Experimental Investigation of Hydrogen Enrichment on Performance and Emission Behaviour of Compression Ignition Engine

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Abstract

Continuous induction of hydrogen in compression ignition engine offers an advantage of proper mixing with air results in proper combustion. In the present study hydrogen at the constant flow rate of 4 1pm was inducted in the intake, a distance of 40 cm from the intake manifold, along with air. Two different fuels, one i.e. 40% blend of used transformer oil (UTO 40) and 60% diesel fuel and the second was neat Used transformer oil (UTO 100) were tested as main fuels in single cylinder, 4-stroke, air cooled direct injection diesel engine developing a power of 4.4 KW, rated speed of 1500 rpm. The performance and emission parameters of the engine were obtained in the investigation and compared with the diesel fuel are presented in this paper

Keywords: Used Transformer Oil, Diesel fuel, Hydrogen, Diesel engine, Performance, emission.

1. Introduction

The present energy situation has stimulated active research interest in non-petroleum, renewable and non-polluting fuels.

Much of the present world‟s energy demand may still be supplied by exhaustible fossil fuels (natural gas, oil and coal), whic h are also the material basis for the chemical industry. It is well known that combustion of fossil fuel causes air pollution in cities and acid rains which damages forests, and leads to the build up of carbon dioxide, changing the heat balance of earth. In recent years, the concern for cleaner air, along with stricter air pollution regulation and the desire to reduce the dependency on fossil fuels have rekindled the interest in hydrogen as an automobile (vehicular) fuel. Hydrogen has been considered for many years as an alternative fuel of future to replace the fuels derived from the rapidly depleting petroleum resources.

Generally, the arguments for and against hydrogen as an alternative fuel is based on some of its characteristics rather than on its Overall characteristics. Clean burning and rapid recycling Characteristics are on the positive side and the explosive characteristics are on the other side. With this concept Hydrogen is expected to be the future fuel for the internal combustion engines. Therefore attempts have been made to utilize hydrogen in the compression ignition engine. But, hydrogen cannot be used as a sole fuel in compression ignition engine because of its high self ignition temperature (858k); therefore some other liquid fuel is used as a main fuel. In this investigation, the aim is to eliminate the use of diesel fuel from the fuel tank. Therefore two different fuels, i.e., one 40% blend of used transformer oil (UTO 40) and 60% diesel fuel and the second one was neat transformer oil(UTO 100) were tested as a main fuels while hydrogen was inducted by mixing with air into the engine.

Transformer oils are an important class of insulating oils. They act as heat transfer medium so that the operating temperature of a transformer does not exceed the specific acceptable limits. Transformer oils have negligible amounts of contaminants which have adverse effects on the electrical properties [1]. In general, transformer oils are produced from wax-free naphthenic oils.

Although these types of crudes permit production of exceptionally low pour point insulating oils without the need for dew axing or special attention to the degree of fractionation or distillate cut width, they also contain high percentages of sulphur and nitrogen which must be removed in order to satisfy the stringent stability Requirements of insulating oils [2]. It has been found that a highly aromatic, low paraffinic content naphthenic crude oil is a suitable raw material to prepare good transformer oil. Transformer oil is used for cooling purpose and after its application it is thrown out in the form of waste. But after testing the waste transformer oil it has been seen that the Property of waste transformer oil is nearly same as that of diesel. The waste transformer oil is taken to filtration we often that the "Property after treatment". So attempts have been made to eliminate the diesel fuel and tried to utilize the waste transformer oil in the engine.

Recently, experiments have been carried out to use used transformer oil –diesel fuel blends as a fuel in a single cylinder, four strokes, air cooled, direct injection compression ignition engine. Due to high viscosity of used transformer oil, the blending of used transformer oil and diesel fuels was tested as a fuel. The used transformer oil-diesel blends of 10%, 20%, 30%, 40%, 50%, 60%and sole used transformer oil i.e. UTO 100% was used as alternative fuels [3].Results indicated that the UTO 40 as the most acceptable blend among all the tested blends. But while using the sole used transformer oil (UTO 100), the engine was not able to run satisfactorily. So it was expected that by inducting hydrogen, due to its high energy, engine will be able to run with UTO 100. The various properties of used transformer oil are shown in the table 1.

Table 1. Various properties of UTO and their blends

Property	UTO	UTO40
Sp.Gravity at, 27 °C	0.830	0.866
Kinematic Viscosity, cst@ 27°C	13	7.3
Gross Calorific Value KJ/kg	39120	41928
Flash Point, °C	150	90
Fire Point, °C	172	102.4
Sulphur Content, %	0.020	0.035
Ash Content, %	NIL	.00
Carbon Residue, %	0.020	0.029

Therefore in this present study, by knowing the fact that, hydrogen cannot be introduced as a sole fuel in diesel engine, attempts have been made to use the hydrogen gas as a secondary fuel and UTO 40 and UTO 100 as the main fuel. UTO 40 represents the 40%used transformer oil blended with 60 %diesel fuel and UTO 100 represents 100 % waste transformer oil.

2. Use of hydrogen in compression ignition engine.

It is not a difficult task to use hydrogen as a sole fuel in a petrol engine, but in the case of a diesel engine, since the auto ignition temperature of hydrogen is about 858K, it is not possible to achieve the ignition of hydrogen by compression alone [4]. Researchers from Cornell university failed to get the ignition temperature of hydrogen at a compression ratio of 29 [5].

3. Experimental Setup and Procedure

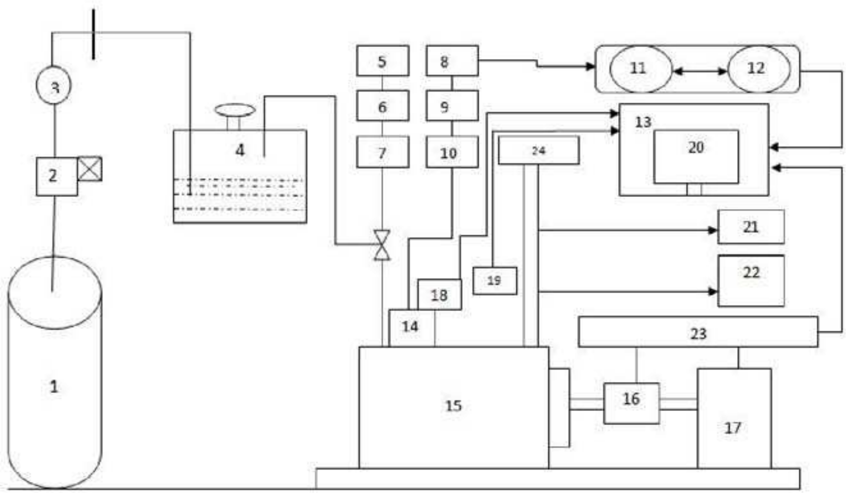
The schematic diagram of the experimental setup is shown in fig 1. And the engine specification is given in table 2. The engine used for the present investigation is a single cylinder four stroke air cooled diesel engine. Initially the engine was operated with neat diesel and the performance, emission parameters were evaluated. Then the engine was allowed to run with UTO 40 and UTO 100 respectively without hydrogen. Again the performance, emission parameters were evaluated. Now for the third test, hydrogen gas is introduced by considering first UTO 40 as a main fuel and then UTO 100 as a main fuel.

Table 2. Test engine specification

Make	Kirloskar
Type of Engines	4-stroke cycle, single cylinder, compression ignition engine
Speed	1500 rpm
Bore	87.5
Stroke	110
Compression ratio	17.5
Method of cooling	Air cooled with radial fan
Injection timing	
Nozzle opening pressure	200-205 Kg/cm^2

Hydrogen fuel from a high pressure cylinder was inducted through an intake pipe. A double stage diffusion pressure regulator was employed over the high pressure cylinder. The regulator is used to control the outlet pressure. Hydrogen fuel, at a pressure of 2 bars and a constant flow rate of 4 lpm is then supplied to the flame arrester and flame trap and finally to the intake pipe (a distance of 40 cm from the intake manifold) where it mixes with air and finally, this hydrogen- air mixture gets inducted into the engine cylinder [20].

Experimental setup is shown in fig 1.



1. Hydrogen Cylinder
2. Pressure Regulator
3. Flashback arrester
4. Flame Trap
5. Air filter
6. Air box
7. Airflow sensor
8. Fuel tank
9. Fuel filter
10. Fuel pump
11. Fuel sensor
12. Burette
13. DAS
14. Injector
15. Engine
16. Alternator
17. Dynamometer
18. Injection pressure sensor
19. Combustion pressure sensor
20. Laptop
21. Exhaust gas Analyzer
22. Smoke meter
23. control panel
24. To exhaust

Used transformer oil of 40% blended with 60% diesel fuel (UTO 40) on volume basis is introduced from the fuel tank into the engine cylinder by direct injection. Then engine is allowed to run for different loads. The same procedure is adopted by considering 100% waste transformer oil as a main fuel with hydrogen flow rate of 4 lpm

Performance and combustion parameter is obtained by computer provided into data acquisition system. AVL exhaust gas analyzer is used to calculate the emission Parameter whereas smoke meter is used to get smoke values. Combustion diagnosis was carried out by means of a Kistler make quartz piezoelectric pressure transducer (Model Type 5395A) mounted on the cylinder head in the standard position. Hydrogen was allowed to pass through the flame trap used to suppress the flashback if any in the intake manifold. The flame trap was made of mild steel iron to suppress the flame and water to put off the flame. The hydrogen from the flame trap was sent into the inlet manifold to mix it with the air. The process of mixing the inlet air and fuel is called as enrichment. Thus by keeping the flow of hydrogen as 4 lpm [6]

4. Results and Discussion

4.1. Performance Parameter

In the present work, hydrogen gas – air mixture is used for compression ignition engine where UTO 40, UTO 100 is used as a main fuel for duel fuel mode operation. The performance and emission characteristics of UTO 40 with and without hydrogen, UTO 100 with and without hydrogen are compared with baseline diesel operation. For dual fuel operation, hydrogen fuel, at a constant flow rate of 4 lpm were supplied through a flame arrester and flame trap and finally it was admitted into the intake pipe (at a distance of 40 cm from the intake manifold) where it mixed with air and this hydrogen-air mixture was inducted into the engine cylinder [20].

4.1.1. Brake Thermal Efficiency

The variation of brake thermal efficiency with brake power is shown in fig 2.The brake thermal efficiency for hydrogen with UTO 40 is 42.14% at full load with a flow rate of hydrogen is 4lpm. Whereas that of UTO 40 is 32.01% and that of baseline diesel is 28.64%. UTO 100 exhibits the brake thermal efficiency of 31.72% at full load, and that is increase after supplying hydrogen to 38.91%.Higher brake thermal efficiency is due to better mixing of hydrogen with air which results in better combustion and also due to wider ignition limit and high burning velocity [7].

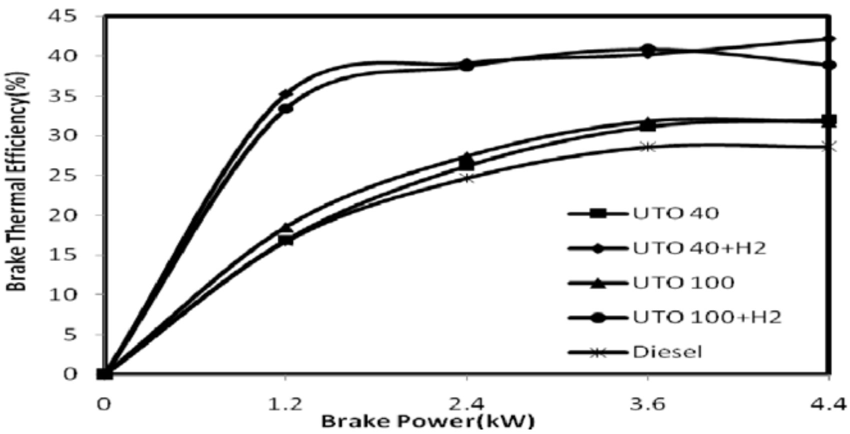


Fig 2. Variation of brake thermal efficiency with brake power

4.1.2 Brake specific energy consumption

Fig 3. Shows the variation of brake specific energy consumption with the brake power. The specific energy consumption of UTO 40 and UTO 100 with hydrogen induction is found to be lower compared to UTO 40 ,UTO 100 without hydrogen and baselinr diesel fuel.

The lower specific energy consumption is due to the better mixing of hydrogen with air, results in complete combustion of the fuel[17]. The specific energy consumptoin of UTO 40 with hydrogen is found to be 11.2443MJ/KW-hr which is lower compared to 8.5411 MJ/KW –hr for UTO 40 without hydrogen at full load. The diesel shows the maximum energy consumption at all the loads.

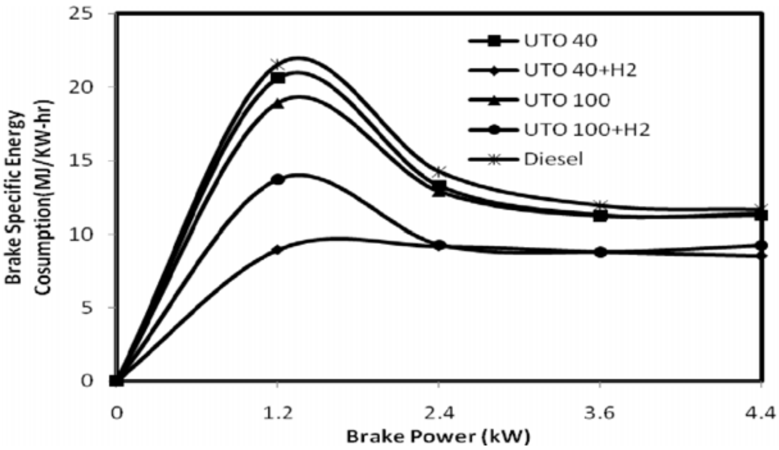


Fig 3. Variation of brake specific energy consumption with brake power

4.1.3 Exhaust gas temperature

The variation of exhaust gas temperature with brake power is shown in fig 4. The exhaust gas temperature of UTO 40 with hydrogen is 365^0C at full load while that of UTO 40 is 325^0C and that of diesel is 269.54^0C while the exhaust gas temperature of UTO 100 with hydrogen is 375^0C at full load while that of UTO 100 is 361^0C. The exhaust gas temperature of UTO 100 with hydrogen is more compared to UTO 40 with and without hydrogen and also with baseline diesel. The reason is may be due to high auto ignition temperature of hydrogen. It requires high temperature to ignite. Therefore the residence time is more for the hydrogen. The high viscosity and more residence time are Responsible for increase in exhaust gas temperature [16]. Due to this the heat that is generated due to the compression stroke gets shifted its direction toward the exhaust side and increases the exhaust gas temperature.

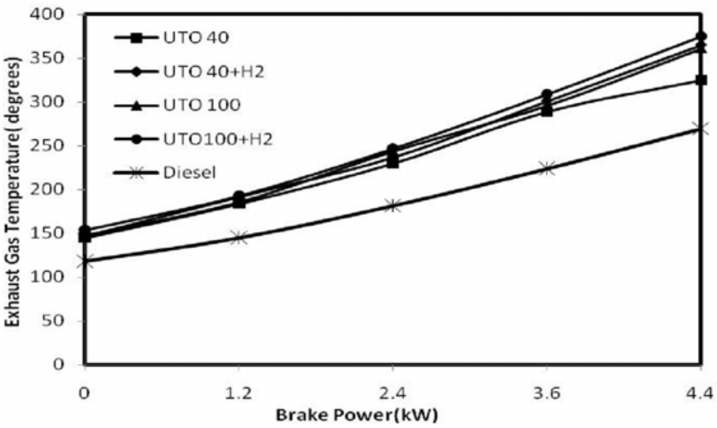


Fig 4. Variation of exhaust gas temperature with brake power

4.2. Emission Parameter

4.2.1. CO Emission

The variation of Carbon monoxide with brake power is given in the fig. 5. The carbon monoxide emission of UTO 40 and UTO 100 with hydrogen is lower compared to baseline diesel and UTO 40 and UTO 100 without hydrogen..The carbon monoxide emission is lower may be due to the absence of carbon atoms present in the hydrogen structure [7]. Some CO emissions are present because of the combustion of lubricating oil and also due to the carbon present in the structure of UTO 40 and UTO 100.

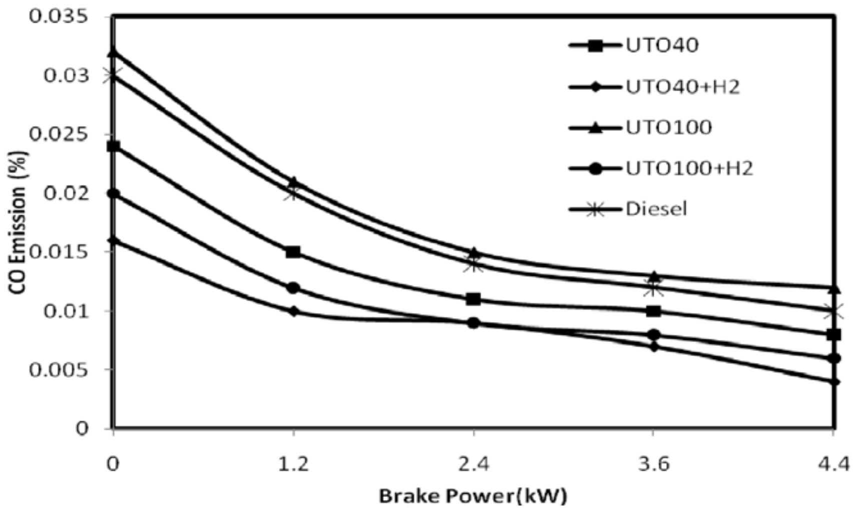


Fig 5. Variation of CO emission with brake power

4.2.2. HC Emission

Fig 6. Shows the variation of hydrocarbon emission with brake power. The HC emission is lower for UTO 40 and UTO 100 with hydrogen compared with the other fuels without hydrogen and baseline diesel. The HC emission of UTO 40 with hydrogen is about 3ppm at full load compared to diesel 5.6 ppm while UTO 100 with hydrogen exhibits 4.8 ppm at full load. UTO 40 and UTO 100 without hydrogen shows more unburnt hydrocarbon emission and this value gets lowered after supplying hydrogen fuel. The reason is due to the absence of carbon in hydrogen and also because of high cylinder temperature the carbon particles, present in lubricating oil and main fuel, gets oxidizes and converted into CO_2[15].

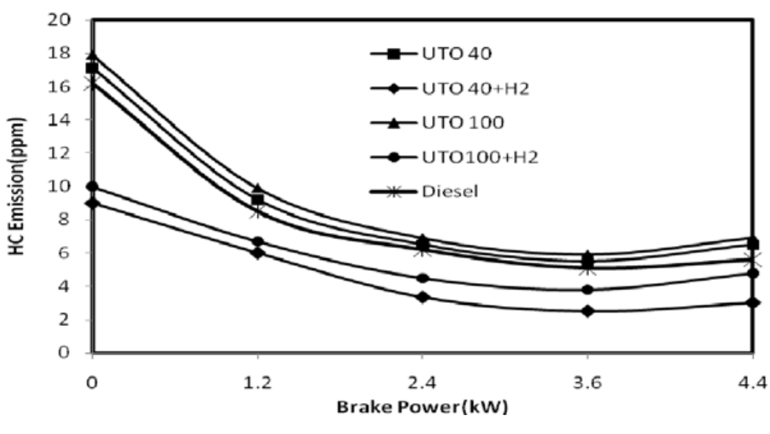


Fig 6. Variation of HC emission with brake power

4.2.3. CO_2 Emission

The variation of carbon dioxide with brake power is shown in fig 7. As due to high temperature achieved during combustion of hydrogen, the CO get oxidized and converted into CO_2. Therefore the carbon dioxide emission increases with increase in load but very less compared to UTO 40 and UTO 100 without hydrogen and diesel. The CO_2 emission was low because of less carbon present in hydrogen fuelled mixture [7]. At full load the carbon dioxide emission is 1.3% for UTO 40 with hydrogen and 1.4% for UTO 100 with hydrogen while that of UTO 40 and UTO 100 without hydrogen shows 2% and 1.8% CO emission respectively and that of diesel is 1.7% at full load.

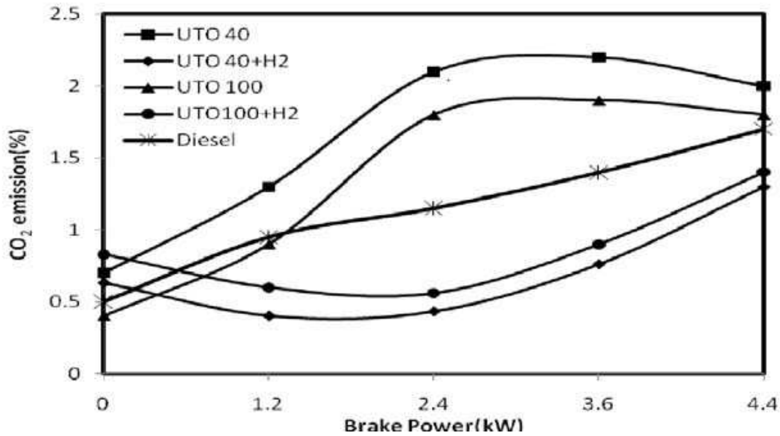


Fig 7. Variation of CO_2 emission with brake power

4.2.4. NO_x Emission.

Oxides of nitrogen which occur in the engine exhaust are a combination of nitric oxide (NO) and nitrogen dioxide (NO_2). The Variation of NO emission with brake power is shown in fig 8. The NO emission of UTO 100 and UTO 40 with hydrogen is found to be higher compared to UTO 100 and UTO 40 without hydrogen and also baseline diesel. The reason is due to the high viscosity, availability of oxygen and more residence time associated when hydrogen is supplied. Due to high auto ignition temperature of hydrogen, it takes more time to ignite. Therefore the phenomenon called rapid combustion takes place which contribute to increase the inside cylinder temperature. More the inside cylinder temperature, the NO emission will be more. Also the availability of oxygen in UTO 100 and UTO 40 is another factor for NO emission

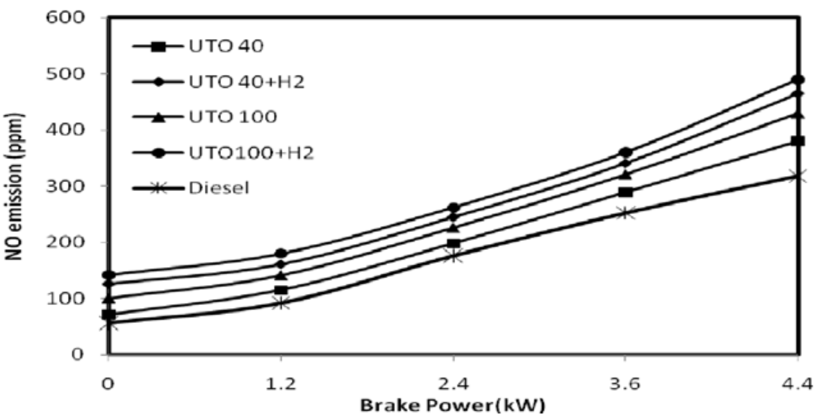


Fig 8. Variation of NO emission with brake power

Nitrogen and oxygen react at relatively higher temperatures. Therefore, high temperature and oxygen Availability are the two main reasons for the NO emission. When the proper amount of oxygen is available the higher the peak combustion temperature the more is the NO formed. The NO_x is formed in the atmosphere as NO oxidizes [8]. The UTO 100 with hydrogen shows more NO emission of 490 ppm at full load while UTO 40 with hydrogen is found to be 465 ppm. The baseline diesel shows lower NO emission of about 318 ppm. The NO emission of UTO 40 and UTO 100 without hydrogen was found to be 380 ppm and 430 ppm respectively at full load. The high NO formation of UTO 40 and UTO 100 with hydrogen can be reduced by adopting exhaust gas recirculation technique or by adding some charge diluents like helium, water, nitrogen etc.

4.2.5. Smoke Emission

The variation of smoke intensity with brake power is shown in fig 9. Sole used transformer oil shows higher smoke emission due to coarse spray formation and poor mixing with air [16]. At full load the smoke emission for UTO 100 was found to be 25.5 BSU (Bosch Smoke Units) which is much higher than diesel 19.2 BSU at full load. UTO 40 shows 18.1 BSU. However smoke emission was reduced after supplying hydrogen.

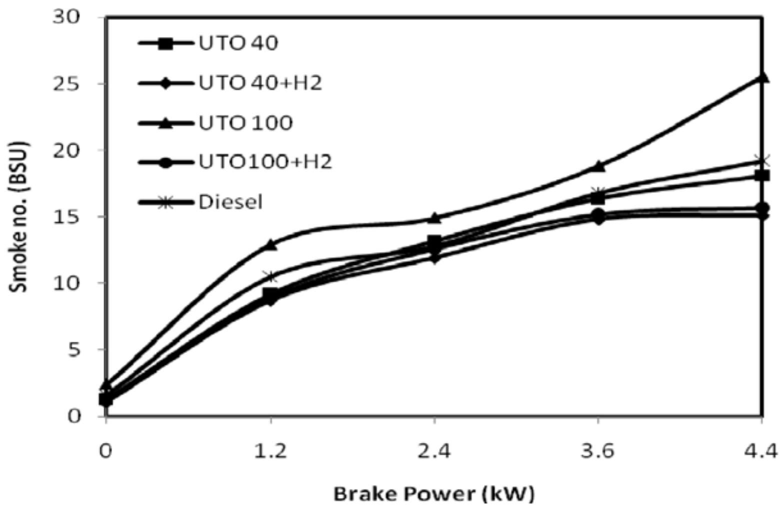


Fig 9. Variation of smoke density with brake power

UTO 40 in addition of hydrogen shows lower smoke emission of 15.1 BSU at full load while UTO 100 shows 15.7 BSU. The reduction in smoke emission after inducting hydrogen is because the combustion of hydrogen does not contribute to the formation of smoke due to the absence of carbon in hydrogen. The proper mixing of hydrogen and air improves the combustion of used transformer oil and their blends with diesel and reduced the smoke intensity. It was found that at all the loads the smoke density was lower in case of hydrogen enrichment.

5. Conclusion

A single cylinder, four stoke, air cooled direct injection compression ignition engine was operated successfully using hydrogen gas, supplying at a flow rate of 4 lpm and inducting at a distance of 40 cm from the intake manifold. The performance and emission parameters of the engine using UTO 40 and UTO 100 as a main fuel, with and without hydrogen enrichment were obtained in the investigation and compared with the diesel fuel are presented in this paper.

1. The brake thermal efficiency for both the main fuel enriched with hydrogen was found to be high because of proper combustion and high burning velocity. The brake thermal efficiency for hydrogen with UTO 40 is 42.14% at full load with a flow rate of hydrogen is 4lpm, where as that of UTO 40 are 32.01% and that of baseline diesel is 28.64%. UTO 100 exhibits the brake thermal efficiency of 31.72% at full load while that of UTO 100 with hydrogen addition was 38.91 %.

2. The brake specific energy consumption of UTO 40 and UTO 100 with hydrogen induction was found to be lower compared to UTO 40 and UTO 100 without hydrogen and baseline diesel fuel due to better mixing of hydrogen with air,results in complete combustion of the fuel.

3. The exhaust gas temperature of UTO 40 with hydrogen is 365^0C at full load while that of UTO 40 is 325^0C and that of diesel is 269.54^0C while the exhaust gas temperature of UTO 100 with hydrogen is 375^0C at full load while that of UTO 100 is 361^0C . The exhaust gas temperature of UTO 100 with hydrogen is more compared to UTO 40 with and without hydrogen and also with baseline diesel because of more residence time and high viscosity of UTO 100.

4. The carbon monoxide emission of UTO 40 and UTO 100 with hydrogen enrichment was lower compared to baseline diesel and UTO 40 and UTO 100 without hydrogen due to the absence of carbon atoms present in the hydrogen structure.

5. The HC emission is lower for UTO 40 and UTO 100 with hydrogen enrichment was found to be lower compared with the UTO and UTO 100 without hydrogen and baseline diesel.

6. The carbon dioxide emission increases with increase in load but very less compared to UTO 40 and UTO 100 without hydrogen and diesel. The CO_2 emission was low because of less carbon present in hydrogen fuelled mixture. At full load the carbon dioxide emission was 1.3% for UTO 40 with hydrogen and 1.4% for UTO 100 with hydrogen while that of UTO 40 and UTO 100 without hydrogen was found to be 2% and 1.8% CO emission respectively and that of diesel was 1.7% at full load.

7. The NO emission of UTO 100 and UTO 40 with hydrogen is found to be higher compared to UTO 100 and UTO 40 without hydrogen and also baseline diesel. The reason is due to the high viscosity, availability of oxygen and more residence time associated when hydrogen is supplied.

8. Smoke emission was reduced after supplying hydrogen.

6. Acknowledgement:

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7. References

[1] G.L. Goedde, A.P. Yerges, Dielectric Fluid for Use in Power Distribution Equipment US Patent 5,766,517, 1998.
[2] L.E. Reid, D.A. Gudelis, Low Pour Point Transformer Oils from Paraffinic Crudes, US Patent 4, 018, 666, and 1977.
[3] P.Behera, S.Murugan,"combustion, performance, and emission parameters of used transformer oil and its diesel blends in a DI diesel engine", Fuel manuscript no: JFUE-D-11-00382,2011.
[4] L.M.Das," Hydrogen Engines: R&D programmes in IIT Delhi", Int J Hydrogen Energy, Vol 27, pp 953-965, 2002.
[5] H S Homan,"An experimental study of reciprocating internal combustion engine operated on hydrogen", PhD. Thesis Cornell University, 1978.
[6] Gandhi pullagura,"" Effect of hydrogen enrichment on the combustion characteristics of a bio-fuel diesel engine"" IOSRJEN *ISSN: 2250-3021* Vol. 2 Issue 1, Jan.2012, pp. 001-006.
[7] N. Saravanan, G.Nagarajan, S. Narayanswamy,"An experimental investigation of DI diesel engine with hydrogen fuel", Renewable Energy 33, pp 415-421, 2008.
[8] N.Saravanan, G.Nagarajan, K.M.Kalaiselvan, C.Dhanasekaran,"An experimental investigation on hydrogen as a dual fuel for engine system with exhaust gas recirculation technique" Renewable Energy 33, pp 422-427, 2008.
[9] N. Saravanan, G. Nagarajan, "Performance and emission studies on port injection of hydrogen with varied flow rates with diesel as an ignition source", Applied Energy,Vol.87,pp 2218-2229,2010.
[10] N. Saravanan, G. Nagarajan, G. Sanjay, C. Dhanasekaran, K.M. Kalaiselvan, "Combustion analysis on a DI diesel engine with hydrogen in dual fuel mode", Fuel 87,pp 3591-3599, 2008.
[11] J.Nazar,A.Ramesh and B.Nagalingam,"Experimental investigation on the performance of karanja oil-hydrogen dual fuel engine".Proceedings of the 19th National Conference on I.C. Engines and Combustion, Annamalai University,Chidambaram, pp 131-136, 2005.
[12] G.Sankaranarayanan,J.Jayaraj,N.Saravanan,K.Jeyachandran,"Performance and emission studies on DI diesel engine using madhuca indica oil and hydrogen as dual fuel", Proceedings of the 19th National Conference on I.C. Engines and Combustion, Annamalai university,Chidambaram, pp 83-86, 2005.
[13] T. Lakshmanan, G.Nagarajan,"Experimental Investigation on dual fuel operation of acetylene in a DI diesel engine" , Fuel processing technology, Vol 91,pp 496-503,2010.
[14] T.Lakshmanan and G.Nagarajan,"Experimental investigation of timed manifold injection of acetylene in direct injection diesel engine in dual fuel mode", Energy, Vol 35, pp 3172-3178.
[15] Seung Hyun Yoon and Chang Sik Lee," Experimental investigation on the combustion and exhaust emission characteristics of bio gas – biodiesel dual – fuel combustion in a CI engine", Fuel Processing Technology, pp 1-9, 2011.
[16] M.Senthil Kumar, A.Ramesh and B.Nagalingam," Complete vegetable oil fuelled dual fuel compression ignition engine", SAE 2001-28-0067.
[17] Siebers DL, "Hydrogen combustion under diesel engine conditions" Hydrogen energy 1998,23,pp 363-71.
[18] Shudo T, "Thermal efficiency analysis in a hydrogen premixed combustion engine" JSAE Rev 2000, pp 177-82.
[19] L.M. Das, "Fuel induction techniques for a hydrogen operated engine", Int. J. Hydrogen Energy, Vol 15,pp 833-842,1990
[20] Gandhi pullagura, „"Effect of Hydrogen Enrichment on the Performance and Emissions of a Diesel Engine Fueled with Bio-fuel Emulsions"" International Journal of Research in Engineering and Technology (IJRET) Vol. 1 No. 1