

The Impact of Hydrogen Substitutions on Performance, Combustion and Emission Parameters of a Single Cylinder Diesel Engine

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ABSTRACT: Hydrogen is one such fuel which has been credited as a remarkable fuel in the conventional IC engines and appears to be proving itself as the best transportation fuel of the future. . Moreover, hydrogen has increasing importance because of its wide flammability limits, minimum ignition energy, and high calorific value and apart from that it does not contain any carbon atom which eliminate harmful emissions of CO, CO₂ and unburnt hydrocarbons. In the present work, hydrogen has been introduced as an alternative fuel to CI engine to increase the efficiency and to overcome the polluting emissions as well as to extend the life of fossil fuels. This experimental investigation focuses on performance, combustion and exhaust emissions of a diesel engine using dual fuel approach with hydrogen being inducted at varied percentages i.e. 10%, 20%, 30% by mass of fuel at a rated injection opening pressure of 200 bar and performance characteristics were calculated. The effect of hydrogen substitutions on emissions were measured and reported. The peak pressure and heat release rate were also measured.

KEYWORDS: Hydrogen, CI Engine, Performance, Combustion and Exhaust Emissions.

I. INTRODUCTION

As a well-known fact, the energy resources for the major prime movers are discounting from the world, leaving toxic and fatal foot prints on the environment and human health. Diesel is one of such a fossil fuel which is used in the compression ignition engines, where these engines are majorly used in prime movers in medium and heavy vehicles, generators, pumps and machineries in most of the developed countries. But the amount of pollutants such as CO₂, CO, NO_x, unburnt hydrocarbons that are thrown out into the atmosphere through the exhaust emission of automotive vehicles is also increasing. So the compression ignition engines have occupied irreplaceable designation whereas replacement of fuel has been found. Hydrogen is one of such fuel which has already shown off itself as a remarkable fuel for spark ignition engine, and also become a beckoning fuel for compression ignition engine researchers. The fossil fuel, which is used as a main fuel for the compression ignition engines is getting depreciated as a common knowledge [1] and leaving exhaust emissions in the atmosphere leading to global warming and health hazards. Coming to the grounds, the researchers around the world are in search of a duck soap solution for the problem.

Hydrogen is a beckoning I.C Engine fuel for such researchers, due its advantages such as renewable, non-toxic, non-odorant, abundant availability in nature and also results in complete combustion. Hydrogen is considered to meet energy, environment and sustainable development needs [2, 3]. It has many potential uses, is safe to manufacture and is environment friendly [4]. According to Yadav et.al. Hydrogen combustion will produce no greenhouse gases, no ozone layer depletion chemicals and little or no acid rain ingredients and pollution.

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II. HYDROGEN FOR CI ENGINES

According to studies conducted by the Ma et. al. [5] hydrogen can be used as sole fuel for S.I. engine. However signified drop in brake power of the engine was observed due to low compression ratio. Increase in compression ratio would result in knocking. When hydrogen needs to be used for C.I. engines, it is to be noted that the self-ignition temperature of the hydrogen is 576°C , and is not possible to achieve the temperature during normal compression stroke even at higher compression ratios. Researchers at Cornell University failed to achieve Compression Ignition of hydrogen at Compression ratio of 29, this concluded some external sources are required to ignite hydrogen[6]. In-case of diesel engine co-fuelling of diesel with LPG [7, 8], methane [9, 10], natural gas [11] and hydrogen-methane combination were studied. Most research in dual fuel engine has concentrated on defining the extent of dual fuelling and its effect on emissions and performance [12] hydrogen addition to methane has been reported to be effective to promote combustion at homogeneous lean operation.

Table 1. Properties of Diesel and Hydrogen[13].

Property	Diesel	Hydrogen
Auto ignition temperature (K)	530	858
Flammability limits (% vol. in air)	0.7-5	4-75
Density at 16°C and 1 Bar (kg/m^3)	833-881	0.0838
Flame Velocity (cm/s)	30	265-325

III. EXPERIMENTAL SETUP AND TEST PROCEDURE

3.1. Engine and Instrumentation Systems

The essential components for the experimental setup were chosen properly and assembled keeping in mind the objectives of the present work. The instrumentation systems were selected judiciously with a clear understanding of their working, range and limitations.

The engine used in the present study is Kirloskar TV-1, fully computer interfaced, single cylinder, water cooled, four stroke compression ignition diesel engine with specifications given in Table 2, while a schematic diagram of the test rig setup is shown in fig. 1. This engine is coupled to an eddy current dynamometer to test the load capability of the engine. Air temperature sensor, coolant temperature sensor and throttle position are connected to open electronic control unit which controls fuel injector, fuel pump and idle air. The test rig include other standard engine instrumentation, such as thermocouple to measure oil, air, inlet manifold and exhaust temperatures and pressure gauges mounted at relevant points. Load on the engine was measured using strain gauge load cell. Coolant water supplied to the engine is measured using a Rotameter. Hydrogen is stored in a compressed gaseous form at a pressure of 150 bar in commercially available cylinders with pressure indicators to read the inside pressure and with pressure reduction valves to reduce the pressure to atmospheric level before injecting in the inlet manifold. Hydrogen flows were measured by using a specially designed flow meter. To damp the pressure fluctuations in the intake line which particularly occur with large displacement single cylinder engines, flashback arrestor for hydrogen was provided at the inlet of the engine. Additionally, along with the flashback arrestor, a flame arrestor is also used in the hydrogen supply line. It consists of two interconnected stainless steel cylinders half filled with water. Hydrogen has to pass through these arrestors before reaching the engine manifold. In case of any accidental flame generation in the supply hose pipe, the flame is put off by water.

The exhaust gas analyser used is MN-05 multi gas analyser (5gas version) is based on infrared spectroscopy technology with signal inputs from an electrochemical cell. Non-dispersive infrared measurement technique used for the measurement of CO, CO₂, and HC gases. Each individual gas absorbs infra-red radiation that can be used to calculate the concentration of sample gas. The Gas Analyser uses an electrochemical cell to measure oxygen concentration. It consists of two electrodes separated by an electrically conducted liquid or cell. The cell is mounted behind a polytetrafluorethene membrane through which oxygen can diffuse. The device therefore measures oxygen partial

1.Engine 2.Variable Compression Ratio 3.Eddy Current Dynamometer 4.CA Encoder 5.Load Sensor 6.Rotameter 7.Loading Unit 8.Burette 9.U-Tube Manometer 10.Hydrogen Cylinder 11.Pressure Guage 12.Pressure Regulator 13.Flash Back Arrestor 14.Hydrogen Flow Meter 15.Flame Arrestor 16.Mixing Chamber 17.Ambient Air 18.Fuel Line Pressure Sensor 19. Cylinder Pressure Sensor Line 20.NI-6210 USB Multifunction Line 21.Exhaust Gas Analyzer

Fig.1. Schematic Layout of Hydrogen-Diesel Dual Fuel Engine Test Rig

Table 2. Specifications of Test Engine

Particulars	Specifications
Type	Vertical, 4-Stroke Cycle, Totally Enclosed, Water cooled
Make	Kirloskar Oil Engines
Model	TV-1
Type of Ignition	Compression Ignition
Rated Power (kW)	3.5
Constant Speed (rpm)	1500
Bore (mm)	87.5
Stroke (mm)	110
Connecting Rod Length (mm)	234
Compression Ratio	17.5
Cylinder Capacity (cc)	661
Fuel Injection	Direct Injection
Injection Timing	23° BTDC
Dynamometer	Eddy Current Type
Piston Bowl	Hemispherical
Starting	Auto Start
Injection Pressure (bar)	200
Injector Nozzle Diameter (mm)	0.15

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Vol. 5, Issue 2, February 2016

3.2. Experimental Procedure

Several series of experimental cycles were conducted with varying hydrogen substitutions at 10%, 20% and 30% by mass of fuel. At each cycle, the engine was operated at rated injection opening pressure of 200 bar and the exhaust emissions were noted. The experiment was carried out at a constant speed of 1500 rpm and at a compression ratio of 17.5:1. The injection timing was set to a value of 23° BTDC. The load was varied from 0% to 100% at an interval of 25%. The in-cylinder pressure was recorded using a piezoelectric sensor. A digital shaft encoder was used to measure crankshaft position. The signals from piezo sensors and the crank encoder were acquired using national instruments logical card. Data acquisition and combustion data analysis were measured using National Instruments Lab VIEW acquisition system developed in-house. The combustion analysis was based on the averaged value 100 cycles after the engine reached steady state operation.

The engine was first started on diesel stable operation and hydrogen was gradually inducted through the intake manifold. Initially the hydrogen from the cylinder enters into the flash back arrestors and then into the flame arrestors and then into the mixing chamber with the desired flow rate by using flow meter. Here the hydrogen mixes with air. Because of the enrichment of hydrogen with air in the mixing chamber, proper atomisation takes place with the diesel fuel and peak pressure was observed inside the combustion chamber. The diesel is used as a pilot fuel. When hydrogen supply was increased, the diesel injection was automatically decreased due to the governor mechanism of the engine to maintain a constant speed. During the operation of the engine all the parameters are noted from digital display and digital data acquisition system and the data to calculate performance and combustion parameters are noted from the computer. Engine exhaust emissions are noted using exhaust gas analyser by inserting the gas analyser gun in exhaust gas pipe of the engine.

IV. EXPERIMENTAL RESULTS

An experimental investigation was carried out for performance, combustion and exhaust emissions of the engine by inducting hydrogen at various percentages and at different loads and various performance, combustion and emission parameter graphs have been drawn with respect to brake power. The plotted graphs depicts the comparative study of a diesel engine operating under pure diesel mode and dual fuel mode.

4.1 Effect of Hydrogen Substitution on Performance Parameters

4.1.1. Brake Thermal Efficiency (BTE)

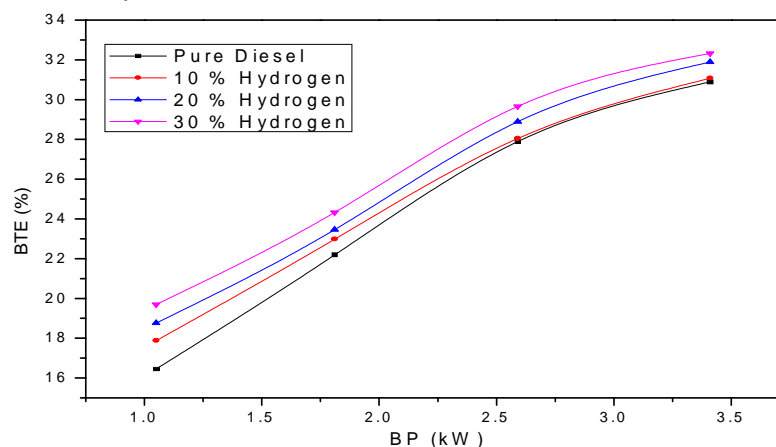


Fig. 2. Influence of BTE Vs BP at different Hydrogen Substitutions and Pure Diesel

Brake thermal efficiency is the measure of performance of the engine calculated as the ratio of brake power generated to the heat input. From the above fig. 2 it was depicted that as the substitution of hydrogen increases BTE also increases at all load conditions. At full load conditions the BTE was maximum for 30% of hydrogen and then followed by 20%, 10%

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 2, February 2016

and then for pure diesel. Highest value of BTE was at 30% hydrogen i.e. 32.5%. The reason behind high values of BTE are the unique properties of hydrogen such as its wide flammability limits, high flame velocity and high calorific value.

4.1.2. Brake Specific Fuel Consumption (BSFC)

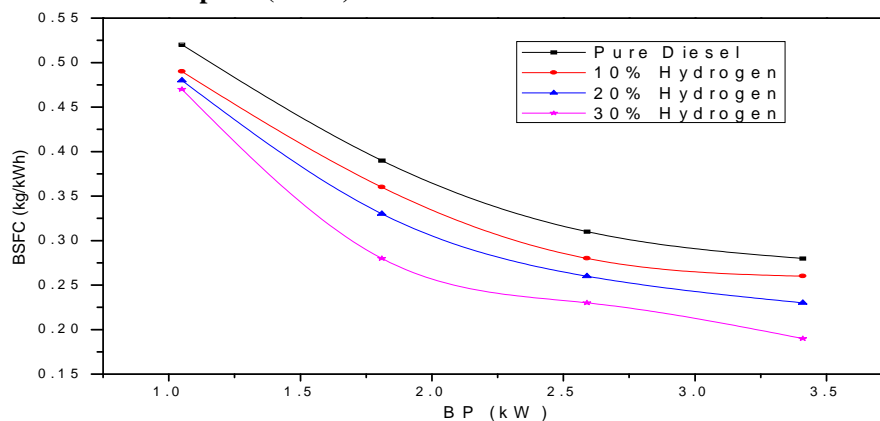


Fig. 3. Influence of BSFC Vs BP at different Hydrogen Substitutions and Pure Diesel

Brake specific fuel consumption is the measure of quantity of fuel consumed to produce per kW of power in an hour. From the above fig. 3 it was clearly noticed that as the percentage of hydrogen substitution increased, the corresponding value of BSFC decreased for all loading conditions. The lower brake specific fuel consumption for hydrogen-diesel dual fuel was due to better mixing of hydrogen with air resulting in complete combustion of fuel. Minimum value of BSFC was observed at 30% hydrogen substitution i.e. 0.19 kg/kWh operating under full load condition.

4.1.3. Volumetric Efficiency

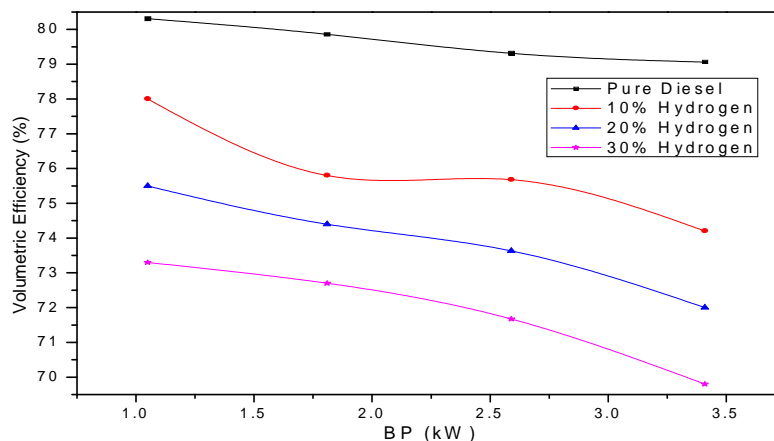


Fig. 4. Influence of Volumetric Efficiency Vs BP at different Hydrogen Substitutions and Pure Diesel

The above figure depicts the variation of volumetric efficiency with BP for different substitutions of hydrogen compared with the pure diesel. Volumetric efficiency of an engine is defined as the ratio of actual air capacity to the ideal air capacity. To ignite pure diesel, the requirement of air quantity was more than that of the air quantity required for different hydrogen substitutions. Hence the volumetric efficiency for pure diesel mode operation was higher than that of hydrogen substitutions. Highest value of volumetric efficiency was observed for pure diesel operation i.e. 80.31% at no load condition. The trend of volumetric efficiency from low loads to high loads was decreasing gradually.

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 2, February 2016

4.2. Effect of Hydrogen Substitution on Emission Parameters

4.2.1. Carbon Monoxide (CO) Emissions

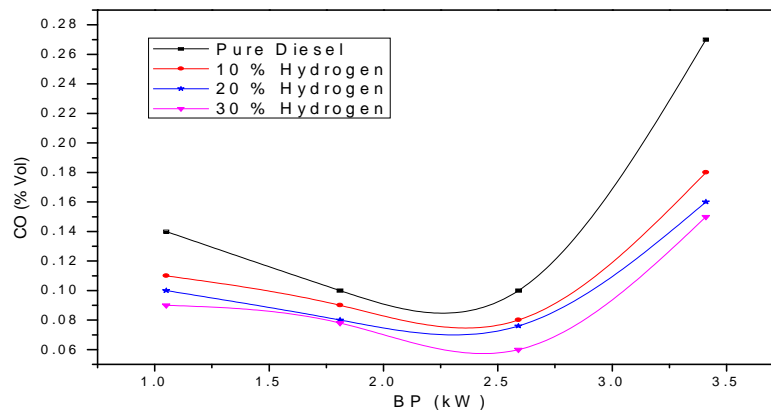


Fig. 5. Influence of CO Vs BP at different Hydrogen Substitutions and Pure Diesel

The above figure reveals the formation of CO with BP at different loads. It was observed that as the load increased up to 75%, the formation of CO decreased at all percentage substitutions of hydrogen. Since hydrogen is free from carbon content, the formation of CO emissions decreases up to 75% load. In pure diesel mode operation, due to the presence of more excess air, the carbon oxidation reaction is almost complete and the considerable amount of CO is not produced until the smoke limit is reached. But as the load increased from 75% to full load, CO formation increases rapidly, because CO is a product of incomplete combustion due to insufficient amount of air in air-fuel mixture and insufficient time in the cycle for completion of combustion at full load. The minimum CO content was observed at 30% hydrogen substitution at 75% load i.e. 0.06% by volume.

4.2.2. Carbon Dioxide(CO₂) Emissions

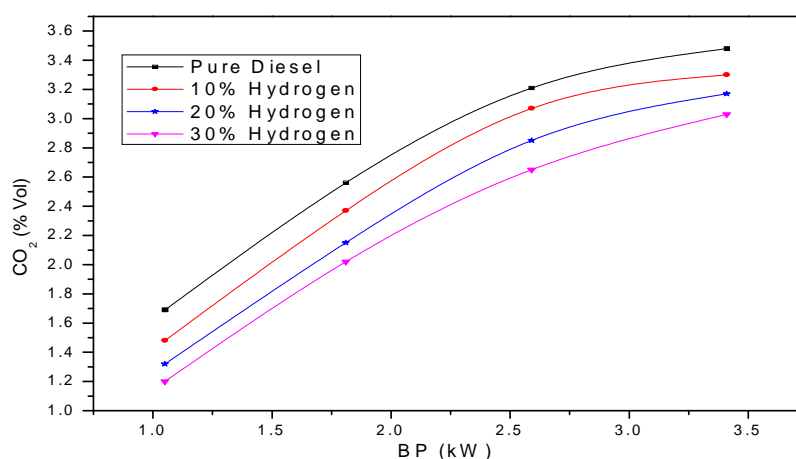


Fig. 6. Influence of CO₂ Vs BP at different Hydrogen Substitutions and Pure Diesel

The effect of carbon dioxide with BP is explained in the above fig. 6. It was noticed that the content of CO₂ emissions were maximum under pure diesel mode compared to different substitutions of hydrogen at all loads. As the load increased from 0% to 100%, the CO₂ content increased for all substitutions of hydrogen and pure diesel because more amount of diesel was injected as the load was increased for the same amount of hydrogen.

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 2, February 2016

4.2.3. Nitrous Oxide(NO_x) Emissions

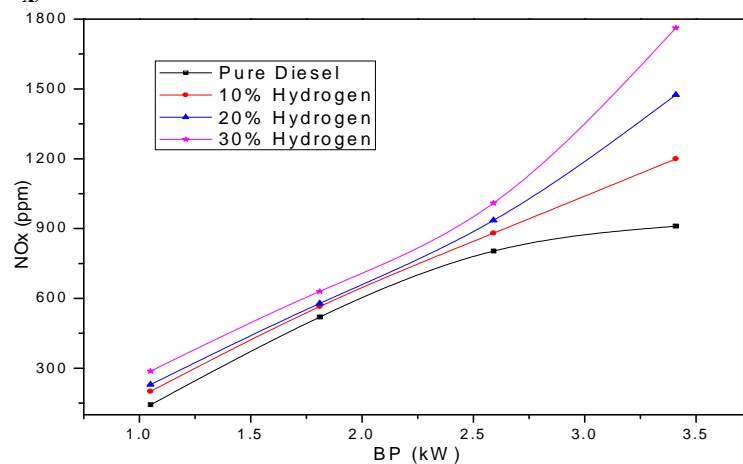


Fig. 7. Influence of NO_x Vs BP at different Hydrogen Substitutions and Pure Diesel

The above fig. 7 shows the effect of oxides of nitrogen with BP. Nitrous oxides are formed inside the combustion chamber due to the presence of excess oxygen and high combustion temperature that favours for oxidation reaction. It was noticed that as the percentage substitutions of hydrogen increased, the NO_x content also increased when compared to pure diesel mode. The burning velocity of hydrogen is so high that the rapid combustion is achieved, this leads to the formation of more amount of NO_x compared to pure diesel mode. Maximum amount of NO_x was observed at full load for 30% of hydrogen substitution i.e. 1660 ppm.

4.2.4. Unburnt Hydrocarbon (UHC) Emissions

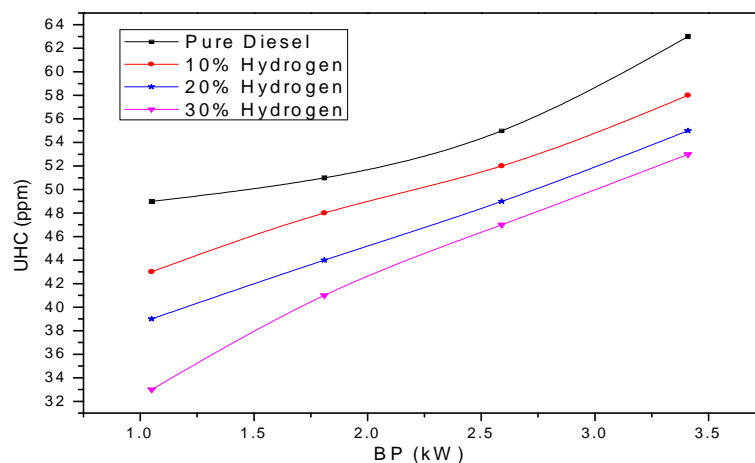


Fig. 8. Influence of UHC Vs BP at different Hydrogen Substitutions and Pure Diesel

The above figure depicts the variation of UHC with BP at different substitutions of hydrogen and pure diesel. As the brake thermal efficiency was maximum for 30% hydrogen substitution compared to pure diesel, hence UHC content was less. The reason behind less UHC content was maximum amount of diesel particles taking part in the combustion process under dual fuel mode as well as proper atomization of fuel occurs when hydrogen is inducted in dual fuel mode. Minimum content of UHC was observed at full load for 30% hydrogen substitution i.e. 50 ppm.

4.3.Effect of Hydrogen Substitution on Combustion Parameters

4.3.1. Cylinder Pressure

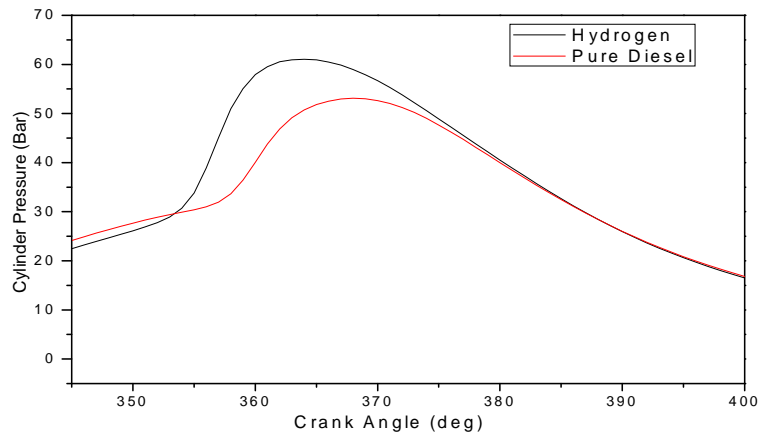


Fig. 9. Effect of Hydrogen Substitution on Cylinder Pressure

The fig. 9 depicts the relation between cylinder pressures and crank angle. Cylinder pressure is one of the important combustion parameter. As the substitution of hydrogen increased in different proportions with diesel, the cylinder pressure increased because of unique properties of hydrogen such as higher flammability limits, rapid combustion and better air-fuel mixture. Comparatively cylinder pressure was high for hydrogen substitution compared to pure diesel mode. The peak pressure was observed to be 61.6 bar at 363.8° crank angle for hydrogen substitution.

4.3.2. Net Heat Release Rate

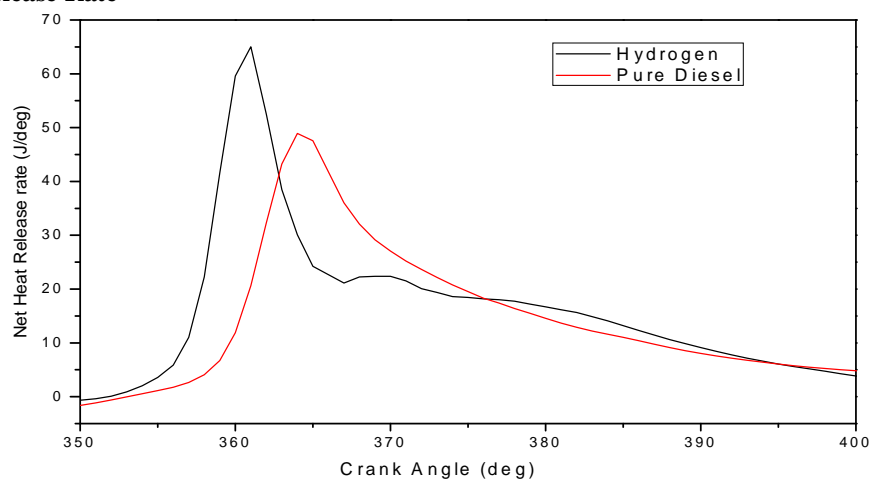


Fig. 10. Effect of Hydrogen Substitution on Net Heat Release Rate

The above fig. 10 represents the variation of net heat release with crank angle at full load condition. The trend of net heat release rate of hydrogen was continuously increasing when compared with pure diesel operation. The peak net heat release rate for hydrogen is 64.41 J/deg at 362.29° crank angle. This is because burning of hydrogen gives higher flame velocity and also instantaneous combustion and heat liberated in the premixed combustion zone is higher.

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(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 2, February 2016

V. CONCLUSIONS

- From the experimentations, it was noticed that BTE was maximum for 30% hydrogen followed by 20%, 10% hydrogen and then for pure diesel operation. There was a continuous increment in the BTE as the hydrogen substitution increased due to the properties of hydrogen such as wide flammability limits and high calorific value.
- Brake specific fuel consumption decreased as the substitutions of hydrogen increased when compared to pure diesel mode. Minimum BSFC was observed at 30% of hydrogen at full load condition. The lower BSFC for hydrogen-diesel dual fuel was due to better mixing of hydrogen with air resulting in complete combustion of fuel.
- Volumetric efficiency was maximum for pure diesel mode. It was noticed that volumetric efficiency was higher at low loads for all substitutions of H₂ and similar to pure diesel.
- As percentage substitutions of hydrogen increased, CO content decreased up to 75% load compared to pure diesel. But as the load increased from 75% to full load, CO formation increases rapidly due to incomplete combustion.
- It was noticed that the content of CO₂ emissions were maximum under pure diesel mode compared to different substitutions of hydrogen at all loads.
- The burning velocity and combustion temperature are maximum under hydrogen operation, hence the formation of NO_x inside the combustion chamber at any substitutions of hydrogen was more than that of pure diesel mode.
- At all hydrogen substitutions the BTE was higher than that of pure diesel mode, and hence UHC content was minimum for all hydrogen substitutions. Also due to proper atomization and maximum participation of fuel in the combustion process, UHC content was less.
- As the substitution of hydrogen increased in different proportions with diesel, the cylinder pressure increased. Comparatively cylinder pressure was high for hydrogen substitution compared to pure diesel mode.
- Since burning of hydrogen gives higher flame velocity leading to instantaneous combustion, the peak net heat release rate was noticed for hydrogen substitutions compared to pure diesel mode.

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