International Journal of Scientific & Engineering Research, Volume 5, Issue 10, October-2014
ISSN 2229-5518

Experimental Investigations on influence of Gaseous Hydrogen (GH2) Supplementation in In-direct Injection (IDI) Compression Ignition Engine fuelled with Pre-Heated Straight Vegetable Oil (PHSVO)

P. S. Ranjit, Pankaj Kumar Sharma & Mukesh Saxena

Abstract: Depletion of fossil fuels and increased emissions alarmed the researchers and scientists to rethink on alternative fuels to work with IC Engines. Being the same power contain in the vegetable oils can be used as alternative fuels have good heating value nearer to conventional diesel. Jatropa's Straight Vegetable Oil (SVO) was used in unmodified, 4 stroke, constant speed, single cylinder, 7.4 kW, water cooled, vertical, stationary engine was selected for experimentation. Gaseous hydrogen (GH2) in the range of 0.3 gm/min to 1.0 gm/min was supplemented with pre-heated straight vegetable oil at 900 C (PHSVO 90) was tested under constant speed and variable loading conditions.

Results shown that, with 0.5 gm/min gaseous hydrogen (5% of total energy contributed by pilot fuel) supplementation with PHSVO 90, Brake thermal efficiency was raised by 1.2%, brake specific energy consumption was reduced by 546.94 kJ/kW-hr, Smoke was reduced by 7 HSU, HC was reduced by 7 ppm, CO was reduced by 0.18 % by volume, NOx were increased by 105 ppm, Pmax was increased by 1.47 bar with CA advancement by 0.50, Heat release rates peaks increased in pre-mixed as well as diffusion phases, Reduction in ignition delay by 0.30 CA when comparing to pure PHSVO 90 without any supplementation. Hence, small dose of hydrogen supplementation in IDI engines will have a promising growth in performance and reduction in emissions can possible.

Keywords: Straight vegetable oil, gaseous hydrogen supplementation, performance, combustion, emission, dual fuel based engines, alternative fuels.

◆

1.0 Introduction

Degradation of environment and depletion of fossil fuels concerns the researchers to accelerate their research as alternative fuels. During some time back there was an era of bio-diesel.

When comparing the bio-diesel versus bio-fuel through the life cycle impact assessment (LCIA) includes both non- toxicological and toxicological categories and shown bio-fuel is very good environmental friendly than the bio-diesel [1]. Jatropa based straight vegetable oil and hydrogen are the two alternative fuels being selected in this experimental work. However, use of straight vegetable oil in the unmodified diesel engine leads to poor combustion and

---

Corresponding Author: P.S. Ranjit, Research Scholar (CoES), University of Petroleum & Energy Studies (UPES), Dehradun. Mobile: +91 999 7 999 448, E-mail: psranjit@ddn.upes.ac.in

Co-Authors: Dr. Pankaj Kumar Sharma, Assoc. Professor, UPES Dehradun and Dr. Mukesh Saxena, Professor & Pro- Vice Chancellor- UTM, Shillong

increase of exhaust emissions. Whereas hydrogen being a good renewable source, having high heating values, high flame velocity, wide flammability and zero GHGs. Further, hydrogen is also being human ecofriendly by having non-toxic and non - corrosive by nature [2-4]. Vegetable oils are being an alternative concern for conventional diesel fuels having almost similar power output when compared to conventional diesel except a slight reduction of its performance and increase in exhaust smoke because of its high viscosity, high density , low volatility and low reaction rate of unsaturated HC chains [5]. Though different vegetable oils like, babasu, Corn, cotton seed, cramble, Jatropa, linseed, peanut, palm, safflower, soyabean, sunflower, sesam etc. are available Jatropa exhibits good properties with respect to its heating value. Further, Jatropa plants can grow in any fertile or sandy areas even at scarcity of water [6]. Further, supplemented with hydrogen in a conventional diesel engine with petroleum diesel and vegetable oil shown that , the performance improved and emissions were reduced at peak loads, whereas at part loads, same was decreased due to its lean mixtures causes increase in its emissions[7-13]. In this work, a single cylinder, 4S, water cooled, vertical, constant speed, under square, In-direct Injection, compression ignition engine was selected to work with Jatropa based pre heated straight vegetable oil as pilot fuel being injected and gaseous hydrogen as inducted fuel through inlet manifold. Most of the energy was derived from the pilot fuel and gaseous hydrogen was used a supplemented fuel. Experiments were conducted with varying load at constant speed and varying the hydrogen quantity ranging from 0.3 gm/min to 1.0 gm/min.

Figure (1): Photographic view of Engine test set up

2.0 Engine and Test bench Set up:

Different facilities were installed to monitor and control the engine and its variables on engine test bench. Field Marshal make, 4S, water cooled, vertical, constant speed-1000 rpm, under square, 7.4 kW, Lister diesel engine with In-Direct Injection was coupled with Dynomerk made EC-70 model, 70 HP, bidirectional, eddy current dynamometer. The schematic and photographic views of engine test bench was shown in Figure (1). The engine can be controlled with constant speed and variable mode of the dynamometer. Constant Speed mode was selected for this experimentation. AVL make Digas 4000 Light model 5 gas analyzer and 437 model based Smoke meter were used to check the exhaust emissions. In order to authenticate the exhaust emissions, being a single cylinder, 4 stroke, diesel engine emitting exhaust smoke is in intervals but is not in continuous mode leads to variations in the exhaust gas emissions measurement data, sampling unit was used to send the same constant pressure and volume to the 5 Gas analyzer and smoke meter.

A glass burette along with reservoir was used to measure the fuel consumption at various loads under constant speed under gravimetric method. Fuel coming through the tank is passing through counter flow heat exchanger to pre-heat the SVO to 90^0C (PHSVO 90) before entering in to the engine. There is L-2001E model thermocouple with Cr/Al sensor was used to measure the temperature of the entering Pre-heated straight vegetable oil (PHSVO 90) nearer to Injector. Two separate valves were provided for change of fuel from PHSVO to conventional diesel and diesel to PHSVO 90 in order to avoid the cold staring. Thermal stability of the engine and proper changeover of fuel was ensured before taking the final readings.

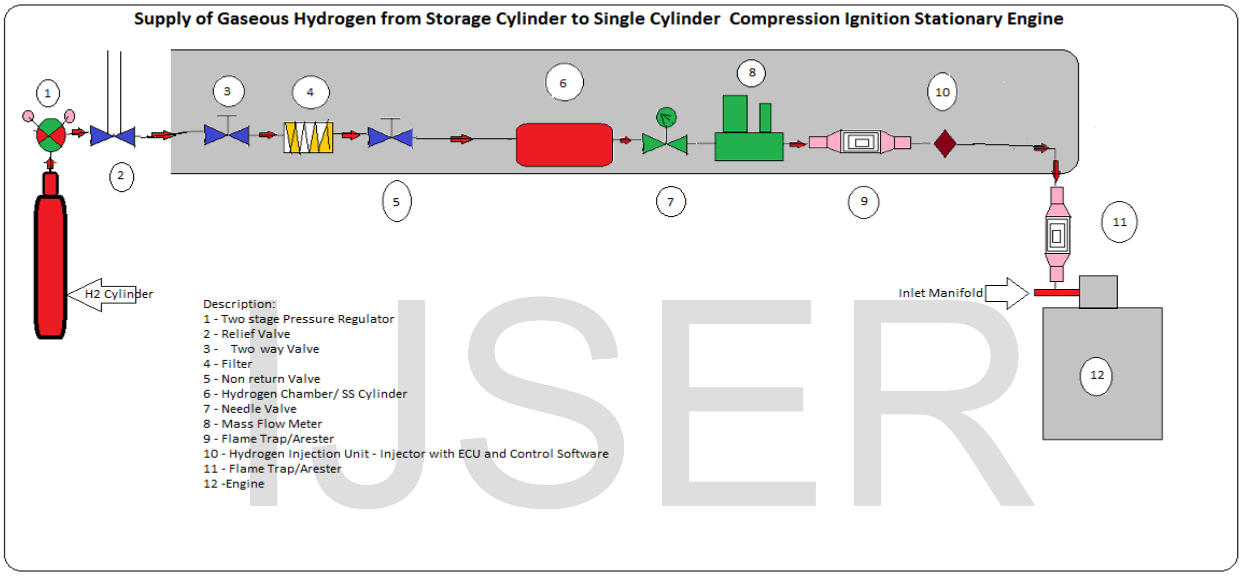

Figure (2): Design of gaseous hydrogen supply system to the engine

For supplementing the Gaseous Hydrogen to the engine, design shown in Figure (2), was made available. It consists of 140 bar pressure, 47 liter water capacity 99.99% pure Hydrogen bottle, Tubing, Two stage Pressure regulator, Relief valve, Two way valve, Filter, Non Return Valve, Hydrogen Chamber, Needle Valve, Mass Flow controller, Flame Arrester, Hydrogen Injection Unit along with metering software and Flame Trap.

Further, In-cylinder thermodynamic measurements were measured with $GaPO_4$ element based AVL make GH15DK model, double shell design, pressure transducer was used[14]. Being an IDI engine, 85% of the cylinder head was made up of hollow. Further, there is no such thickness was available to mount this pressure transducer. In order to synchronize the data of the pressure in the cylinder with respect to position of piston at TDC, AVL 365CC model, 720 pulses Crank Angle Encoder [15] was mounted on one side of the selected engine and same analog signal of the crank angle encoder was transferred to AVL Indismart 612, is a multi-channel indicating system for the acquisition and processing of fast crank angle and time based signals typical for combustion engines [16].

3.0 Experimental Procedure

The engine was always started using diesel fuel and then switched to vegetable oil. The engine was allowed to run for approximately 45 to 50 minutes to make sure that all diesel fuel was flushed out by the vegetable oil before the actual start of the measurements. Similarly, while shutting down, the engine was switched back from vegetable oil to diesel fuel and run for another 45 minutes to ensure that only diesel fuel was left inside the fuel system to avoid problems associated with cold start. In the mean while Smoke meter and 5 Gas analyzer were switched on to get heat up to set temperature in smoke meter and to be prepared for leak test for 5 Gas analyzer. Leak test was carried out in Hydrogen line with snoop solution to avoid any accidents. Final data was recorded only after engine reached the steady state condition under constant speed and varying load conditions. Different emissions like, Smoke opacity, NOx, CO, and HC were paralley measured, whereas combustion parameters like: Cylinder Pressure, differential heat release rate and ignition delay was measured with an average of 100 cycles. Heat release rate was calculated from the measured cylinder pressure versus CA data using AVL Indismart 612 and advanced combustion analyzer supplied by AVL. Further, performance parameters like brake thermal efficiency, brake specific energy consumption were calculated.

4.0 Results and Discussions

4.1 Performance data

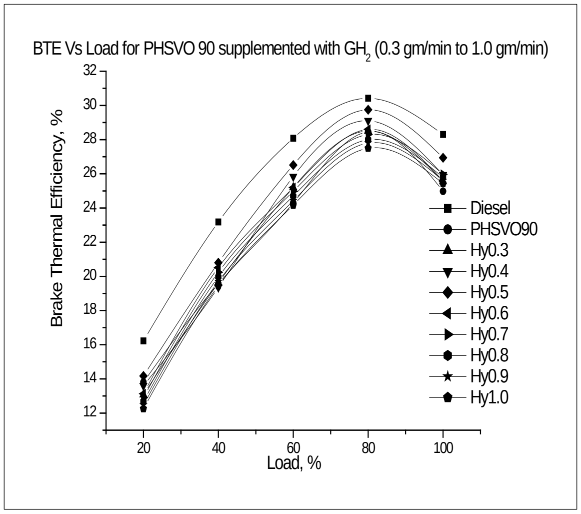

Figure (3): Comparison of BTE for different GH_2 supplemented PHSVO 90 with baseline diesel and pure PHSVO 90

It is observed from the Figure (3) that, inducted Gaseous Hydrogen (GH_2) through inlet manifold shown change in Brake Thermal Efficiency with PHSVO 90 . At part loads , inducted gaseous hydrogen shows inferior performance shown due to lean mixture at part is not sufficient to burn the inducted hydrogen leads to net increase in energy content for given output. As load is increasing, mixture becoming richer and is able to burn the available hydrogen in the combustion chamber for optimum utilization of inducted fuel. With 0.5 gm/min GH_2 supplemented PHSVO 90 at 80% load brake thermal efficiency was raised to 29.7% , which is 1.2% higher than PHSVO 90 and still 0.7% lesser than the conventional diesel. Further, with higher rate of GH_2 supplementation at this 20^0 bTDC injection timing, shown inferior performance due to formation of hydrogen envelop in the combustion chamber makes barrier between injected pilot fuel and inducted air.

4.2. Emissions

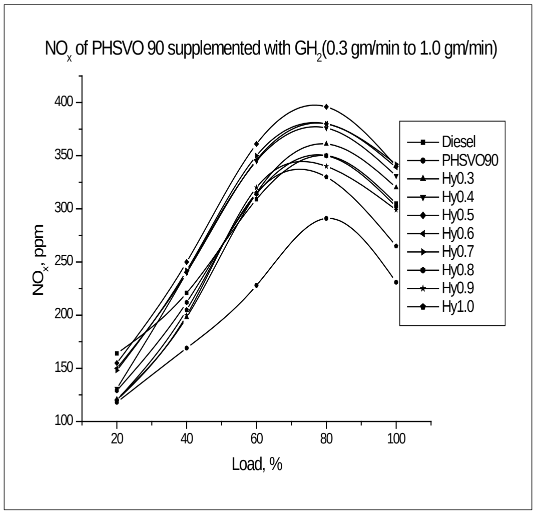

Figure (4): Comparison of NOx for different GH_2 supplemented PHSVO 90 with baseline diesel and pure PHSVO 90

It is seen from the Figure (4). that, NOx was increased with increasing load in all injected and inducted fuels. At part load, increase in NOx was slighter less, because of injected pilot quantity is not sufficient to burn the available injected fuel, by which active participation of GH_2 in the combustion chamber leads to decrease of temperatures leads to reduction of NOx at part loads when comparing to peak loads. At maximum efficiency point, with 0.5 gm/min GH_2 supplemented PHSVO 90, NOx was raised to 396 ppm which is 46 ppm higher than the conventional Diesel and 105 ppm more than the pure PHSVO 90. This is because of enhanced combustion due to high flame speed, high burning velocity, wide flammability of inducted gaseous hydrogen causes rapid heat release rate leads to higher temperature in the combustion chamber, which is a favorable condition for N_2 to oxidize and formation higher NOx. From the above Figure(5), the smoke opacity is increased with load due to increased pilot fuel consumption with increasing load. At 0.5 gm/min GH_2 supplementation with PHSVO 90 smoke was reduced by 7 HSU when comparing to pure PHSVO 90, whereas with conventional diesel it is still 4 HSU higher. This is due to inducted GH_2 reduces the quantity of injected fuel and by which smoke quantity reduces. Further, it is speculated that inducted GH_2 at 0.5 gm/min makes homogeneous mixture that burns more rapidly and the overall mixture contains less carbon from which smoke can form. At higher dosage of GH_2, because of improper combustion, smoke level was slightly increased.

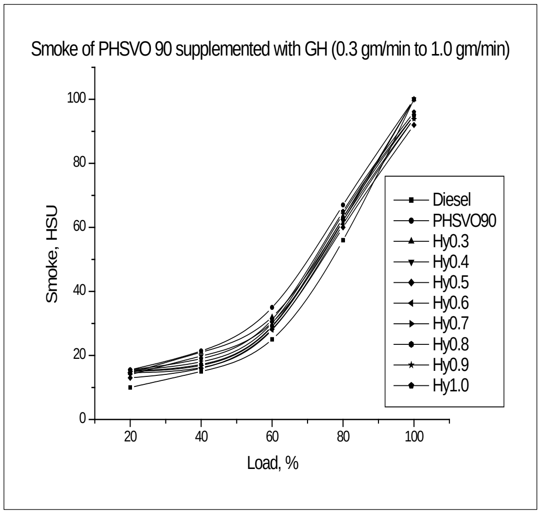

Figure (5): Comparison of Smoke for different GH_2 supplemented PHSVO 90 with baseline diesel and pure PHSVO 90

HC emissions increased with increasing with load as observed in Figure (6)., at 80% load HC for conventional diesel was 10 ppm whereas for pure PHSVO 90 recoded 15 ppm. For supplemented PHSVO 90 at 80% load with GH_2 mass share of 0.5 gm/min HC was reduced by 8 ppm. Which is 2 ppm less than the conventional diesel and 7 ppm less than the pure PHSVO 90. Since, the viscosity and density of vegetable oil is higher than the diesel, spray becomes coarser than the conventional diesel spray leads to poor mixing of pure PHSVO 90 with air as a result of inferior combustion makes HC emissions more in the pure PHSVO 90.

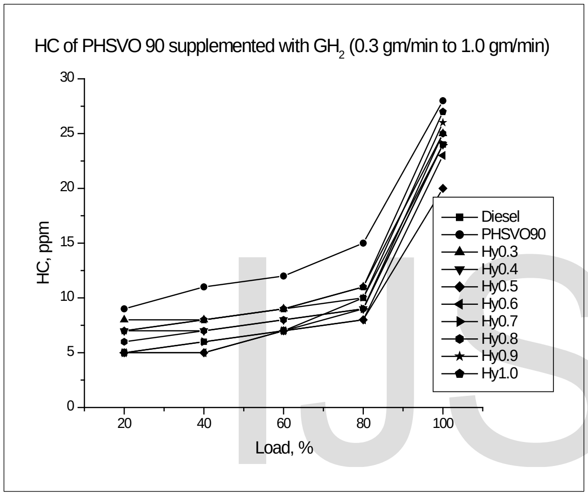

Figure (4): Comparison of HC for different GH_2 supplemented PHSVO 90 with baseline diesel and pure PHSVO 90

Further, burning of GH_2 increases the combustion temperature and presumably leads to more complete oxidation of injected PHSVO 90. However, at higher doses of GH_2 induction makes an envelope, and acts as a barrier between injected fuel and inducted air leads to poor combustion by which HC was slightly increased when comparing to conventional diesel but all over which is less when compared to pure PHSVO 90.

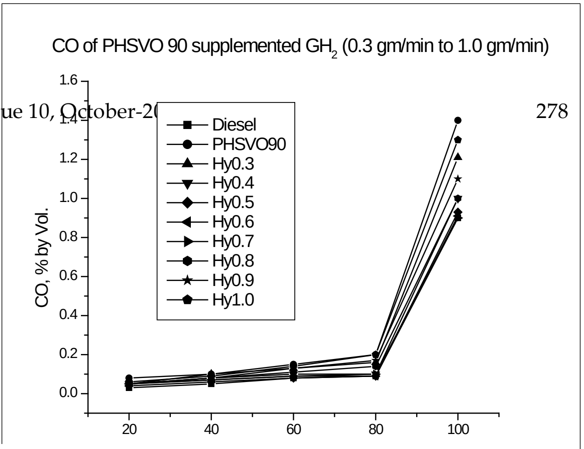

Figure (7): Comparison of CO for different GH_2 supplemented PHSVO 90 with baseline diesel and pure PHSVO 90

It is observed from Figure (7). that, with increasing of load, CO was increased for all fuels starting from conventional diesel to GH_2 supplemented PHSVO 90 including pure PHSVO 90. Further, increase of GH_2 share from 0.3 to 1.0 gm/min , up to 0.7 gm/min as GH_2 share increases CO was reduced. Later doses same was slightly increased because of envelop formation of GH_2, and acts as a barrier between injected fuel and inducted air leads to poor combustion by which HC was slightly increased when comparing to conventional diesel but all over which is less compared to pure PHSVO 90.

4.3. Combustion Parameters

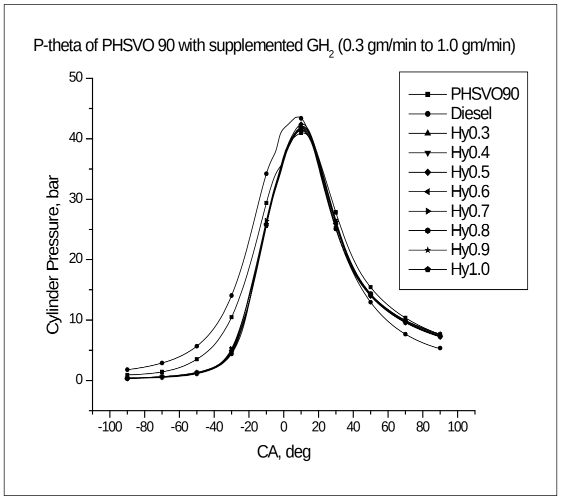

Figure (8): Comparison of P-θ for different GH_2 supplemented PHSVO 90 with baseline diesel and pure PHSVO 90

It was seen from the Figure 8, that, in all doses of GH_2 supplementation with PHSVO 90, Pmax was increased when comparing to pure PHSVO 90 and reaching nearer to conventional Diesel. Further, in the range of 0.4 to 0.7 gm/min shown promising growth when comparing to other GH_2 supplementations. At 80% load, with 0.5 gm/min GH_2 supplementation with pure PHSVO 90 shown 42.45 bar Pmax at 10.5^0 CA, which is 1.47 bar more than pure PHSVO 90 and 1.16 bar less than the conventional Diesel. Further, Pmax was advanced by 0.5^0 CA with this dosage when compared to pure PHSVO 90 and still lagging by 2^0 CA compared to conventional Diesel. This is because of inducted GH_2 is actively participating in the combustion in the range of 0.4 to 0.7 gm/min. But at higher rate dosages, the inducted GH_2 is becoming an envelope during interaction of injected fuel with inducted air and makes inferior combustion. In all dosages of GH_2 supplementations at 20^0 bTDC injection timing at 175 bar injection pressure, pre-mixed combustion phase was increased when comparing to pure PHSVO 90 and conventional Diesel. Further, during diffusion phase a wavy nature was experienced due to GH_2 at 20^0bTDC injection timing , accumulated pilot fuel was not sufficient to burn the GH_2 leads to improper combustion. Rise of this pre-mixed as well as diffusion combustion phases were mostly for lower dosages of GH_2 rather than at higher side. It is because of envelope formation GH_2 during combustion leads to improper combustion, thereby decreasing thee HRR at higher dosages of GH_2 supplemented with pure PHSVO 90 for this engine as shown in Figure (9).

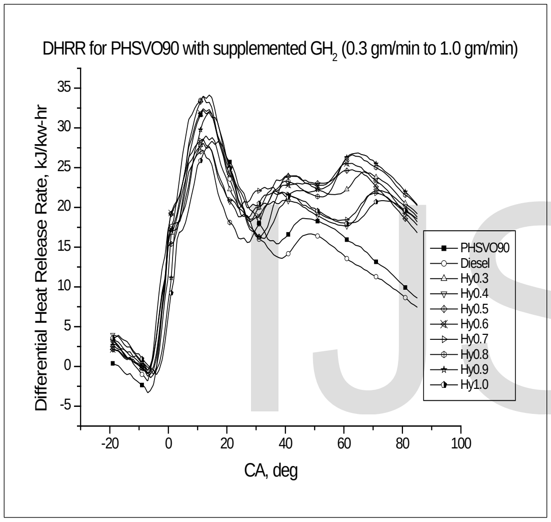

Figure (9): Comparison of DHRR Vs CA for different GH_2 supplemented PHSVO 90 with baseline diesel and pure PHSVO 90

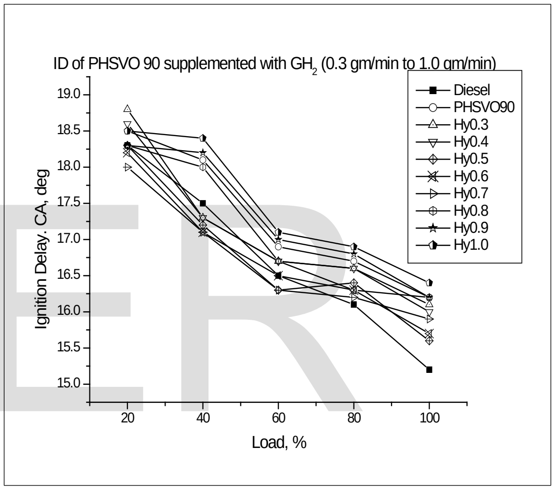

Figure (10): Comparison of Ignition Delay Vs CA for different GH_2 supplemented PHSVO 90 with baseline diesel and pure PHSVO 90

It is observed that, from the Figure (10)., as the load increases ignition delay decreases, further, increasing of GH_2 mass share up to 0.7 gm/min ignition delay was decreased and later slightly increased. After 0.7 gm/min the inducted GH_2 becoming an envelope with air and not allowing to properly burn the pilot fuel on time leads to deteriorating the combustion caused by reduction in combustion temperatures by that ignition delay is increasing. The ignition delay of conventional diesel at maximum efficiency point is 16.01 CA deg., whereas for PHSVO 90 this was raised to 16.7 CA deg., because of increase in its physical delay due to viscous and denser vegetable oil which in turn get effects the fuel atomization, vaporization and mixing with air. However, at 0.5 gm/min GH_2 share with PHSVO 90 the same ignition delay was reduced to 16.4 CA deg., because of involved chemical processes consists of pre-combustion reactions in the mixture of air, GH_2 and pilot fuel, which is lesser than pure PHSVO 90 by 0.3 CA deg., and still 0.39 CA deg. more than the conventional diesel.

5.0 Conclusion

It was observed that, in the given band of GH_2 ranging from 0.3 to 1.0 gm/min with an increment of 0.1 gm/min at engine manufacturer recommended 20^0 bTDC injection timing and 175 bar injection pressure of a 4 stroke, compression ignition, water cooled, single cylinder IDI, 7.4 kW engine designed and optimized for conventional diesel that, pure PHSVO 90 shown some inferior performance comparing to conventional diesel fuel because of increase in its physical delay due to viscous and denser vegetable oil which in turn get effects the fuel atomization , vaporization and mixing with air resulting poor combustion leads to inferior performance and increase in emissions. When GH_2 is supplemented with pure PHSVO 90, a promisable change noticed in the band of 0.4 to 0.7 gm/min mass shares. Further, at 0.5 gm/min GH_2 (5% of total energy contributed by pilot fuel) supplemented with pure PHSVO 90, shown a very good response among other the other identified GH_2 range when compared to pure PHSVO 90.

1. Brake thermal efficiency was raised to 29.7% , which is 1.2% higher than pure PHSVO 90 and still 0.7% lesser than the conventional diesel.
2. NOx was raised to 396 ppm which is 46 ppm higher than the conventional Diesel and 105 ppm more than the pure PHSVO 90. This is because of enhanced combustion due to high flame speed, high burning velocity, wide flammability causes rapid heat release rate leads to higher temperature in the combustion chamber, which is a favorable condition for N_2 to oxidize and formation higher NOx.
3. Smoke was reduced to 60 HSU which is 7 HSU lower when comparing to pure PHSVO 90. Whereas with conventional diesel it is still 4 HSU higher. This is due to inducted GH_2 reduces the quantity of injected fuel and by which smoke quantity reduces. Further, it is speculated that, inducted GH_2 at 0.5 gm/min and even up to 0.7 gm/min makes homogeneous mixture that burns more rapidly and the overall mixture contains less carbon from which smoke can form. At higher dosage of GH_2, because of improper combustion, smoke level was slightly increased.
4. At 80% load HC for conventional diesel was 10 ppm whereas for pure PHSVO 90 recorded as 15 ppm. For supplemented PHSVO 90 at 80% load with GH_2 mass share of 0.5 gm/min HC

was reduced to 8 ppm. Which is 2 ppm less than the conventional diesel and 7 ppm less than the pure PHSVO 90. Since, the viscosity and density of vegetable oil is higher than the diesel, spray becomes coarser than the conventional diesel spray leads to poor mixing of pure PHSVO 90 with air as a result of inferior combustion makes HC emissions more in the pure PHSVO 90. Whereas in dual fuel engine as engine inducts the GH_2 through the inlet manifold, there is no carbon associated with inducted fuel makes the homogeneous mixture with PHSVO 90 and air leads to better combustion reduces the smoke emissions.

5. CO was reduced to 0.09 % by volume, which is 0.11% by volume lesser than the pure PHSVO 90 and equal to the conventional diesel.
6. At 80% load, with 0.5 gm/min GH_2 supplementation with pure PHSVO 90 shown 42.45 bar Pmax at 10.5^0 CA, which is 1.47 bar more than pure PHSVO 90 and 1.16 bar less than the conventional Diesel. Further, Pmax was advanced by 0.5^0 CA with this dosage when compared to pure PHSVO 90 and still lagging by 2^0 CA compared to conventional Diesel. This is because of inducted GH_2 is actively participating in the combustion
7. In all dosages of GH_2 supplementations at 20^0 bTDC injection timing at 175 bar injection pressure, pre-mixed combustion phase was increased when comparing to pure PHSVO 90 and conventional Diesel. Further, during diffusion phase a wavy nature was experienced because of GH_2 participation. This is because at 20^0 bTDC injection timing, accumulated pilot fuel was not sufficient to burn the GH_2 there by inferiority shown .Rise of this pre-mixed as well as diffusion combustion phases were mostly for lower dosages of GH_2 rather than at higher side. It is because , at higher doses of GH_2 leads to formation of envelope during combustion leads to improper combustion, thereby decreasing the Heat Release Rate at higher dosages of GH_2 supplemented with pure PHSVO 90 for this engine.
8. The ignition delay of conventional diesel at maximum efficiency point is 16.01 CA deg., whereas for PHSVO 90 this was raised to 16.7 CA deg., because of increase in its physical delay due to viscous and denser vegetable oil which in turn get effects the fuel atomization, vaporization and mixing with air. However, at 0.5 gm/min GH_2 share with PHSVO 90 the same ignition delay was reduced to 16.4 CA deg., because of involved chemical processes consists of pre-combustion reactions in the mixture of air, GH_2 and pilot fuel, which is lesser than pure PHSVO 90 by 0.3 CA deg., and still 0.39 CA deg., more than the conventional diesel.

From the above results, it was observed that, inducted small doses gaseous hydrogen have very good compatibility with injected pilot fuel, PHSVO 90, thereby thermal efficiency increased and smoke. CO, HC were reduced. Further engine variable like advancement of injection timing and increase of injection pressure may further enhances the performance of the engine. For this unmodified engine, 0.5 gm/min at 80% load is the optimized GH_2 supplementation.

Acknowledgement

Authors would like to thank UPES for the encouragement and the Ministry of New and Renewable Energy (MNRE), Government of India, New Delhi, for their support in sponsoring the project to work on "Performance Enhancement, Evaluation and Analysis of an IDI Diesel Engine Using Straight Vegetable Oil (SVO) with Hydrogen Supplementation".

Project Sanction Letter No.103/143/2008-NT, Dt: 12/01/2011 of MNRE, Govt. of India, New Delhi.

References

1. Bernat Esteban et.al., " Is it environmentally advantageous to use vegetable oil directly as biofuel instead of converting it to bio diesel?", Biomass & Bio Energy, 35, 2011, pp 1317-1328.
2. P.S.Ranjit & Mukesh Saxena " A Review on hydrogen utilization in Internal Combustion Compression Ignition Engines", International Journal of Science, Technology and Management (IJSTM)", Vol.3, Issue 2, Sept. 2012, pp.1-21, ISSN: 2229-6646.
3. P.S.Ranjit & Mukesh Saxena " Prospects of Hydrogen utilization in Compression Ignition Engines- A Review", International Journal of Scientific Research (IJSR), Volume 2, Issue 2, February 2013, pp. 137-140, ISSN: 2277-8179.
4. P.S.Ranjit & Mukesh Saxena " State-of-the-art of Storage and Handling issues related to High Pressure Gaseous Hydrogen to make use in Internal Combustion engines", International Journal of Scientific & Engineering Research (IJSER), Vol.3, Issue 9, Sept. 2012, pp.1-17, ISSN: 2229-5518.
5. Y.D. Wang et.al., " An Experimental Investigation of Performance and Gaseous exhaust Emissions of a diesel engine using blends of a vegetable oil", Applied Thermal Engineering, 26, (2006), 1684-1691
6. R.D. Misra and M.S. Murthy, " Straight Vegetable Oil usage in a Compression Ignition Engine – A Review" Renewable and Sustainable Energy Reviews", 14, (2010), 3305-3013.
7. B. HaraGopala Rao, K. N. Shrivastava and H.N. Bhakta, "Hydrogen for dual fuel engine operation", International Journal of Hydrogen Energy, Vol.8, No.5, pp.381-384, 1983.
8. H. B. Mathur, et.al., " Hydrogen fueled Diesel engine: performance Improvement through charge dilution techniques: International Journal of Hydrogen Energy, Vol.18, No.5, pp.421-431, 1993.
9. J.D. Naber and D.L. Siebers, " Hydrogen combustion under diesel engine conditions", International Journal of Hydrogen Energy,Vol.23, No.5, pp.363-371, 1998.
10. M. Senthil Kumar, A. Ramesh and B. Nagalingam, " Use of Hydrogen to enhance the performance of a vegetable oil fuelledcompression ignition engine", International Journal of Hydrogen Energy, Vol.28, pp.1143-1154, 2003.
11. N. Saravanan, G.Nagarajan et.al., "Experimental Investigation ofHydrogen Port fuel injection in Direct Injection Diesel Engine", International Journal of Hydrogen Energy, Vol.32, pp.4071-4080, 2007.

12. J.M. Gomes Antunes et.al., “An Experimental Study of a direct injection compression Ignition Hydrogen engine”, International Journal of Hydrogen Energy, Vol.34, pp.6516-6522, 2009.
13. V. Edwin Geo, G. Nagarajan, B. Nagalingam, “ Studies on dual fuel operation of rubber seed oil and its biodiesel with hydrogen as the inducted fuel, International Journal of Hydrogen Energy, Vol.33, pp.6357-6367, 2008.
14. AVL make Pressure Sensor for Combustion Analysis, Data Sheet, GH15DK, TIGG1383A.01, May 2011, AT377E, Rev.01, AVL List GmbH, Headquarters, Graz- Austria.
15. AVL make Angle Encoder, 365CC/ 365X, Product Guide, Feb. 2007, AT2041E, Rev.03, AVL List GmbH, Headquarters, Graz- Austria.
16. AVL make AVL INDISMART 612, Product Guide, August 2009, AT3042E, Rev.00, AVL List GmbH, Headquarters, Graz- Austria.