EMISSION ESTIMATION OF NEAT PARADISE TREE OIL COMBUSTION ASSISTED WITH SUPERHEATED HYDROGEN IN A 4-STROKE NATURAL ASPIRATED DICI ENGINE

by

Karthikayan SUNDARARAJAN [a*], ***Ganesan SUBBIAH*** [b], ***and Sankaranarayanan GOMATHINAYAKAM*** [c]

[a] Department of Mechanical Engineering, Karpagam College of Engineering, Coimbatore, Tamil Nadu, India
[b] Sathyabama University, Chennai, Tamil Nadu, India
[c] Sree Sastha Institute of Engineering and Technology, Chennai, Tamil Nadu, India

Original scientific paper
DOI: 10.2298/TSCI16S4137S

This research work investigates the use of neat paradise tree oil in a 4-stroke natural aspirated direct injection compression ignition engine assisted with the help of superheated hydrogen (hydrogen in gaseous state or above its saturation temperature) as a combustion improver. The high calorific gaseous fuel hydrogen gas was used as a combustion improver and admitted into the engine during the suction stroke. A 4-stroke single cylinder Diesel engine was chosen and its operating parameters were suitably modified. Neat paradise tree oil was admitted through standard injector of the engine and hydrogen was admitted through induction manifold. Inducted superheated hydrogen was initiated the intermediate compounds combustion of neat paradise tree oil. This process offers higher temperature combustion and results in complete combustion of heavier molecules of neat paradise tree oil within shorter duration. The results of the experiment reveal that 40% higher NO_x, 20% lower smoke, 5% lower CO, and 45% lower HC than that of neat paradise tree oil fuel operation and the admission of superheated hydrogen has improved the combustion characteristics of neat paradise tree oil. The investigation successfully proved that the application of neat paradise tree oil with 15% of hydrogen improver is possible under a regular Diesel engine with minimal engine modification.

Key words: *neat paradise tree oil, hydrogen, CO, HC, NO_x, smoke*

Introduction

All the neat vegetable oils are more suitable alternate fuel which has a capability to drive a normal Diesel engine without engine modification. Many researchers have proved that the raw vegetable oil is a good substitute for compression ignition engines [1-3]. However, the raw oil appliance posed a variety of engine operating problems such as lubricant dilution, smoke emission and carbon deposit in engines [4-6]. Hence, the application quantity of neat oil was restrained upto 20% by volume [2, 3, 7]. The heavier molecular structure, higher viscosity, and unsaturation in its molecular structure are the main reasons for the poor performance of neat oil [8]. However, many researchers have defeated this issue by the trans-esterification process. The

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

trans-esterification process is a chemical reaction which converts the raw vegetable oil into ester. Although the biodiesel is a perfect fuel for the compression ignition (CI) engine it was not attracted due to its inherent fuel properties [9]. The main disadvantage of the biodiesel is a bulky chemical process and cost of production [10, 11]. Thus, many engine researchers have applied vegetable oil in neat form [12] or in modified form (biodiesel form).

Many methodologies have been tried to apply large proportion of raw vegetable oils in CI engine [13, 14]. Those methodologies have eliminated major shortcomings of ester conversion and laid a trouble free path for raw vegetable oil application in CI engine. Some of them recommended engine modifications [15] and some of them required fuel modifications [16, 17]. The common engine modifications recommended by them are increasing the compression ratio, adiabatic chamber combustion, air pre heating, and application of combustion improver [18-20].

This investigation initiated with the engine modification to apply neat paradise tree oil (NPTO) in direct injection compression ignition (DICI) engine. The combustion enhancing method is used for applying NPTO in CI engine. Hydrogen gas is used as a combustion improver. The higher calorific value, simple molecular structure, and higher flame speed makes the fuel to burn with high temperature. The high temperature during hydrogen combustion helps to improve the NPTO combustion. Hence, the NPTO combusts completely without leaving smoky exhaust. The results of the experiment confirm a significant enhancement in performance, combustion, and emission characteristics of NPTO while using hydrogen as a combustion improver.

Paradise tree oil

Paradise tree [21] (common names are *simarouba glauca, lakshmi taru*, and *aceituno*) a multipurpose tree that can grow well under a wide range of hostile ecological conditions. It is appropriate for non-edible purposes. The oil is removed from the oil seeds in the oil mills and processed by adopting conventional methods. Each well-grown tree yields 15-32 kg nut lets equivalent to 2.6-5.3 kg oil. It is nearly 1-2 ton oil per hectare per year. The properties of NPTO are given in tab. 1.

Table 1. Properties of NPTO

No.	Physical and chemical properties of NPTO		
	Properties	Diesel	NPTO
1	Auto ignition temperature [°C]	250	≤250
2	Boiling point [°C]	180-340	250-260
3	Cetane number	45-50	45-49
4	Density [kgm^{-3}] at 20 °C	820	906
5	Flammability limit [vol.%]	1-6.0	1-5.2
6	Flash point [°C]	74	226
7	Latent heat of vaporization [kJkg^{-1}]	230	–
8	Lower heating value [kJkg^{-1}]	42.700	38.100
9	Molecular weight	200	436
10	Specific gravity at 20 °C	0.820	0.910
11	Viscosity centistokes at 20 °C	03-04	17.30

Literature review

Senthil *et al*. [16] conducted an engine trial to estimate the CI engine performance. The engine was primarily fueled with jatropha oil and a small quantity of hydrogen. Results reported that an enhancement in the brake thermal efficacy (BTE) with 7% of hydrogen share (mass basis) at maximum power output point. The smoke emission was reduced at the best efficacy point. There was a large reduction in HC and CO emissions were attained at maximum power output point. Hydrogen induction raised the combustion rates. The results of the research concluded that the induction of small quantities of hydrogen considerably enhanced the vegetable oil performance.

Saravanan and Nagarajan [22] conducted an engine trial the dual fuel engine combustion using diesel and hydrogen. Hydrogen was admitted through the inlet manifold and diesel was injected through usual fuel injection system. The introduction of hydrogen improved the thermal efficacy, NO_x and reduced smoke emission comparatively to the diesel. In hydrogen-diesel dual fuel mode the BTE increases by 15% compared to diesel fuel at 75% load. The NO_x emissions were increased by approximately 2% compared to diesel fuel operation.

Sankaranarayanan *et al*. [23] conducted an engine test using mahua oil and hydrogen induction in a single cylinder Diesel engine. The experiment proved that the hydrogen improved BTE and reduced smoke. The hydrogen increased the combustion rate of mahua oil consequently increased NO emission.

Experimental set-up

A single cylinder 4-stroke air cooled vertical type DI type Diesel engine capable of developing 4.4 kW has been used for this experiment. The engine was co-axially coupled with an electrical type dynamometer. The suction side of the engine has anti pulsating drum, orifice meter, air intake temperature measuring probe, and air temperature measuring probe. In engine exhaust side was equipped with exhaust gas temperature measuring probe, smoke sampling pump, and exhaust gas analyzer. The fuel flow rate is measured by flow measuring device. A piezoelectric pressure pick up and a crank angle encoder are fixed in engine head and on the engine main shaft, respectively. It acquires in-cylinder pressure data with regard to crank degrees.

The NI LABVIEW based software is used to calculate the combustion performance parameters using the acquired in-cylinder pressure data. Air intake rate was measured by manometer and an orifice meter. Air temperature and exhaust temperature are measured by chromyl-alumel, *k*-type thermocouples. The hydrogen supply system admits hydrogen through intake manifold. The gaseous hydrogen is supplied through flow meter and flame arrester. The experimental set-up is shown in fig. 1 and the engine specifications are shown in tab. 2.

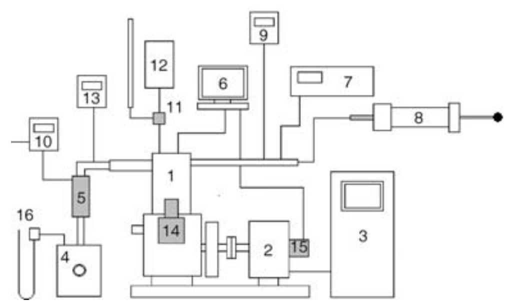

Figure 1. Engine experimental set-up
(1) the CI engine, (2) electrical type dynamometer, (3) eddy current dynamometer control, (4) anti pulsating drum, (5) air pre-heater, (6) computer with DAQ, (7) gas analyzer, (8) smoke sampling pump, (9) exhaust temperature indicator, (10) energy meter, (11) two way valve, (12) diesel fuel, (13) air inlet temperature indicator, (14) fuel injection pump, (15) crank angle encoder, (16) manometer, (17) gaseous hydrogen cylinder, (18) gas regulator, (19) flame arrester, (20) flow meter for gas flow rate, (21) hydrogen admittance manifold

Table 2. Engine specifications

No.	Engine specifications	Parameters
1	Make and model	Kirloskar , TAF-1
2	General details	4-stroke, constant speed, DICI, vertical, air-cooled
3	Number of cylinders	One
4	Bore and stroke	0.0875 m and 0.11 m
5	Cubic capacity	0.661 L
6	Compression ratio	17.5:1
7	Rated output and speed	4.4 kW at 1500 rpm
8	Fuel injector needle opening pressure and timing in crank angle	180 bar at 23º bTDC
9	Nozzle diameter	230 micron

Experimental method

The objective is to apply NPTO in DICI engine using gaseous hydrogen as combustion improver. To do this, regular Diesel engine has been modified in such a way to apply NPTO through fuel nozzle and hydrogen gas through the intake manifold. A flame arrester was connected in-between hydrogen cylinder and manifold. The hydrogen flow rate was measured using a gas flow meter and varied using a gas regulator. This research studies the effect of superheated hydrogen over NPTO combustion at various hydrogen quantities. The supply of superheated hydrogen was measured in terms of energy share using the given relation:

$$\text{Hydrogen energy share} = \frac{\text{total energy supplied by superheated hydrogen alone}}{\text{total energy content contributed by raw oil and hydrogen}} \tag{1}$$

Experimental procedure

- Initially the engine was started with diesel later switched over to the NPTO operation.
- Hydrogen gas of the required quantity was inducted into the engine through the inlet manifold.
- Engine performance and emission parameters were observed in various loads at various hydrogen energy shares.

Engine modifications

Taguchi optimization was used to optimize the engine operating variables. The optimum values of engine operating parameters used in the present work are given in tab. 3. The intake side of the engine was prepared with gaseous fuel admission device. In addition to that the engine test set-up was fitted with a facility for measuring intake air quantity, intake air temperature, power consumption of air heater, exhaust temperature, exhaust gas analyzer, and smoke meter.

Table 3. Optimum values of engine operating parameters

	Parameters	Optimum level
1	Injection pressure [bar]	275
2	Injection timing [°bTDC]	27
3	Compression ratio	19.5
4	Inlet air temperature [°C]	65

Results and discussion

The experimental results of the operating parameters modified engine, fueled with NPTO and hydrogen gas are offered to study the effect of hydrogen over NPTO combustion. The engine operating parameters were relocated using the optimum values arrived in the previous experiment. The engine was operated as per the procedure previously mentioned and its emission and combustion parameters were observed in various loads at various hydrogen energy shares.

Effect of hydrogen on NPTO combustion

In this work, superheated hydrogen was used as a combustion improver and was used in various proportions from 0% -30% in steps of 5% on energy share through the suction manifold. The supply of hydrogen changes the engine performance, in-cylinder combustion, and exhaust emission of the neat oil. The changes in performance and emission characteristics of the neat oil concerning the hydrogen energy share are represented.

Brake thermal efficiency

From fig. 2 shows the variation of BTE for the NPTO + hydrogen. The trend shows the similar pattern for all the percentage of operation (0-30%, in steps of 5%) from no load to full load. Among all the proportions of hydrogen mode operations, 15% hydrogen + NPTO are performing better. Comparing this with diesel and NPTO, it is found that, 15% H_2 + NPTO gives 33% BTE where as diesel reported as 32% and for NPTO as 29%. This could be due to the increase in hydrogen energy share. The increase in hydrogen energy share, effects and increases BTE upto 15% of hydrogen energy share. This trend reverses when hydrogen fraction exceeds 15%.

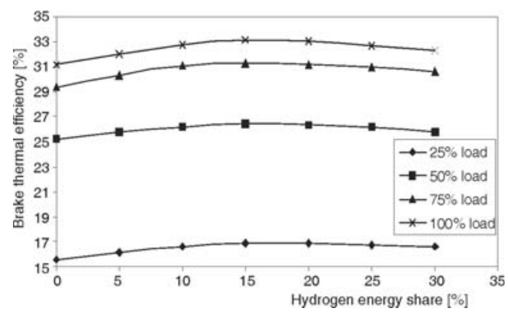

Figure 2. Effect of hydrogen energy share on BTE in NPTO combustion at various loads

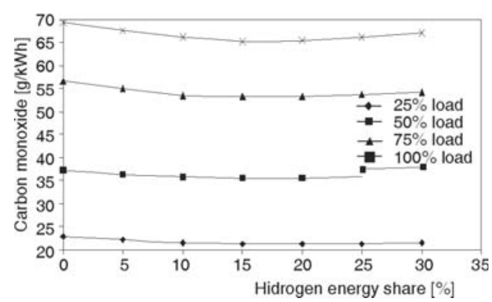

Figure 3. Effect of hydrogen energy share on CO emission of NPTO combustion at various loads

The CO and HC emission

From figs. 3 and 4, it is observed that the introduction of hydrogen decreases the CO and HC emission due to the betterment of combustion. This effect reverses when hydrogen energy share exceeds 15%. Introduction of hydrogen improves combustion process and enhance combustion temperature. This effect causes the mixture to burn completely without leaving a higher amount of CO and HC components.

However, this effect reverses when hydrogen percentage exceeds 15%. Higher hydrogen energy share (more than 15%) suppresses the combustion property of mixture by reducing the self ignition property. Hence, the higher fraction of hydrogen utilization increases CO and HC emission. The same trend is discernible in all load conditions and the mixture performed well at around 15% of hydrogen energy share at all load conditions.

NO_x emission

Figure 5 shows that the addition of hydrogen increases NO_x and then decreases. The highest NO_x emission is obtained near 15% of hydrogen energy share. The improved combustion and rapid production of intermediate compounds of the higher combustion temperature, de-

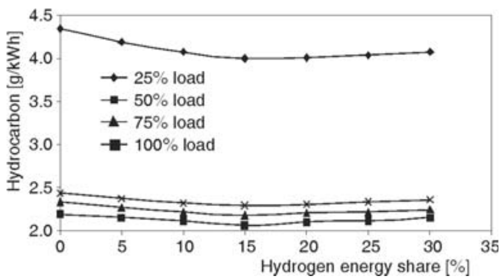

Figure 4. Effect of hydrogen energy share on HC emission of NPTO combustion at various loads

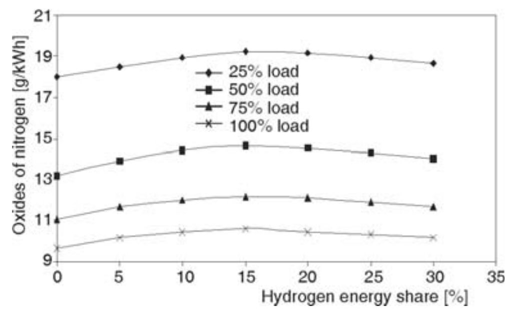

Figure 5. Effect of hydrogen energy share on NO_x emission of NPTO combustion at various loads

veloped by hydrogen combustion are the main reason for the rising trend of NO_x emission upto 15% of hydrogen energy share. This trend reverses after 15% of hydrogen energy share owing to the reduced combustion behaviour of neat oil. The unwarranted addition of hydrogen suppresses combustion characteristics and lowers the self-ignition property of mixture. The same trend is noticeable in all load conditions and the mixture performed well at around 15% of hydrogen energy share at all load conditions.

Smoke emission

Figure 6 shows the addition of hydrogen decreases smoke and then increases. The lowest smoke emission is found near 15% of hydrogen energy share. The addition of hydrogen improves combustion behaviour and increases combustion temperature. This is the main factor for the lowest smoke of neat oil near 15% of hydrogen energy share. The enhancement of combustion and rapid production of breakdown products is the main reasons for the reduction of smoke upto 15% of hydrogen. This tendency reverses when hydrogen percentage exceeds 15%. The excessive addition of hydrogen after 15% reduces the combustion characteristics and increased smoke. The same trend is visible in all load conditions and 15% of hydrogen energy share offered the best performance at all load conditions.

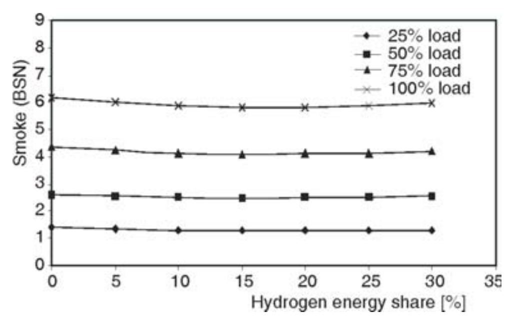

Figure 6. Effect of hydrogen energy share on smoke emission of NPTO combustion at various loads

Conclusion

The outcome of the engine trial revealed that the emission of NPTO was improved sufficiently by hydrogen combustion improver. The greater properties of hydrogen such as higher flame speed, calorific value, gaseous nature, and simpler molecular structure helps to combust NPTO with higher performance and lower emission level. The application of 15% H_2 + NPTO performance is superior to other percentage hydrogen induction. It is compared with NPTO operation (without enhancer), and the results are 15% in BTE, 40% higher NO_x, 20% lower smoke, 5% lower CO, and 45% lower HC than that of NPTO fuel operation. The overall result of the experiment that the neat oil combustion emission has been improved significantly by the hydrogen combustion enhancer.

Nomenclature

bTDC – before top dead center
BSN – Bosh smoke number
CI – compression ignition
DI – direct injection
DICI – direct injection compression ignition
kW – kilowatt
rpm – revolution per minute

References

[1] Avinash, K. A., Rajamanoharan, K., Experimental Investigations of Performance and Emissions of Karanja Oil and Its Blends in a Single Cylinder Agricultural Diesel Engine, *Appl. Energy, 86* (2009), 1, pp. 106-112
[2] Hossein, H., *et al*., Grey Relational Analysis to Determine the Optimum Process Parameters for Open-End Spinning Yarns, *Journal of Engineered Fibers and Fabrics, 7* (2012), 2 , pp. 81-86
[3] Kalam, M. A., *et al*., Exhaust Emission and Combustion Evaluation of Coconut Oil-Powered Indirect Injection Diesel Engine, *Renewable Energy, 28* (2003), 15, pp. 2405-2415
[4] Deepak, A., Avinash, K. A., Performance and Emission Characteristics of Jatropha Oil (Preheated and Blends) in a Direct Injection Compression Ignition, *Applied Thermal Engineering, 27* (2007), 13, pp. 2314-2323
[5] Elango, T., Senthilkumar, T., Performance and Emission Characteristics of CI Engine Fuelled with Non Edible Vegetable Oil and Diesel Blends, *Journal of Engineering Science and Technology, 6* (2011), 2, pp. 240-250
[6] Hazar, H., Aydin, H., Performance and Emission Evaluation of a CI Engine Fuelled with Preheated Raw Rapeseed Oil (RRO)-Diesel Blends*, Appl. Energy, 87* (2010), 3, pp. 786-790
[7] Babu, A. K ., Devaradjane, G., Vegetable Oils and Their Derivatives as Fuels for CI Engines: An Overview. SAE Technical paper 2003-01-0767, 2003
[8] Agarwal, D., Agarwal, A. K., Performance and Emissions Characteristics of Jatropha Oil (Preheated and Blends) in a Direct Injection Compression Ignition Engine, *Appl. Therm. Eng., 27* (2007), 13, pp. 2314-2323
[9] Chauhan, B. S., *et al*., Performance and Emission Study of Preheated Jatropha Oil on Medium Capacity Diesel Engine, *Energy, 35* (2010), 6, pp. 2484 - 2492
[10] Cheng, C. H., *et al*., Comparison of Emissions of a Direct Injection Diesel Engine Operating on Biodiesel with Emulsified and Fumigated Methanol, *Fuel, 87* (2008), 10-11, pp. 1870-1879
[11] Deepanraj, B., *et al*., Performance and Emission Characteristics of Diesel Engine Fuelled with Rice Bran Oil Methyl Ester Blends, *Daffodil University Journal Science and Technology, 7* (2012), 2, pp. 51-55
[12] Karthikayan, S., Sankaranarayanan, G., Influence of Engine Parameters Optimization in the Neat Non-Edible Oil + LSD Fuel Combustion Analysis: Measurement of Cylinder Pressure and Heat Release at Various Loads, *International Journal of Applied Engineering Research, 9* (2014), 22, pp. 12741-12756
[13] He, Y., Bao, Y. D., Study on Cottonseed Oil as a Partial Substitute for Diesel Oil in Fuel for Single-Cylinder Diesel Engine, *Renewable Energy, 30* (2005), 5, pp. 805-813
[14] Yilmaz, N., Morton, B., Effects of Preheating Vegetable Oils on Performance and Emission Characteristics of Diesel Engines, *Biomass and Bioenergy, 35* (2011), 5, pp. 2028-2033
[15] Karthikayan, S, Sankaranarayanan, G., Study of Air Intake System of Turbo Charged Diesel Engines, *Proceedings*, Frontiers in Automobile and Mechanical Engineering, Chennai, India, 2010, pp. 175-178
[16] Senthil, K. M., *et al*., Use of Hydrogen to Enhance the Performance of a Vegetable Oil Fuelled Compression Ignition Engine, *Int. J. Hydrogen Energy, 28* (2003), 10, pp. 1143-1154
[17] Shahid, E. M., Jamal, Y., Production of Biodiesel: A Technical Review, *Renewable and Sustainable Energy Reviews, 15* (2011), 9, pp. 4732-4745
[18] Banapurmath, N. R., *et al*., Performance and Emission Characteristics of a DI Compression Ignition Engine Operated on Honge, Jatropha and Sesame Oil Methyl Ester, *Renewable Energy, 33* (2008), 9, pp. 1982-1988
[19] Sukumar, P. N., *et al*., Performance and Emission Study of Mahua Oil (Madhuca Indica Oil) Ethyl Ester in a 4-Stroke Natural Aspirated Direct Injection Diesel Engine, *Renewable Energy, 30* (2005), 8, pp. 1269-1278
[20] Suryawanshi, J. G., Deshpandel, N., Experimental Investigation on a Pongamia Oil Methyl Ester Fuelled Diesel Engine, SAE paper 2004-28-008, 2004
[21] ***, http://www.jatrophabiodiesel.org

[22] 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
[23] Sankaranarayanan., *et al*., Performance and Emission Studies on DI Diesel Engine Using Madhuca Indica Oil and Hydrogen as Dual Fuel, *Proceedings*, 19th National Conference on I. C. Engines and Combustion, Annamalai University, Chidambaram, Tamil Nadu, India, 2005, Vol. 1, pp. 83-86

Paper submitted: September 15, 2015
Paper revised: January 12, 2016
Paper accepted: February 4, 2016