in ignition delay period but enhance the combustion process substantially. Brake thermal efficiency increased from 27.3% to a maximum of 29.3% at 7% of hydrogen on mass share at maximum power output. Smoke was reduced from 4.4 to 3.7 Bosch smoke unit (BSU). Reduction in HC and CO emissions were 130 to 100 ppm and 0.26 to 0.17 vol.% , respectively, however, NO_x emission increased from 735 to 875 ppm.

Using pure hydrogen or hydrogen containing gas produced through water electrolysis, are notably different [20].

Bari and Mohammad Esmaeil conducted their experimental work with the use of H_2/O_2 mixture produced by water electrolysis. Results showed that the HC emission decreased from 192 ppm to 97 ppm by adding 30.6 lpm of H_2/O_2. NO_x emission was found to be increased from 232 ppm to 307 ppm, at 22 kW of load. The minimum amount of CO_2 was achieved at 19 kW with 31.75 lpm of H_2/O_2 induction. CO was reduced from 0.24% to 0.012% at 22 kW of load [18].

Samuel and McCormick [19] run the engine with addition of hydrogen-oxygen mixture generated by the water electrolysis process. By using 1.5 lpm of hydrogen-oxygen mixture, the concentration of NO_x in emission reduced to 17.9%. However, when the mixture supply was further increased to 2.8 lpm, NO_x emission increases.

Birtas *et al.* [20] made their investigation of using the HRG gas, on a naturally aspirated direct injection, tractor diesel engine with four cylinders in-line having the total capacity of 3759 cm^3, nominal power of 50 kW at 2400 rpm, maximum torque of 228 Nm at 1400 rpm, and the compression ratio of 17.5. The gas, produced by water electrolyzer was aspirated along with the air stream inducted into the cylinder. It was found that the addition of HRG gas has a slight negative impact, up to 2%, on the engine brake thermal efficiency. Smoke is significantly reduced up to 30% with HRG enrichment, while NO_x concentrations vary in both senses, up to 14%, depending upon the engine operation mode.

More recently, Hsin-Kai Wang *et al.* [21] studied the effects of induction of hydrogen and oxygen mixture (H_2/O_2) on the emission characteristics of a heavy-duty diesel engine (HDDE). The results showed that the NO_x concentration got increased from 60.05 ppm for neat diesel to 67.22 ppm for 70 lpm of H_2/O_2 addition.

The present experimental work provides a feasible solution for onboard production of hydrogen, which avoids the storing of hydrogen in heavy pressurized tanks. In the present process, the hydrogen on demand along with oxygen is available at any desired rate by the process of water electrolysis. An electrolyzer, which decomposes distilled water into a new fuel composed of hydrogen, oxygen and their molecular and magnecular bonds, called oxygen enriched hydrogen-HHO (OEH-HHO) gas [27, 28] was produced. The produced gas was inducted into the cylinder along with intake air, at the flow rate of 1 lpm and 3.3 lpm thereby; the effectiveness of OEH-HHO gas on performance, emission and combustion characteristics of the engine was determined at various rated loads of the test engine.

Test engine set-up

The present investigation was carried out in a Kirloskar make single cylinder, water-cooled, four stroke, direct injection (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. For loading the engine, eddy current dynamometer was coupled to the engine. The OEH-HHO 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 of air cooled type with an inline charge amplifier. The amplified signals were correlated to the signal from crank angle encoder having an accuracy of 0.1 degree crank angle. The data obtained were stored on a personal computer for analysis. The exhaust gas emissions such as carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbon (UBHC), oxides of nitrogen (NO_x) and excess oxygen (O_2) available in exhaust were measured by Crypton 290 EN2 five gas analyzer. The smoke was measured by AVL smoke meter. The experimental set-up is shown in fig. 1. NO_x, CO, CO_2, and smoke were measured with accuracy of ±10 ppm, ±0.03%, and ±1 HSU, respectively.

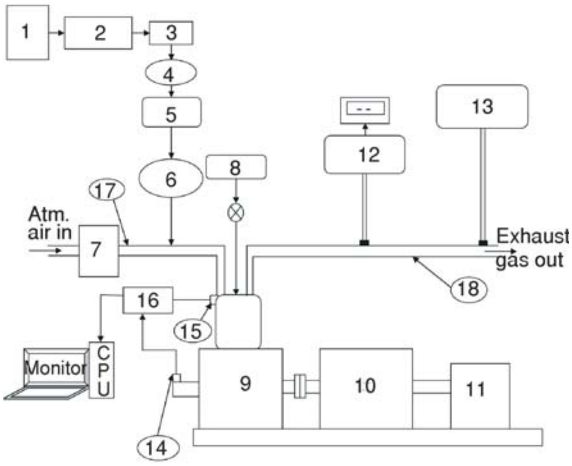

Figure 1. Experimental set-up
1 – DC power supply, 2 – electrolyzer, 3 – drier, 4 – mass flow controller, 5 – flash back arrestor, 6 – flame trap, 7 – air box, 8 – diesel tank, 9 – engine, 10 – eddy current dynamometer, 11 – load cell, 12 – AVL smoke meter, 13 – crypton 5 gas analyzer. 14 – crank angle encoder, 15 – pressure pickup sensor, 16 – analog to digital convertor, 17 – inlet manifold, 18 – exhaust manifold

Experimental procedure

When DC power supply is switched on, in present study 12 V was supplied. The potential difference across the anode electrodes and the cathode electrodes along with the aqueous electrolyte solution present in the electrolyzer produces OEH-HHO gas instantly 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 is used to remove the moisture content present in the gas. Flashback arrestor and flame trap are used to suppress the flame if a back fire from the engine occurs.

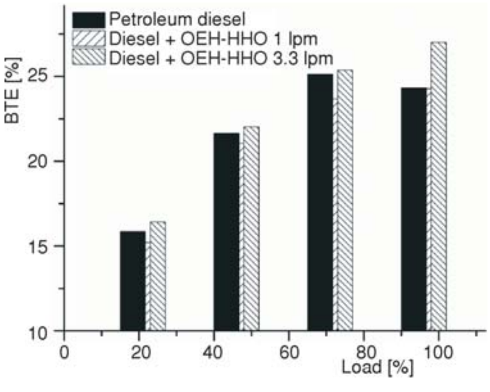

Figure 2. Variation of BTE with load

Results and discussion

Performance characteristics

Brake thermal efficiency

Brake thermal efficiency (BTE) is the significant yard stick, to measure the efficiency of an engine. BTE can be defined as the ratio between the useful power available at the crank shaft of the engine to the input energy given to the engine in the form of chemical energy available in the fuel. Figure 2 represents the effect of OEH-HHO gas of 1 lpm and 3.3 lpm of flow rates on the BTE of the engine at different rated load of a test engine. When going through the graph, the BTE increases, when OEH-HHO gas is used as an additive in combustion of pure petroleum diesel combustion.

When the flow rate is 3.3 lpm at 100% rated load of the engine, the BTE increases from 24.32% to 27.01%, increase by 11.06% comparing to pure petroleum diesel combustion. The increase in efficiency is due to higher-calorific value of hydrogen present in the gas mixture, its high flame velocity and also due to the presence of atomic hydrogen and oxygen [28], as they are in the high-energy level than their dual molecule counterparts. Because of this quality, when the ignition is initiated by petroleum diesel, they immediately start to fracture the heavier hydrocarbon molecule of diesel fuel and initiated the chain reaction, which results in efficient combustion and higher BTE than petroleum diesel. However; when OEH-HHO gas with a flow rate of 1 lpm is introduced at 25% of rated load into the combustion process of diesel, results in decrease in brake thermal efficiency from 15.86% to 15.2%, by a decrease of 4.15%. This reduction in efficiency is due to too lean mixture present in the cylinder [26] at low load range of the engine. Combustion of hydrogen-air mixtures at such a low hydrogen fuel concentration is dependent on the local temperature around parcels of fuel mixtures [24].

Brake specific energy consumption

Brake specific energy consumption (BSEC) can be defined as fuel energy utilized to produce unit brake power. The graphical representation of effectiveness of OEH-HHO gas of various flow rates on the BSEC of the engine at various load conditions is shown in fig. 3. At 100% rated load of the test engine, the BSEC decreases from 14.8 MJ/kWh to 13.32 MJ/kWh, when 3.3 lpm of OEH-HHO gas is inducted into the combustion of petroleum diesel, decrease by 9.96% comparing to pure petroleum diesel combustion. The decrease in BSEC is due to high-energy content of the hydrogen present in the gas mixture, and also the combustion rate is high due to faster chain reactions initiated after the start of diesel ignition. When OEH-HHO gas with a flow rate of 1 lpm is introduced at 25% load condition into the combustion process, results in an increase in BSEC from 22.69 MJ/kWh to 23.68 MJ/kWh, by an increase of 4.33% comparing to pure petroleum diesel combustion. This increase in BSEC is due to, at low level concentrations, hydrogen is in subdued mode. As the lean mixture presented in the cylinder is out of range of flammability limit of hydrogen and also the cooling loss at low load condition is more, resulted in low temperature atmosphere inside the combustion chamber.

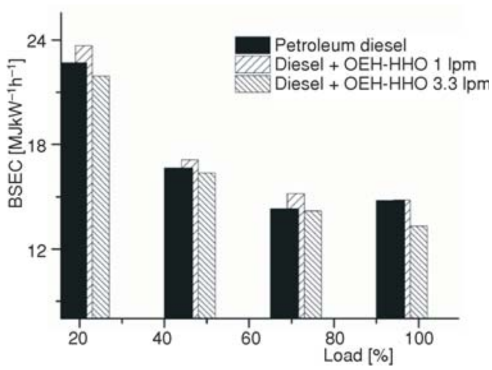

Figure 3. Variation of BSEC with load

Emission characteristics

Carbon monoxide

Figure 4 shows the effectiveness of OEH-HHO gas on CO emission of the test engine, when used in combustion of petroleum diesel. This graph is made for 1 lpm and 3.3 lpm flow rates of OEH-HHO gas at various load ranges of the engine. At 1 lpm of OEH-HHO gas flow rate and at 50% of rated load of the engine, CO emission increases from 0.13 vol.% to 0.14 vol.%, by an average increase of 7.69%. This happens because, at low load condition, the heat loss to the cooling medium is more, and also the low-temperature combustion present in the cylinder results, in high CO emission.

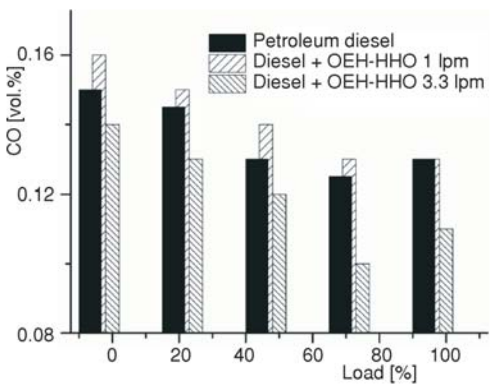

Figure 4. Variation of CO emission with load

When OEH-HHO gas flow rate of 3.3 lpm is inducted into the combustion process, the CO emission decreases from 0.13 vol.% to 0.11 vol.%, by a decrease of 15.38% at 100% rated load of the engine, compared to pure petroleum diesel combustion operation. This is because of good combustion of OEH-HHO gas, and the faster oxidation reaction influenced by it in a further combustion process. When compares the reduction percentage of CO emission at 3.3 lpm at 75% and 100% of rated load of the engine, the reduction percentage in case of 100% rated load is less, due to rich fuel present in the combustion chamber at maximum load condition.

Carbon dioxide

The CO_2 emission of the test engine is shown in fig. 5, for 1 lpm and 3.3 lpm of flow rates of OEH-HHO gas at various load conditions. If combustion is good, the CO_2 emission will be more. Same thing happens during the combustion assisted by the addition of OEH-HHO. When OEH-HHO gas of 1 lpm is introduced at 50% rated load of the engine, CO_2 emission is less compared to pure petroleum diesel combustion, because of the low-temperature atmosphere prevails in the combustion chamber, is inefficient to oxidize the major part of the fuel, resulting in poor combustion. At the flow rate of 3.3 lpm of OEH-HHO gas, the CO_2 emission increases because of the higher combustion efficiency obtained due to catalytic action of OEH-HHO gas on combustion. The higher diffusing property of OEH-HHOg as makes the fuel mixture more homogeneous and also due to its high flame velocity, resulting in more CO_2 emission when the combustion is initiated by diesel combustion. When, OEH-HHO gas flow rate of 3.3 lpm is introduced into the combustion process, the CO_2 emission increases from 3.3 vol.% to 3.5 vol.%, by an increase of 6.06%.

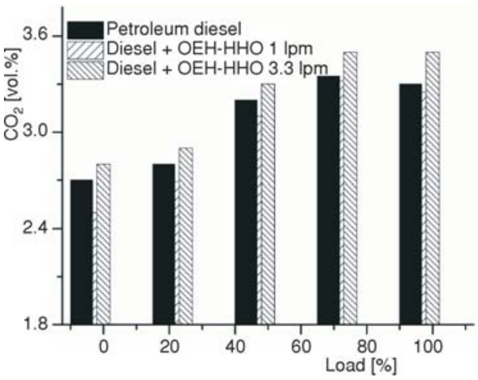

Figure 5. Variation of CO_2 with load

Unburned hydrocarbon

Figure 6 represents the variation of UBHC emission, when the test engine was operated with the assistance of OEH-HHO gas at 1 lpm and 3.3 lpm. When 3.3 lpm gas mixture is introduced into the cylinder, resulting in 54 ppm at 100% rated load of the engine, at the same time the UBHC emission of pure petroleum diesel is 66 ppm, by a decrease of 18.18%. This decrease in percentage is due to more oxygen percentage presents in the overall fuel mixture, flame quenching distance of the hydrogen present in the gas is very least, the fracturing action of heavier hydrocarbon molecules by atomic hydrogen and oxygen present [28] in the OEH-HHO gas and subsequent oxidation reaction initiated by them increases the rate of combustion. However; when 1 lpm of

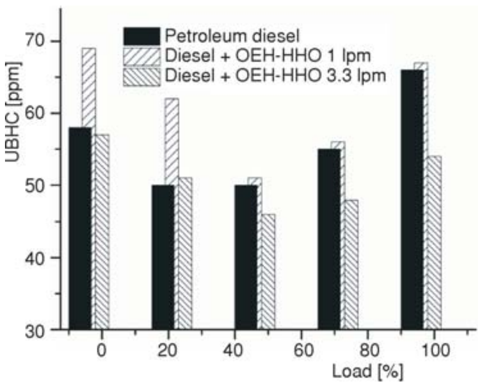

Figure 6. Variation of UBHC emission with load

OEH-HHO gas flow at 50% of the rated load, the UBHC emission is more compared to pure petroleum diesel combustion, because at low load conditions, the combustion is incomplete. Hydrogen is inactive in low temperature reactions also.

Oxides of nitrogen

Figure 7 represents the NO_x emission during the combustion, when OEH-HHO gas was supplied to the engine at 1 lpm and 3.3 lpm of flow rates and at various load ranges of the engine. NO_x is formed during the combustion because of three factors, high temperature, oxygen concentration, and residence time. If these three factors present in a combustion chamber, the NO_x formation is more. By analyzing the fig. 7, clearly the NO_x emission various depends upon the flow rate of OEH-HHO gas. When the flow rate is 1 lpm and at 50% of rated load of the engine, the NO_x emission decreases from 226 ppm to 191 ppm compares to petroleum diesel combustion, by a decrease of 15.48%, because of poor combustion rate, results in low temperature atmosphere, which is insufficient to produce NO_x. At low to part load conditions, with low concentration of hydrogen in fuel mixture, results in low NO_x emission [19]. When OEH-HHO gas flow rate of 3.3 lpm is inducted at 100% of rated load of the engine, the NO_x emission is 467 ppm whereas, the pure petroleum diesel combustion results in 420 ppm, by an increase of 11.19%. This happens, because of high temperature produced by an instantaneous combustion of OEH-HHO gas, when ignition is assisted by pilot diesel fuel.

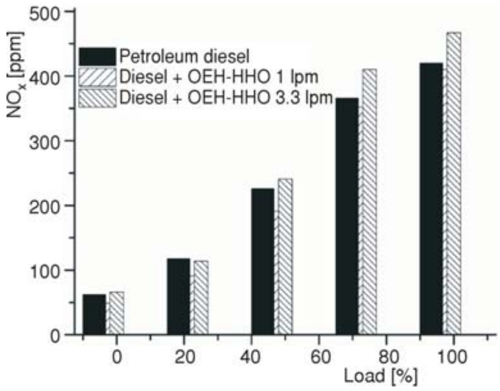

Figure 7. Variation of oxides of NO_x with load

Smoke

Figure 8 compares the amount of smoke emission by the test engine during its combustion, when pure petroleum diesel was combusted and when petroleum diesel with 1 lpm and 3.3 lpm of flow rates of OEH-HHO gas at various load ranges of the engine. When OEH-HHO 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. If heavier hydrocarbon fuel molecule structure is fractured into lighter and smaller hydrocarbon structure in less time, the homogeneous mixture can be formed. This is what happens, when OEH-HHO gas is inducted into the combustion process of the diesel engine. When OEH-HHO gas of 3.3 lpm is inducted at 100% rated load of the engine, the smoke unit is 31 HSU compares to pure petroleum diesel combustion of 42 HSU, by a decrease of 26.19%, which was also proved earlier by Birtas *et al*. [20]. On the other hand, when OEH-HHO gas flow rate is 1 lpm and at 50% rated load of the engine, the smoke emission increases from 13 HSU to 14 HSU, by

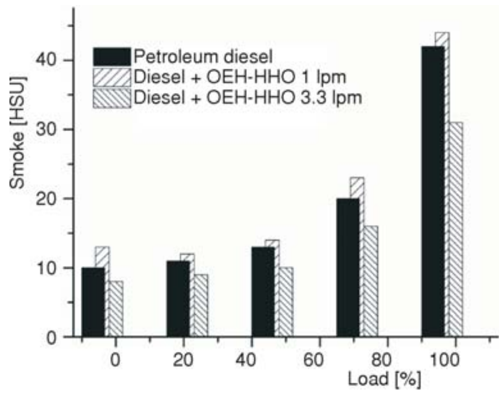

Figure 8. Variation of smoke emission with load

an increase of 7.69%. This increase in smoke is due to low adiabatic temperature prevails in the combustion chamber at low concentration of hydrogen. Combustion of hydrogen-air mixtures at such a low hydrogen fuel concentration is dependent on the local temperature around parcels of fuel mixtures [24].

Combustion characteristics

Heat release rate

Figure 9 compares the HRR, when OEH-HHO gas of flow rate of 3.3 lpm at 100% rated load of the engine and pure petroleum diesel combustion at the same rated load. It is very clear from the graph that the HRR during OEH-HHO gas influenced combustion of petroleum diesel is more, compared to pure petroleum diesel combustion. The heat release of OEH-HHO gas shows distinct characteristics of premixed type combustion compares to typical diffusion type combustion of diesel fuel. The peak HRR of 86 J per deg. CA is achieved with OEH-HHO gas flow rate of 3.3 lpm assisted petroleum diesel combustion compared to 80 J per deg. CA achieved in combustion of petroleum diesel without the assistance of OEH-HHO gas. This is due to high flame speed assisted by high diffusivity of hydrogen makes the fuel-air mixture more homogeneous and creates instantaneous combustion, when OEH-HHO gas is ignited by pilot petroleum diesel. The maximum heat addition occurs nearer to top dead centre in OEH-HHO gas combustion process, which resulted in higher cycle efficiency.

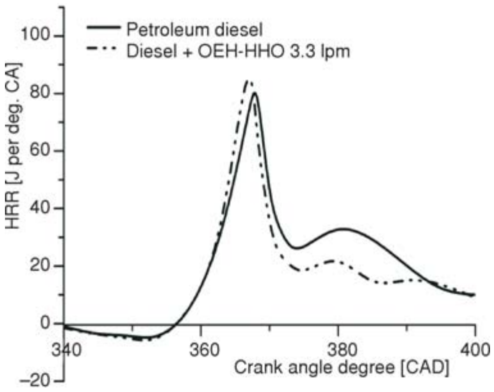

Figure 9.Variation of HRR with crank-angle at 100% rated load of the engine

In-cylinder pressure

Figure 10 compares the in-cylinder pressure developed during 3.3 lpm of OEH-HHO gas influenced petroleum diesel combustion and in-cylinder pressure developed during the combustion of pure petroleum diesel. When, OEH-HHO gas is introduced into the combustion process of petroleum diesel, the ignition delay increases by 1°. As the self-ignition temperature of OEH-HHO gas is more than the pure petroleum diesel, it can't combust on its own, needs an assistance to start its combustion. When OEH-HHO gas is assisted by the ignition of petroleum diesel, the combustion is instantaneous and creates high pressure and high temperature inside the combustion chamber. When analyzing the graph, it is evident that a small fall followed by an immediate hike in the pressure curve, is due to the heat observed by fuel droplets during their vaporization from surrounding heated air presented in a combustion chamber. The pressure of 72 bar results, when

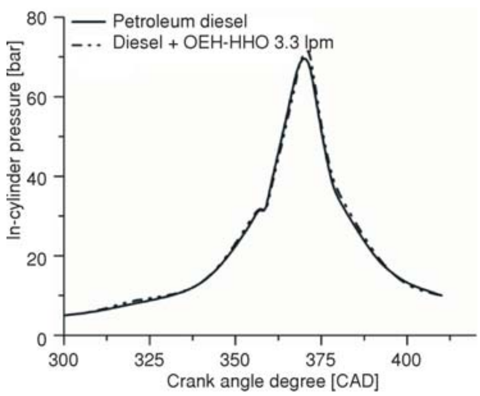

Figure 10. Variation of in-cylinder pressure with crank-angle at 100% rated load of the engine

OEH-HHO gas of 3.3 lpm is inducted into the combustion process, at 100% rated load of the engine. In pure petroleum diesel, the peak pressure resulted in combustion is 70 bar, an increase of 2 bar, when OEH-HHO gas is used as an additive in the combustion of petroleum diesel. The rate of pressure rise is also higher, as a result of instantaneous combustion of gas mixture.

Conclusions

The following facts are derived based on the present investigation of using OEH-HHO gas in the combustion process of a DI diesel engine.

- When 3.3 lpm of OEH-HHO gas was introduced into a combustion process of diesel, the brake thermal efficiency increases from 24.32% to 27.01%, by 11.06%. CO emission decreases from 0.13% vol. to 0.11% vol., by a decrease of 15.38%. CO_2 emission increased by 6.06%. NO_x emission increased by 11.19% and smoke reduced substantially by 26.19 %.
- However, when 1 lpm of OEH-HHO gas was introduced into a combustion process of diesel, the brake thermal efficiency decreased by 4.15%. NO_x emission decreases from 226 ppm to 191 ppm, by a decrease of 15.48%. Smoke emission increases from 13 HSU to 14 HSU, by an increase of 7.69% and CO emission increases by an average increase of 7.69%.

Nomenclature

BSEC – brake specific energy consumption, [MJkW^{-1}h^{-1}]
HRR – heat release rate, [Jdeg.$^{-1}$]

Acronyms

BSU – Bosch smoke unit
EGR – exhaust gas recirculation
HRG – hydrogen rich gas
HSU – Hatridge smoke unit
LCV – lower calorific value
lpm – litre per minute
NTP – normal temperature and pressure
OEH-HHO – oxigen enriched hydrogen-HHO
UBHC – unburned hydrocarbon

References

[1] Huang, Z., *et al.*, Combustion Characteristics of a Direct-Injection Engine Fueled with Natural Gas-Hydrogen Mixtures, *Energy & Fuels, 20* (2006), 20, pp. 540-546
[2] Nanthagopal, K., *et al*.,Hydrogen Enriched Compressed Natural Gas – A Futuristic For Internal Combustion Engines, *Thermal Science*, *15* (2011), 4, pp. 1145-1154
[3] Blomen, L. J. M. J., Mugerwa, M. N., *Fuel Cell Systems*, Plenum Press, New York, USA, 1993
[4] Prigent, M., On Board Hydrogen Generation for Fuel Cell Powered Electric Cars. A Review of Various Available Techniques, *Oil & Gas Science and Technology*, *52* (1997), 3, pp. 349-360
[5] Momirlan, M., Veziroglu, T. N., Current Status of Hydrogen Energy, *Renewable Sustainable Energy Reviews, 6* (2002), 1-2, pp. 141-179
[6] Bockris, J. O. M. *et al*., On the Splitting of Water, *International Journal Hydrogen Energy*, *10* (1985), 30, pp.179-201
[7] Sorusbay, C., Arslan, E., Hydrogen-Fueled Internal-Combustion Engines Performance (in Turkish), *Journal of Engineers and Mechanical, 29* (1988), 339, pp. 23-28
[8] Das, L. M., On-Board Hydrogen Storage Systems for Automotive Application, *International Journal Hydrogen Energy*, *21* (1996), 9, pp. 789-800
[9] Shirk, M. G., *et al*., Investigation of a Hydrogen-Assisted Combustion System for a Light-Duty Diesel Vehicle, *International Journal Hydrogen Energy*, 33 (2008), 23, pp. 7237-7244
[10] Verhelst, S., Wallner, T., Hydrogen-Fueled Internal Combustion Engines, *Progress in Energy and Combustion Science*, *35* (2009), 6, pp. 490-527
[11] Gomes Antunes, J. M., Mikalsen, R., *et al.*, An Experimental Study of a Direct Injection Compression Ignition Hydrogen Engine, *International Journal Hydrogen Energy, 34* (2009), 15, pp. 6516-6522
[12] Saravanan, N., Nagarajan, G., Performance and emission Studies on Port Injection of Hydrogen with Varied Flow Rates with Diesel as an Ignition Source, *Applied Energy*, *87* (2010), 7, pp. 2218-2229

[13] Probir Kumar Bose, Dines Maji, An Experimental Investigation on Engine Performance and Emissions of a Single Cylinder Diesel Engine Using Hydrogen as Inducted Fuel and Diesel as Injected Fuel with Exhaust Gas Recirculation, *International Journal Hydrogen Energy*, *34* (2009), 11, pp. 4847-4854

[14] Shin, B., *et al*., Hydrogen Effects on NO_x Emissions and Brake Thermal Efficiency in a Diesel engine under Low-Temperature and Heavy-EGR Conditions, *International Journal Hydrogen Energy*, *36* (2011), 10, pp. 6281-6291

[15] Wu, H.-W., Wu, Z.-Y., Investigation on Combustion Characteristics and Emissions of Diesel/Hydrogen Mixtures by Using Energy-Share Method in a Diesel Engine, *Applied Thermal Engineering*, *42* (2012), pp. 154-162

[16] Vinod Singh Yadav, S. L., *et al*., Performance and Emission Studies of Direct Injection C. I. Engine in Duel Fuel Mode (Hydrogen-Diesel) with EGR, *International Journal Hydrogen Energy*, *37* (2012), 4, pp. 3807-3817

[17] Murari Mohon Roy, *et al*., An Experimental Investigation on Engine Performance and Emissions of a Supercharged H_2-Diesel Dual-Fuel Engine, *International Journal Hydrogen Energy*, *35* (2010), 2, pp. 844-853

[18] Bari, S., Mohammad Esmaeil, M., Effect of H_2/O_2 Addition in Increasing the Thermal Efficiency of a Diesel Engine, *Fuel*, *89* (2010), 2, pp. 378-383

[19] Samuel, S., McCormick, G., Hydrogen Enriched Diesel Combustion, SAE technical paper 2010-01-2190, 2010

[20] Birtas, A., *et al*., The effect of HRG Gas Addition on Diesel Engine Combustion Characteristics and Exhaust Emissions, *International Journal Hydrogen Energy, 36* (2011), 18, pp. 12007-12014

[21] Wang, H.-K., *et al*., Effect of Regulated Harmful Matters from a Heavy-Duty Diesel Engine by H_2/O_2 Addition to the Combustion Chamber, *Fuel*, *93* (2012), pp. 524-527

[22] Rev. W. Cecil, M. A., On the Application of Hydrogen Gas to Produce a Moving Power in Machinery, *Trans. Cambridge Philosophical Society*, *1* (1820), 2, pp. 217-240

[23] Wong, J. K. S., Compression Ignition of Hydrogen in a Direct Injection Diesel Engine Modified to Operate as a Low Heat Rejection Energy, *International Journal Hydrogen Energy, 15* (1990), 7, pp. 507-514

[24] Varde, K. S., Frame, G. A., Hydrogen Aspiration in a Direct Injection Type Diesel Engine-Its Effects on Smoke and other Engine Performance Parameters, *International Journal Hydrogen Energy*, *8* (1983), 7, pp. 549-555

[25] Yi, H. S., *et a*l., Performance Evaluation and Emission Characteristics of in-Cylinder Injection Type Hydrogen Fueled Engine, *International Journal Hydrogen Energy*, *21* (1995), 7, pp. 617-624

[26] Senthil Kumar, M., *et al*., Use of Hydrogen to Enhance the Performance of a Vegetable oil Fuelled Compression Ignition Engine, *International Journal Hydrogen Energy*, *28* (2003), 10, pp. 1143-1154

[27] Klein, D. J., *et al*., Apparatus and Method for the Conversion of Water Into a new Gaseous and Combustible form and the Combustible Gas Formed Thereby, United States Patent No. US 20060075683 A1, April 13, 2006

[28] Santilli, R. M., A New Gaseous and Combustible Form of Water, *International Journal Hydrogen Energy*, *31* (2006), 9, pp. 1113-1128

Paper submitted: October 14, 2012
Paper revised: May 9, 2013
Paper accepted: June 2, 2013