Experimental Investigations on Hydrogen Supplemented Pinus Sylvestris Oil-based Diesel Engine for Performance Enhancement and Reduction in Emissions

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The paper mainly aims at improving the performance and reduction in exhaust emissions of an indirect injection diesel engine fuelled with alternative and modern biofuel Pinus Sylvestris oil, which is traditionally oxygenated and obtained from the resins of the Pinus Sylvestris tree. Its physical and chemical properties are similar to the regular petro-diesel fuel and can be used without transesterification directly in diesel engines. On the other hand, a lower cetane value hangs its direct use in diesel engines. Hence, the experiment followed a complementary approach to supplementing small dosages of gaseous Hydrogen (GH_2), which is highly flammable, colorless, odorless, and plenty available to overcome the de–merits nature of emissions. Gaseous Hydrogen was inducted through the inlet manifold and controlled by Timed Manifold Injection (TMI) in 5% to 7% of the total energy with the step of 1%. In addition to GH_2 supp–lementation, preheating the inlet air in the range of 40 ^{0}C to 60 ^{0}C with an increment of 10 ^{0}C was allowed to suck through the same inlet manifold. Supplementation of 6% GH_2 and 40 ^{0}C preheated air showed better results than conventional diesel operations without any engine modifications. All required NFPA Class I Division 2 Group B standards in this experiment were considered during the handling and use of gaseous Hydrogen.

Keywords: *Pinus Sylvestris oil, Pine oil, Hydrogen, In-direct Injection, NFPA standards, Performance, and Emissions*

1. INTRODUCTION

Unanimously reports coming from studies into alter–native and renewable fuels expect an enormous fossil fuel demand by 2030, and the sudden rise in oil prices has already influenced these effects. Further, its envi–ronmental impact is a significant concern [1, 2]. Researchers started working on sustainable, reliable, and environmentally friendly alternative fuels to over–come these demerits concerning economic and envi–ronmental issues with fossil fuels. Further, using these alternative fuels may be in the straightway of its use or in the trans-esterified way or blending of either straight vegetable oil or its bio-diesel with conventional diesel operation. Biodiesel is one such option to replace con–ventional diesel. Biodiesel is produced through the trans -esterified process in different catalysts at different tem–peratures [3-7]. Due to their higher free fatty acids, some biodiesel preparations have touched the two-stage trans-esterification process [8, 9].

The use of this biodiesel had reduced the emissions like Smoke, HC, CO, and CO_2, and an increase in NOx was observed [10-13]. However, another set of researchers executed their experimentation with micro-emulsion fuels. Drastic reduction in NOx was observed with a penalty on CO, HC, and thermal brake efficiency [14, 15]. Even alcohols, oxygenated and less Viscosity, and reduced emissions and combustion were enhanced from diesel engines [16]. On the other side, it is also reported that alcohols being less viscous, suffer from miscibility with diesel fuel [17]. Few researchers exten–ded their work with Pinus Sylvestris in diesel engines. Pinus Sylvestris is stable concerning its use as well as storage. Being unique in this direction, its feedstock can be made available from the forest and, having phy–sicochemical properties very close to diesel, can be blended directly with diesel fuel. It is evident from the literature; that more than 30,000 tons of Pinus Sylvestris are produced globally every year [18]. Hydrogen as a supplement with different alternative fuels also succeeded in using diesel engines with enhanced brake thermal efficiency and reduction in emissions [19-22].

However, using these alternative fuels to replace the conventional diesel operation had a penalty on engine performance due to its low heating value and higher Viscosity than Petro-diesel. The high-energy supplement hydrogen overcame such deficiency.

2. MATERIALS & METHODS

Pinus Sylvestris (PS) trees can rise to a height of between 40 and 80 meters and have a smooth crown and

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a dark reddish-brown bark that is strongly fissured. The leaves are needle-like, grey-green, and are found paired in twos. The flowers are orange-yellow, and the cones are pointed. This type of tree is widely called a com–mercial tree worldwide. Pinus Sylvestris is collected through a steam distillation operation from the pine tree's needles, twigs, and cones (also known as the Scottish Pine or Europe-an Pine). Pinus Sylvestris is light yellow and has a woody fragrance but watery Vis–cosity and alcohol. The bulk of the chemical compo–sition of Pinus Sylvestris is made up of a-terpinene and 3-carene. The expected production of Pinus Sylvestris by next year is more than 8,50,000 tons [23].

3. EXPERIMENTAL SETUP

Single Cylinder, 4 strokes, In-direct injection, water-cooled, lister vertical engine with 7.35 kW of power and a torque capacity of 63 N-m is attached to an eddy current dynamometer with a power output of 52 kW and a torque capacity of 91 N-m as shown in Figure 1. Additionally, injection timing at 20°bTDC and an injection pressure of 175 bar were kept constant. Engine, dynamometer, and emission measurement device specifications are shown in Table 1 and are also listed in the earlier papers [21][32]. Physico- Chemical properties of test fuel and conventional diesel were enlisted in Table 2. Foreign materials and dust were filtered using a magnetic filter connected to the engine cooling system's eddy current dynamometer. The engine was operated for at least 20 minutes to steady the engine. When the Pinus Sylvestris Straight Vegetable Oil (PSSVO) is running, the engine was operated for at least 20 minutes after the test to filter out the current straight vegetable oil. In this way, all starting comp–lications and injector concerns can be eliminated. AVL made the Di Gas 5000 model 5 gas analyzer and 437 model smoke meter to measure the exhaust emissions. However, the exhaust gas being a four-stroke, single-cylinder is not continuous; thus, an indigenously designed sampling unit was integrated between the engine and emission measuring equipment. Three times the average of readings was used [24-27] [33-36].

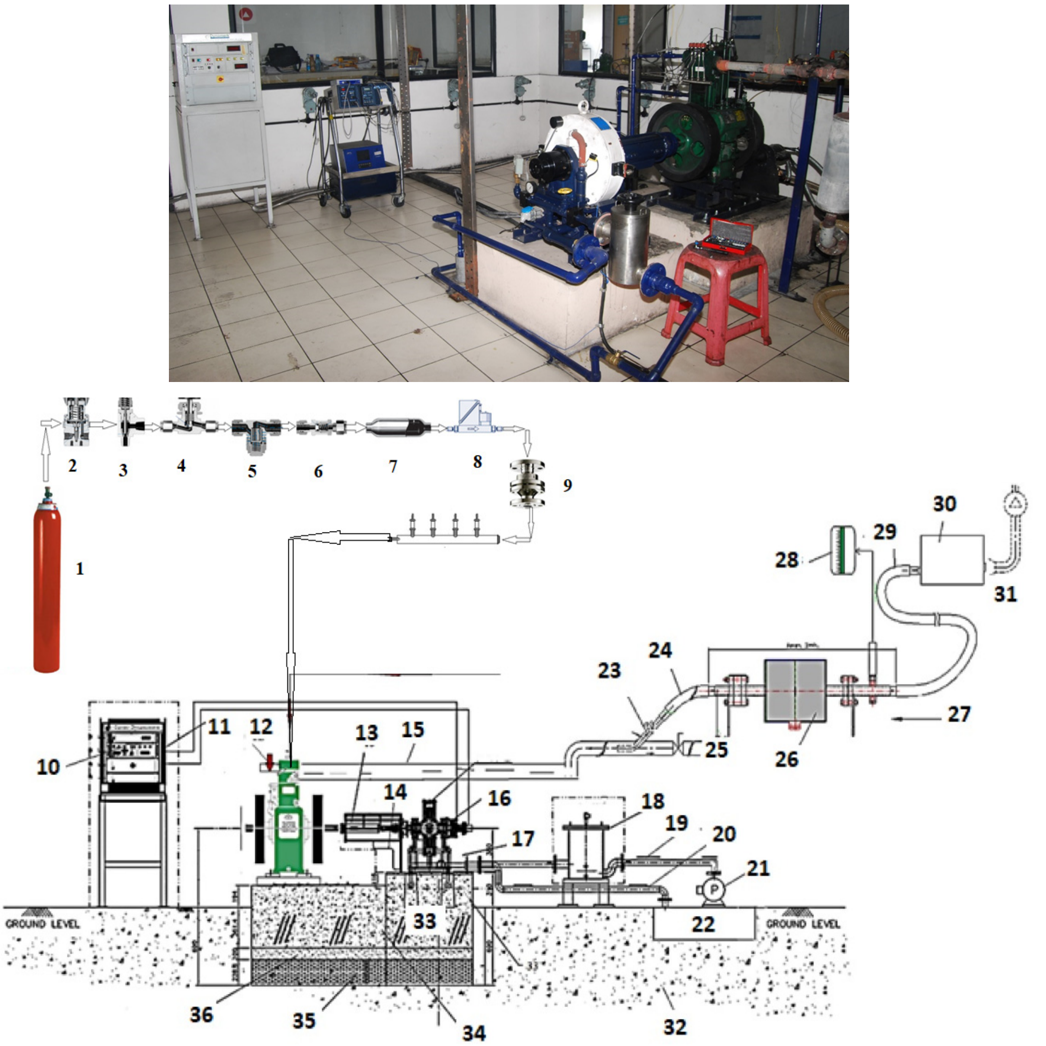


Figure 1 Engine Test Setup 1- GH_2 Cylinder, 2- Two-stage Pressure Regulator, 3-Relief Valve, 4-Two Way Valve, 5-Filter, 6-Non-Return Valve, 7-GH_2 Reservoir, 8-Mass Flow Controller, 9-Flame Arrester, 10-Dynamometer Controller Unit, 11-Diesel Engine, 12-GH_2 LLRF Introducing system, 13-Propeller Shaft Guard, 14-Exhaust Manifold, 15- Eddy Current Dynamometer,16-Magnetic Pickup, 17-Magenetic Filter, 18-Sampling Probe, 19-Flexible Hose, 20-Exhaust Out,21-Exhaust Damper, 22-Sampling System, 23-Flexible Hose, 24-Manometer, 25-Smoke Meter Sensor Unit, 26-Sump Tank, 27-Dynamometer Foundation, 28-Rubble Soiling (9"), 30-Thin Concrete Layer (4"), 31-Propeller Shaft Mounting, 32-Pump, 33-Inlet Pipe, 34-Outlet Pipe, 35-Soil, 36- Load Cell of Dynamometers

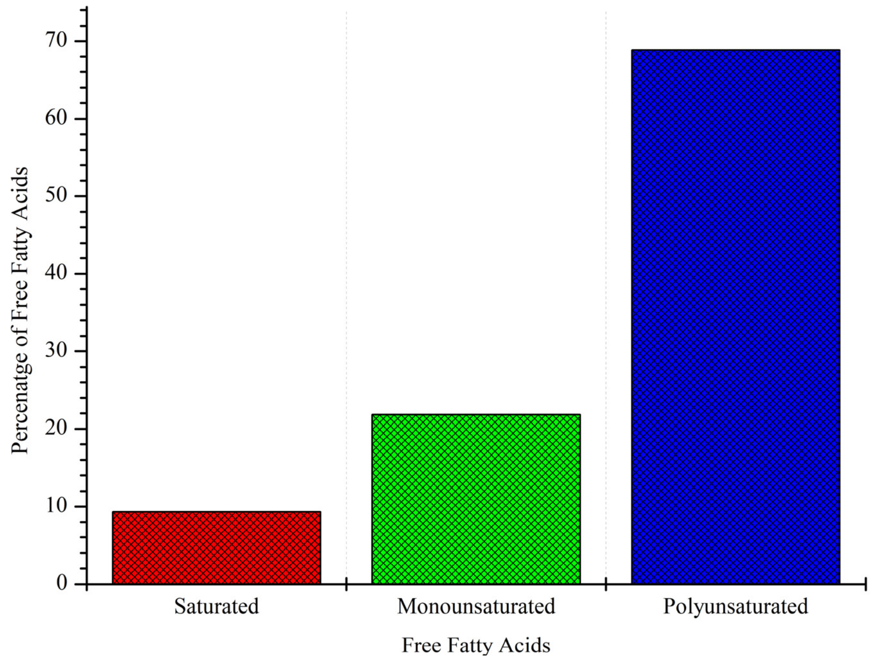


Figure 2. Free Fatty Acids Composition

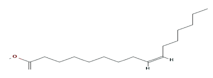
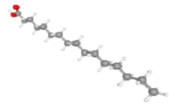
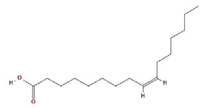
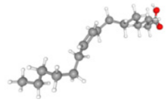
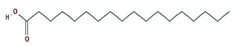
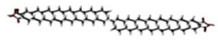
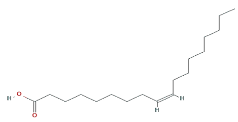
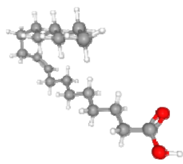
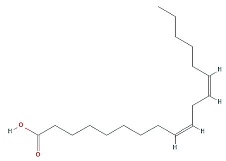
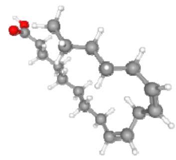
Table 1 Technical Specifications of Engine Test Setup

Description	Technical Specifications
Make	M/s. Field Marshal
Model	FMS10
Method of Injection	Indirect Injection
Number of Strokes	4
Cooling Method	Water Cooled
Other Specifications	Vertical, Lister type
Bore x Stroke (cm^2)	12 x 13
Injection Pressure (bar)	175
Compression Ratio	17:1
Fuel Injection Timing (Static)	20 ^{0}bTDC
Power Output (kW)	7.35
Speed (Constant)	1000 rpm
Bsfc (kg/kW-hr)	0.265
Eddy Current Dynamometer	
Make	M/s. Dynamomerk Control
Model	EC-70
Power Range (hp)	10 -70
Maximum Torque (N-m)	91
Speed range	1000-10000 rpm
Water filter	Magnetic
Power Supply	DC excitation 60 V & 6 amps
Emission Measurement Equipment	
CO, CO_2, O_2, NO_x, & HC	5 Gas analyzer
Make	AVL
Model	Di- Gas 4000 Light
Smoke	Smoke Meter
Make	AVL
Model	437
Sampling Unit	AVL make Indigenously designed

Table 2. Physico- Chemical properties of Pinus Sylvestris Oil and conventional diesel

Description	Pinus Sylvestris Oil	Conventional Diesel
Cetane Number	38.9	54
Oxygen Content	3-6	-
Density (kg m^{-3})	890	828
Lower Heating Value (MJ/kg)	39.85	42.4
Kinematic Viscosity (mm^2 Sec^{-1})	1.8	3.1

Table 3. Free Fatty Acids of PSSVO

Name of the Acid	Fatty Acid	Chemical Formula	Chemical Structure	Crystal Structure/3D conformer	% composition
Palmitic	C16:0	C16H32O2			4.72
Palmitoleic	C16:1	C16H30O2			0.17
Stearic	C18:0	C18H36O2			3.42
Oleic	C18:1	C18H34O2			19.42
Linoleic	C18:2	C18H32O2			61.39

3.1 Free Fatty Acids

To achieve the composition of Fatty Acids of neat Pinus Sylvestris oil, a Flame Ionization Detector-based wax column-type Gas Chromatograph was used along with a Nucon render Flame Ionization Detector, which resulted in the compositions shown in Table 3. PSSVO consists of unsaturated free fatty acids like 21.8 % Mono and 68.88% Polyunsaturated by its presence, and the rest is saturated, as shown in Figure 2.

3.2 Handing of Gaseous Hydrogen (GH_2)

The 130 bar gaseous hydrogen in a 47-liter water capacity was held outside the test cell and the two-stage pressure regulator, which will reduce the pressure from 130 bar to 2 bar. Also, the relief valve is intended to be opened when the device pressure exceeds the fixed pressure (2 bar). Quarter turn ON/OFF Two-way Valve was added to shut off the gas flow if necessary. Later Hydrogen is allowed to move through the 7 Micron Filter to filter the gas's impurities. Even the non-return valve with a downstream pressure of 68.9 bar is familiar with the mechanism which restricts the gas flow in the opposite direction. A double-ended Hydrogen chamber with a pressure rating of 124 bar was initiated between the non-return valve and the mass flow controller, which serves as a gas reservoir and eliminates pulsation during hydrogen suction. Bronkhorst Thermal Mass Flow Controller has a spectrum of 0.16 to 8 gm/min with a pressure drop of 2 bar and the Totalizer device mounted in the rows. A flame arrester was given between the Mass Flow Controller and the Gas Hydrogen Injection Device to prevent fire incidents and avoid the Hydrogen's forward movement during the backfire. All machinery comprises SS 316 with tubing and 1⁄4" OD compression fittings to prevent gas leakage and hydrogen compatibility [1-3].

4. RESULTS & DISCUSSIONS

Its performance and emission assessment were carried out to understand the compatibility of the selected fuel with the diesel engine. A detailed analysis was pre–sented in the following sections.

4.1 Performance Assessment

4.1.1. Brake Thermal Efficiency

Figure 3 depicts the variation of BTE with Engine load. As the load increases, BTE increases up to 80% load, which reduces after that. This behavior remains the same with all fuels. Maximum efficiency was achieved with all environments at 80% rather than full load. BTE of neat Pinus Sylvestris is slightly lesser than con–ventional diesel. Concerning supplementation of GH_2, as GH_2 energy share increases, BTE increases at the maximum efficiency point. Maximum BTE of 27. 44 % was noticed at 7% GH_2 energy share, 2.73 % higher than neat Pinus Sylvestris and 1.76% higher than the regular diesel operation.

However, at the same time, at this GH_2 share, the engine is experiencing more vibrations than in other envi–ronments. At the same time, as GH_2 share increases at part load, BTE was decreased due to the high self-ignition temperature of both the fuels and low cetane number of Pinus Sylvestris, leading to an increase in ignition delay. At the same time, 6% GH_2

energy share, BTE of 26.29%, is also higher than the neat Pinus Sylvestris and conventional diesel without experiencing any vibrations by the engine. Hence, this application identified 6% GH_2 energy share as optimized GH_2 energy share.

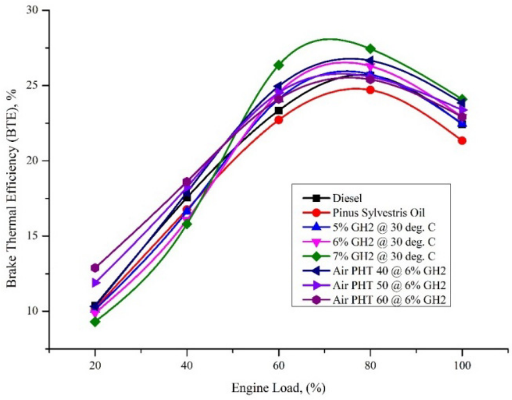


Figure 3. BTE Vs Engine Load

Further, the self-ignition temperature of both Pinus Sylvestris and GH_2 is another attempt called preheating the incoming air in the range of 40 ^{0}C to 60 ^{0}C with an increment of 10 ^{0}C. It is noticed that 40 ^{0}C showed better performance at 80% load than other preheating environments. As the temperature of the inlet air increases, the ignition delay is decreased compared to room temperature 30 ^{0}C, which enhances the combustion. Whereas further air inlet temperature inc–reases, engine volumetric efficiency decreases, which causes reduced inefficiency. Part load, as the engine combustion chamber temperature increased due to the increase in air inlet temperature.

Hence, 6% GH_2 energy share and 40 ^{0}C air inlet temperature were considered the best efficiency compa–red to all other environments.

4.1.2. Brake Specific Energy Consumption

Figure 4 expresses the variation of BSEC with engine load. At part load, the energy required to overcome the friction is high. However, at the maximum efficiency point, i.e., 80% load, minimum BSEC was observed in all conditions.

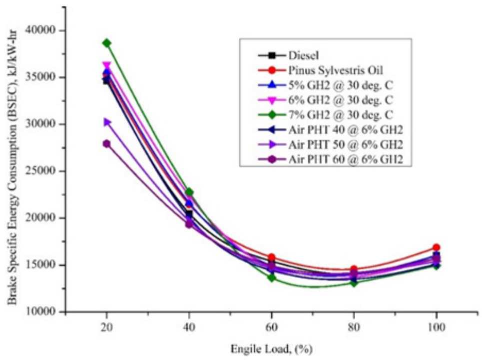


Figure 4 BSEC Vs. Engine Load

A minimum BSEC of 14.94 MJ/kW-hr was noticed with 7% GH_2 supplementation. However, the optimized efficiency of 15.09 MJ/kW-hr was recorded 340 kJ/kW-hr less than the conventional diesel and 953 kJ/kW-hr less than the neat Pinus Sylvestris.

5. EMISSION ASSESSMENT

5.1 Oxides of Nitrogen (NOx)

Figure 5 depicts the formation of NOx with a variation of engine load. it is observed that with increasing the engine load, nox increased up to 80 % load. i.e., maximum efficiency point and later at full load slightly reduced. this is due to the increase of combustion chamber temperature with increasing load and mixture becoming richer with increasing load, and PSSVO being oxygenated. However, at full load, being an IDI engine, a high surface to volume ratio due to maximum heat loss formation of NOx has deteriorated at full load. A maximum NOx of 471 ppm was noticed at 7% GH_2 energy share, 45 ppm higher than the neat PO and 31 ppm higher than the diesel operation. However, optimized efficiency point, i.e., 6% GH_2 energy share and preheated air temperature 40 ^{0}C, 462 ppm of NOx recorded, 36 ppm higher than neat PO 32 ppm higher than conventional diesel. Further, at GH_2 share, at part load, there is no significant rise in NOx was noticed due to high self-ignition temperatures of both PO and GH_2 and longer ignition delay. As load increases, the temperature inside the combustion chamber increases, which is sufficient to burn these fuels at moderate and peak loads, causing a rise in NOx.

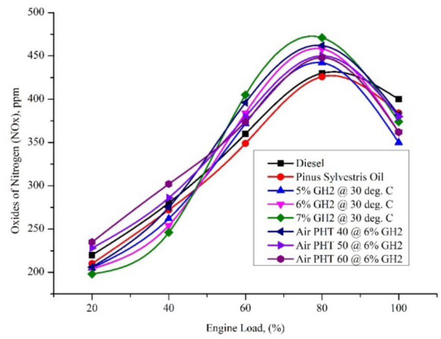


Figure 5 NOx Vs. Engine Load

Further, with increasing the preheating air tempe–rature, NOx deteriorated due to lack of oxygen because of less volumetric efficiency.

5.2 Smoke

Figure 6 illustrates the Smoke emissions with varying engine loads. As the load increases, Smoke emissions increase due to a lack of oxygen. However, being PSSVO is oxygenated fuel, much difference was not identified in Smoke formation at full load. The marginal difference was noticed. However, part loads with GH_2 and preheated air increased smoke compared to conventional diesel. As the load increased to moderate and towards full load, smoke emissions were reduced. This is due to more oxygen available in the PO and the development of high temperature towards the full load oxidizing the smoke. At the optimized efficiency point (80% load, 6% GH_2, and 40 ^{0}C Preheating air), Smoke of 22 HSU was registered, 10 HSU lesser than the conventional diesel, and 8 HSU lesser than the neat PSSVO. Concerning GH_2 supplementation, smoke emi–ssions at 80% load decreased due to more amount of

GH_2 which participating in the combustion releases more heat, which is sufficient to oxidize the smoke. However, some were increased in preheating air due to deficient oxygen as the air gets heated up. Hence the reduction of smoke is due to the presence of inbuilt O_2 in the PO has promoted the oxidation of soot in the flame region of the spray and enhanced combustion due to its supreme fuel properties and further supplemented with high energy GH_2. Even the C/H ratio of PSSVO oil is significantly less when compared to conventional diesel also will prevent the formation of soot and its precursors in the premixed combustion. A more prono–unced premixed combustion phase for PSSVO in the event of longer ID has helped in the oxidation of soot.

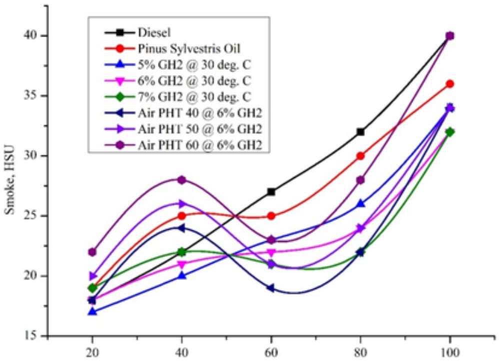


Figure 6 Smoke Vs. Engine Load

5.3 Carbon Monoxide

Figure 7 explains the formation of CO emissions with varying loads. As load increases, CO emissions increases due to a lack of oxygen for the available fuel. The same scenario was experienced with this experimentation. CO emissions were increased at part loads compared to diesel operation because of prolonged ID and lean burning of PSSVO. The longer ID reduces the in-cylinder temperature while the lean burning due to the dilution effect decreases the fuel to air 'φ' to raise the CO emissions at part loads. This effect is slightly reduced with preheating the air as the ID, lean burning is slightly reduced, and even high self-ignition temperatures of both PO and GH_2 also influence more CO at part loads. As the load increased, the formation of CO with GH_2 and preheated air modes was reduced. The same can be noticed in Figure 6.

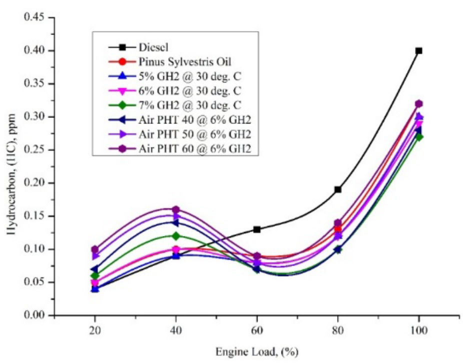


Figure 7. Co Vs. Engine Load

At the maximum efficiency point with 6% GH_2 energy share and 40 ^{0}C, CO of 0.1 % by volume was registered, 0.03 % and 0.09% by volume reduced with PO and regular petro-diesel. Reduction in CO emissions is due to the promotion of oxidation of CO caused by higher in-cylinder temperature due to participation of high energy GH_2 and the intrinsic presence of Oxygen with PSSVO.

5.4 Hydrocarbon

The formation of unburned hydrocarbon in diesel engine combustion is still hypothetical [31]. Some sources are causing the formation of hydrocarbons like; engine crevices, physico & chemical properties of the fuel, air-fuel mixture quality. Figure 8 explains the formation of unburned hydrocarbons for various fuels at different engine loading conditions. From Figure 7, with conventional diesel operation, as load increases, HC emission increases linearly up to 80% load, and after 80 % load, a sharp increase was observed due to high heat transfer at this load leads to poor oxidation resulted in the steep rise in HC emissions at full load. At part load operations, maximum HC emissions were observed with pure Pinus sylvestris SVO, and GH_2 supplemented Pinus sylvestris due to non-proper participation of high self-ignition temperature of hydrogen at part loads. Further, a slight increase in air inlet temperature and lower HC emissions were observed at maximum efficiency.

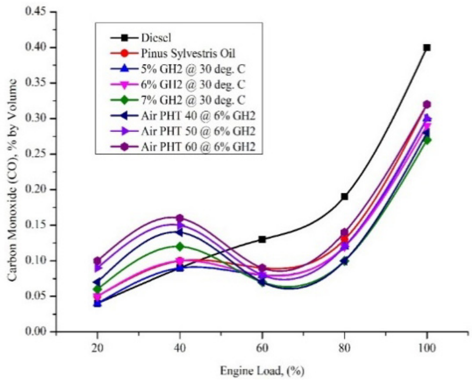


Figure 8 HC Vs. Engine Load

6. CONCLUSION

Use of unexplored Pinus Sylvestris SVO with 6% GH_2 energy share at preheated air temperature of 40 ^{0}C with 7.35 kW, water cooled, vertical lister indirect injection diesel engine revelated the following results:

- Maximum Brake Thermal Efficiency of 26.29% which is 0.61% higher than conventional diesel operation was achieved at 80% load rather than 100% due to its high surface to volume ratio leads higher heat transfer. Minimum Brake Specific Energy Consumption of 15.09 MJ/kW-hr, which is 340 kJ/kW-hr than the conventional diesel operation
- Higher NOx of 462 ppm recorded which is 32 ppm higher than the conventional diesel operation. There are two reasons responsible for formation of NOx. As unsaturated free fatty acids are higher in PSSVO oil leads to increase in chain length of unsaturation degree which may influence the adiabatic flame temperature causes raises in local combustion chamber temperature leads to formation of higher

NOx. Even supplementation of GH2 also influences the raise of NOx..

- Smoke of 22 HSU was registered at the best efficiency point which is 10 HSU lesser than the conventional diesel operation. However at part loads, there is raise in smoke was observed due to longer chain length of PSSVO an increase in total mass particle emissions. Whereas at moderate and high loads participation of GH2 enhances the combustion chamber temperature which influences the oxidation of soot particles at moderate and higher temperatures.
- At maximum efficiency point THC and CO of 6 ppm and 0.1% by volume which are 1 ppm and 0.09% lesser than the conventional diesel operation. Whereas at part loads application as fuel consists of higher boiling and melting points increased chain length can amplify the probability of soot and volatile organic compounds to form higher HC THAT ARE UNABLE TO VAPORIZE. EVEN INDUCTED GH2 also not able to participate due to higher self-ignition temperature unable to burn at part loads.

Overall, the usage with pre-heated air to 40 ^{0}C and 6% GH_2 supplementation at 80% load demonstrated improved efficiency and reduction in emissions compared to traditional petro-diesel service.

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ACRONYMS AND ABBREVIATIONS

PSSVO	Pinus Sylvestris Straight Vegetable Oil
HC	Hydrocarbon
CO	Carbon Monoxide
CO_2	Carbon Dioxide
OD	Outer Diameter
BTE	Brake Thermal Efficiency
GH_2	Gaseous Hydrogen
BSEC	Brake Specific Fuel Consumption
Ppm	Parts per Million
IDI	In-direct Injection
HSU	Hartridge Smoke Units
O_2	Oxygen
C/H	Carbon to Hydrogen Ratio
MNRE	Ministry of New and Renewable Energy
UPES	University of Petroleum & Energy Studies
GoI	Government of India

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ЕКСПЕРИМЕНТАЛНА ИСПИТИВАЊА ДИЗЕЛ МОТОРА НА БАЗИ УЉА ПИНУС СИЛВЕС–ТРИС СА ДОДАТКОМ ВОДОНИКА ЗА ПО-БОЉШАЊЕ ПЕРФОРМАНСИ И СМАЊЕЊЕ ЕМИСИЈА

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Рад углавном има за циљ побољшање перформанси и смањење емисија издувних гасова дизел мотора са индиректним убризгавањем који користи алтерна–тивно и модерно биогориво уље Пинус Силвестрис, које је традиционално оксигенирано и добијено од смола дрвета Пинус Силвестрис. Његова физичка и хемијска својства су слична обичном петро-дизел гориву и могу се користити без трансестерификације директно у дизел моторима. С друге стране, нижа цетанска вредност зависи од његове директне употребе у дизел моторима. Дакле, експеримент је пратио комплементарни приступ допуњавању малих доза гасовитог водоника (ГХ2), који је веома запаљив, безбојан, без мириса и доста

доступан за превазилажење штетне природе емисија. Гасовити водоник је индукован кроз улазну грану и контролисан временским убризгавањем у разводник (ТМИ) у 5% до 7% укупне енергије са кораком од 1%. Поред додавања ГХ2, претходно загревање улазног ваздуха у опсегу од 40 0Ц до 60 0Ц са прирастом од 10 0Ц је дозвољено да усисава кроз исти улазни разводник. Додатак 6% ГХ2 и 40 0Ц претходно загрејаног ваздуха показао је боље резултате од конвенционалних дизел операција без икаквих модификација мотора. Сви потребни стандарди НФПА класе И дивизије 2 групе Б у овом експерименту су узети у обзир током руковања и употребе гасовитог водоника.