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Experimental study of hydrogen use in a diesel engine in automotive

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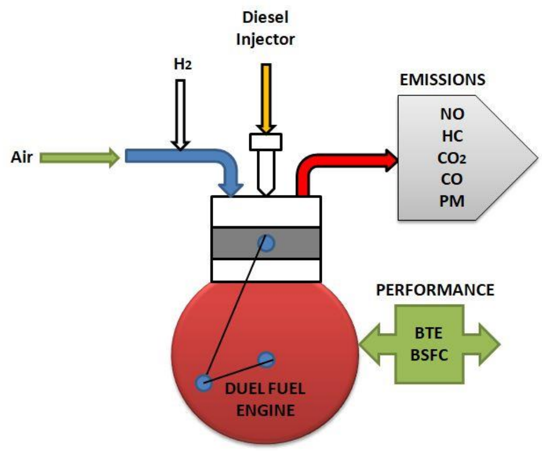
Graphical abstract



Abstract

The main objective of this experiment is to reduce the major pollutants NO and particulate matter that is emitted by diesel engines to avoid green house gases. The critical part is that reducing both the NO and particulate matter simultaneously is not possible. If we try to reduce PM, NO increases and vice versa. Based on this concept in this research, hydrogen is used in addition to diesel, as hydrogen represents a good alternative fuel to reduce emissions. Some experimental aspects with respect to hydrogen flow 0.024, 0.041, 0.08 and 0.09 kg per hour along with diesel fuel. The amount of hydrogen injected into the chamber will be compensated by reducing the diesel quantity 1.081, 1.030, 0.94 and 0.866 kg per hour at one fourth, half , three fourth and full load respectively, at a speed of 1500 rpm water cooling. The engine is equipped with Engine Soft software that captures and stores the data. In the first phase, the experiment was conducted using diesel fuel and in the second phase the diesel fuel and hydrogen at different flow rates were used to enhance the combustion. At full load for 0.041 kg per hour, the gas of hydrogen CO was reduced by 37.5%, HC by 60%,NO by 22.45%. CO_2 was reduced by 45.8% at 0.08 kg per hour of hydrogen. At 0.09 kg per hour of hydrogen injection, the particulate matter was decreased by 79.6%. At full load and for 0.09 kg per hour flow rate, the brake and indicated thermal efficiency was increased by 33.4% and 32.4%, respectively.

Keywords: Hydrogen gas, Green house gases, Combustion, Nitric oxide, Particulate matter, efficiency

1. Introduction

Liu *et al.* (2023) researched the improvement of diesel engine combustion with hydrogen as secondary fuel at variable loads and the impact of EGR and tried to achieve maximum hydrogen substitution. The author observed that as hydrogen quantity increases, the combustion acceleration and the flame propagation were also very faster. The peak cycle pressure and net heat release rate were also increased compared to those of diesel fuel alone. As emissions are concerned the carbon dioxide and NO were reduced at medium loads and increased at higher loads. When the exhaust gas recirculation process was done, the amount of oxygen content was reduced; hence there was a decrease in peak cycle pressure and heat release rate. CO emissions increased and NO emissions were reduced drastically Tutak *et al.* (2023) researched on the performance and emissions using hydrogen with diesel and bio- diesel (co- combustion). The author used hydrogen component up to 34%. The authors observed that the ignition delay had no impact with increasing, hydrogen quantity and efficiency when using rape seed methyl esters. Regarding CO, CO_2, soot emissions decreased, while NO (nitric oxide) and HC increased. The highest efficiency was observed when the hydrogen percentage was taken at 12%. Emissions are related to the fact that diesel and rape seed oil along with hydrogen has shown very positive results. Cernat.et.al. conducted experiments using a single–cylinder test rig using hydrogen substitutes and observed the performance and emissions. When the author used 20% hydrogen, there was a cycle pressure raised by 12.9% compared to diesel. The heat release rte increased because hydrogen has a lower heating value compared to diesel by 42.5%. The author also observed that the rate of combustion increased as the hydrogen component was added to diesel fuel. As regards pollutants, NO was reduced by 50%, whereas CO and CO_2 were reduced by 20% and 8.2%. Soot emission was decreased by 17% Wright *et al.* (2022) worked on a diesel engine with hydrogen as secondary fuel and focused on emissions with modest technology adoption. The author observed engine load as a key factor influencing NO formation. The author observed that as the load increases, the NO component is going to increase by using hydrogen as supplementary fuel. The author also observed that exhaust gas recirculation will decrease NO emissions to some extent. Ekin *et al.* (2022) The author conducted simulations using ANSYS, software in tow modes on test rig by natural gas and diesel as fuel. In the first mode, natural gas and hydrogen were used, and in the second phase hydrogen enrichment on natural gas. The author was observed that the fuel injected is advanced to 30°CA BTDC knocking occurred. Improvements were observed if the injection took place 10 to 18°CA BTDC. The improvement in BSFC in the first mode was 21 to 30% and in the second mode NO increased by 12%. The thermal efficiency was increased in both modes. Cameretti *et al.* (2022) focussed on dual fuel combustion with hydrogen and methane blends to understand the impact of hydrogen on the combustion process and emissions. The author observed that the addition of methane leads to low efficiency and that when hydrogen was added, the efficiency was increased and emissions were decreased. It was also observed that when the temperature component increases, NO_X formation was observed. The author observed that accumulation of hydrogen should not take place in the crevice region.Suryakant *et al.* (2021) In this research, the author used different bio- diesel fuels. The author had conducted experiments using hydrogen gas at a flow rate of 7 litres per minute at the inlet manifold. Bio-diesel rice bran oil, karanja oil, are used in six different combinations. The enrichment of hydrogen improved. The results indicate that hydrogen enrichment improves combustion and results in a 2.5% and 1.6% increase in the thermal efficiency.

By understanding the literature review, it was observed that experiment would be performed with hydrogen injection along with diesel at different flow rates, to identify the optimum flow rate of hydrogen so as to improve the efficiency and reduce the pollutants, especially NO and PM as these two are the major pollutants in diesel engine combustion which are responsible for global warming. This experiment can be conducted on any model of engine. The results are more focused towards simultaneous reduction of NO and soot. It is applicable for other engine types also.

Cost incurring parameters: 1) Hydrogen cylinder with look up table system and 2) Hydrogen gas cost. The look up tables system is provided by the manufacturer based on prior experiments and it lists the mass of the hydrogen with various combinations of pressure and temperature. For example, if the pressure in the cylinder is measured at a given temperature, the table can be used to find the corresponding amount of hydrogen (in grams or kilograms) inside the system.

2. Materials and methodology

Fuels used are diesel and hydrogen gas

Calibration of the Instrumentation Used for the Conduction of Experiments

In the first phase conduction experiment, diesel was used as fuel at all loads.

In the second phase, hydrogen gas is used as secondary fuel in addition to diesel fuel.

Hydrogen injection was taken for 3, 4, 5 and 6 milli seconds with flow rates of 0.024 kg / hour , 0.041kg/ hour,0.08kg/ hour and 0.09 kg/ hour (The weight of hydrogen can be calculated by

{(flow rate of Diesel) x (calorific value of Diesel)}/ (calorific value of hydrogen))

Reduction of diesel fuel to compensate for equivalent hydrogen gas at all hydrogen flow rates

Comparison and analysis of results.

3. Results and discussion

Table 1. Engine specifications

Engine Name	CRDI VCR test (computerized)
Make	Kirloskar
Number of cylinders	1
Number of strokes	4
Type of cooling	Water cooled
Stroke length	110mm
Bore	87.5mm
Conrod length	234mm
Size of orifice	20mm
Dynamometer arm	185mm
Output	3.5 kW
CR range	12.1 to 24.1
Crank angle sensor	Resolution 1 Deg, speed 5500 RPM with TDC pulse
Temperature Sensor	Type RTD, PT 100 and Thermocouple, Type K, Range 0-1200 Deg C
Load sensor	Load cell. Type strain gauge, range 0-50 kg
Fuel tank	Capacity 15lit, Type: Dual compartment
Common rail	With pressure sensor and pressure regulating valve
Injector	Type solenoid driven

3.1.1. Test engine

The experimental setup consists of a cylinder, four- stroke, CRDI engine connected to eddy current dynamometer. It is equipped with the instrumentation for combustion pressure, and other all emissions . All the signal inputs are connected to data acquisition system.

The setup enables study of the performance of the CRDI VCR engine with programmable ECU at different compression ratios and with different Eexhaust Gas Re circulation. The engine performance study includes brake power, indicated power, frictional power, BMEP, IMEP, brake thermal efficiency, indicated thermal efficiency,mechanical efficiency, volumetric efficiency, specific fuel consumption, air fuel ratio, heat balance and combustion analysis.

Table 2. Properties of the fuels used

Properties of fuel	Diesel	Hydrogen
Mass density	824 kg/m^3	0.081 kg/m^3
LCV	42.5mJ/kg	120mJ/kg
HCV	44.8mJ/kg	141.9mJ/kg
Relative density	0.83	0.091
CN	44-55	0
Carbon content	86(% wt.)	0(% wt.)
Hydrogen content	13(% wt.)	100(% wt.)
Mole weight	148.3gm	1.92gm
Auto ignition	524K	854K
Octane N	15-25	130

Figure 1. Engine setup with instrumentation

3.1.2. Fuel and injection system

In this research work, diesel fuel and hydrogen gas are used as fuels with different flow rates. Diesel has a calorific value of 43000 kJ per kg. It is the most abundant element in the universe, with an atomic number of one. With a density of 0.089 g/lit, it has a high calorific value of approximately 120 MJ/kg and an octane number of 130. It produces a high flame speed and heat of combustion. It is also known as a clean or green fuel because it does not emit carbon, CO_2, or HC. However, hydrogen must be operated safely during its applications. The multi fuel port injector system is a fuel injection system that can work with a variety of fuels, including petrol, ethanol, and compressed natural gas (CNG). It employs a set of injectors designed to deliver the appropriate amount of fuel for each fuel type, ensuring that the engine receives the appropriate amount of fuel regardless of the fuel type used. The multifuel port injector system is useful in areas where various types of fuel are available or cost-effective, as it can help reduce emissions and improve fuel efficiency. However, it is more complex and expensive than traditional fuel injection systems, and requires additional maintenance to ensure proper operation.

3.1.3. Data storage system

A digital storage oscilloscope (DSO) is an electronic device that measures and analyzes electrical signals over time. It uses digital sampling and storage technology to display signals as waveforms on a screen. It is widely used in electronics, telecommunications and power systems to perform advanced signal analysis with greater accuracy than traditional analog oscilloscopes. The DSO can store and analyse large amounts of data, making it a powerful tool for troubleshooting complex systems. It provides flexibility and versatility in terms of triggering, waveform capture, and data analysis, making it an indispensable tool for engineers and scientists.

3.1.4. Measurement Of Air/Fuel/Temperature/Pressure

Airflow in an engine is typically measured using a U-tube manometer connected to an air box with an orifice. The orifice diameter is typically around 20 mm, allowing for accurate measurement of airflow. Fuel measurement, on the other hand, involves inserting a fuel flow meter into the fuel line that connects the fuel tank to the engine. This device measures the amount of fuel that passes through the line and is used by the engine control unit (ECU) to improve engine performance by adjusting fuel injection timing.

To measure temperature in an engine, thermocouples with a range of 0 to 1200°C are used. The thermocouple readings are typically transmitted through a 4-20mA current loop, while the device is powered by a 24 V DC power supply. Pressure measurement is also essential for optimum engine performance, and pressure sensors are typically installed in the combustion chamber, intake manifold, and exhaust system. The ECU then uses the pressure readings to adjust fuel injection, ignition timing, and other engine parameters to improve performance and lower emissions.

3.1.5. Emission measurement

Portable exhaust gas analysers are used for measuring emissions. Some models may also measure. A portable exhaust gas analyzer is typically mounted on the tailpipe of the engine under test. The engine is then run under a variety of conditions, such as idle, load, and speed, while the analyser measures the emissions. The results are shown on a screen or printed for analysis.

3.1.6. Results and Discussions

(a) Performance curves

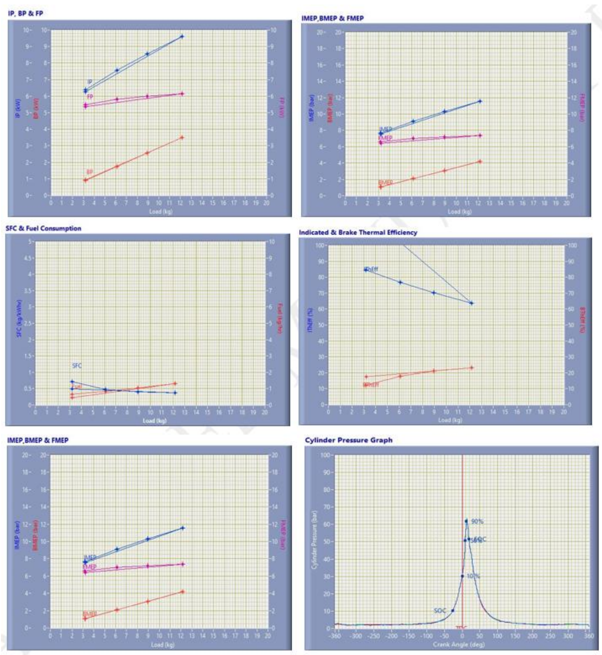


Figure 2. Performance curves for diesel fuel.

From Figure 2 it was observed that in full load conditions the indicated brake and frictional horse power was observed as 6.27, 3.49 and 6.13 respectively. At full load conditions, the indicated mean effective brake mean effective pressure and frictional mean effective pressure were observed as 7.53, 1.11 and 6.42 bars, respectively. Specific fuel consumption was observed at full load of 0.49 kg per kilowatt hour. The indicated and brake thermal efficiency was observed at full load of 63.68 and 23.09%.

The cycle peak pressure was observed at 373 CA 63.17 bars. The torque at full load was observed to be 22.06 N m. Volumetric and mechanical efficiency was found to be 70.63% and 36.26% at full load. The net heat release rate was recorded as 63.23 J/kg at 368°CA.

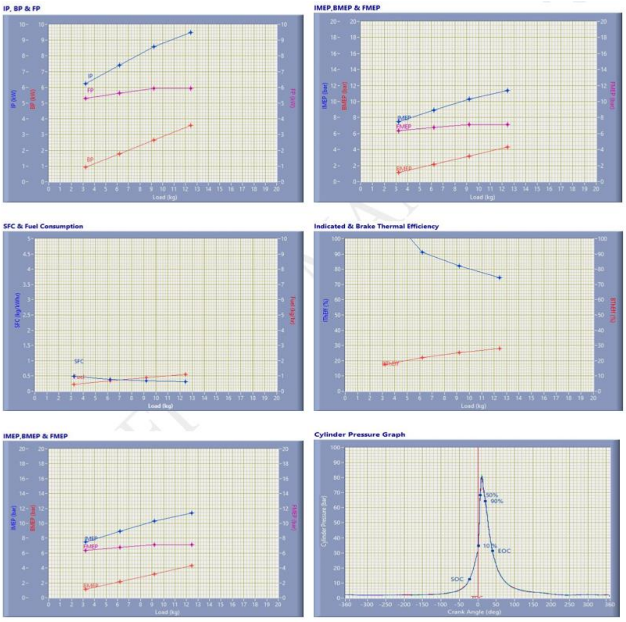


Figure 3. Performance curves for hydrogen at 0.024 kg /hour.

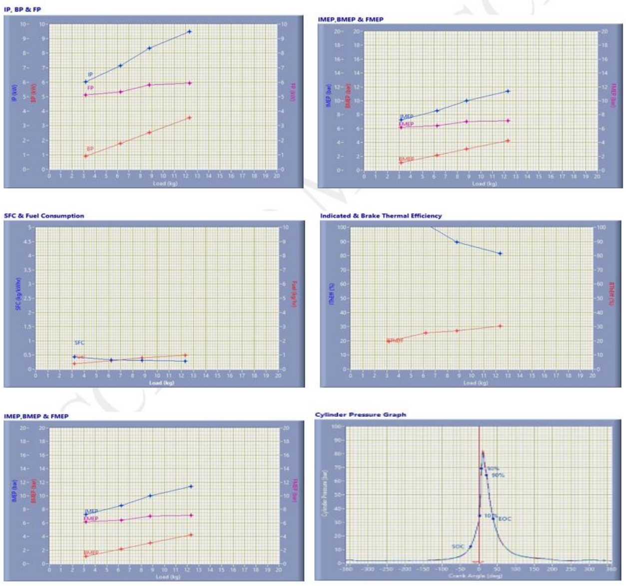


Figure 4. Performance curves for hydrogen at 0.041 kg /hour.

From Figure 3 when hydrogen gas was injected at a rate of 0.024 kg / hour into the cylinder, the brake thermal efficiency was increased by 21.09% when compared to diesel fuel. The indicated thermal efficiency was increased by 16.66%. The air flow was decreased by 0.93%.The fuel flow was decreased by 15.38%. Specific fuel consumption was reduced by 16.22%. Fuel consumption decreased by 14.73% Torque increased by 2.4%. Mechanical efficacy was increased by 3.81%. The volumetric efficiency decreased by 0.52%.The cylinder pressure increased by 28.32% and the net heat release rate also increased by 36.96%.

From Figure 4 When the hydrogen gas was injected at a rate of 0.041 kg per hour injected in the cylinder, the brake thermal efficiency was increased by 32.01% when compared to diesel fuel. Indicated thermal efficiency was increased by 28.25%. The air flow was decreased by 2.06%.The fuel flow decreased by 23.08%. Specific fuel consumption was reduced by 24.32%. Fuel consumption decreased by 22.48%, torque increased by 1.54%. Mechanical efficacy was increased by 2.92%. The volumetric efficiency decreased by 1.03%.The cylinder pressure increased by 28.46% and the net heat release rate also increased by 40.61%.

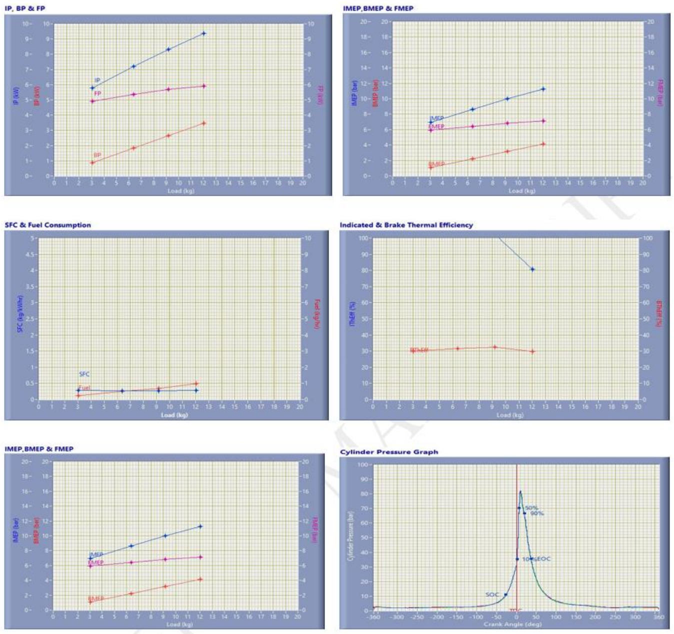


Figure 5. Performance curves for hydrogen at 0.08 kg /hour

From Figure 5 When the hydrogen gas was injected at a rate of 0.08kg per hour in the cylinder, the thermal efficiency increased by 40.49% compared to diesel fuel. Indicated thermal efficiency was increased by 26.59%. Air flow was reduced by 3.44%. Fuel flow decreases by 23.08%. Specific fuel consumption was reduced by 21.62%. Fuel consumption was reduced by 22.48%, torque was decreased by 0.91%. Mechanical efficiency increased by 1.77%. The volumetric efficiency decreased by 1.74 %. Cylinder increased by 28.91% and the net heat release rate also increased by 43.62%.

From Figure 6 when the hydrogen gas was injected at a rate of 0.09kg per hour in the cylinder, the brake thermal efficiency was increased by 50.19% when compared to diesel fuel. Indicated thermal efficiency was increased by 48.15%. The air flow was decreased by 6.6%. The diesel flow decreased by 34.62%. Specific fuel consumption was reduced by 32.43%.Fuel consumption decrease by 34.11%, Torque decreased by 1.95%. Mechanical efficiency decreased by 1.21%. The volumetric efficiency decreased by 2.07%.The cylinder pressure increased by 29.10% and the net heat release rates also increased by 46.15%.

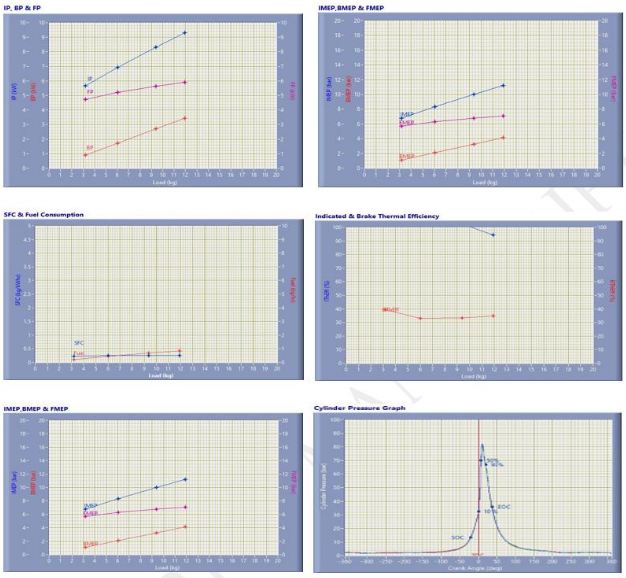


Figure 6. Performance curves for hydrogen at 0.09 kg /hour

(b) Emission curves

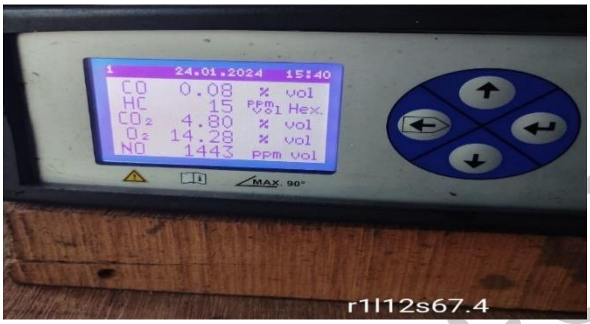


Figure 7.2.1. Emissions only with diesel.

Figure 7.2.2. Emissions diesel with hydrogen at 3ms

Figure 7.2.3. Emissions diesell with hydrogen at 4ms

Figure 7.2.4. Emissions diesel with Hydrogen used at 5ms

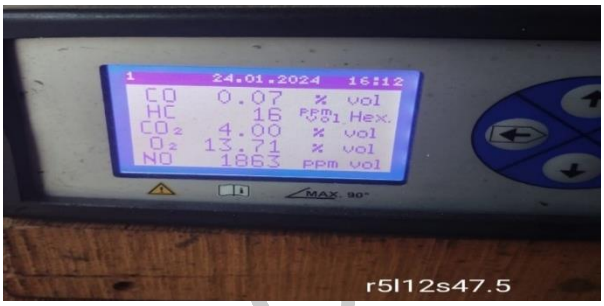


Figure 7.2.5. Emissions diesel with hydrogen at 6ms

Figure 7.2.1 shows that when diesel is used at full load, 67.4 ppm of particulate matter (PM), 0.08% of carbon monoxide (CO), 15 ppm of hydrocarbons (HC), 4.8 % of carbon dioxide (CO2), and 1443 ppm of nitrogen oxides (NO) are released into the air. Figure 7.2.2 shows that using a mixture of diesel and hydrogen (H2) at 3 m/s produces 66.6 ppm of PM, 0.07% volume of CO, 16 ppm of HC, 4.10% volume of CO_2 and 1456 ppm of NO. At 4 m/s (Figure 7.2.3), the diesel-H2 blend produces 53.1 ppm of PM, 0.04% volume of CO, 6 ppm of HC, 2.80% volume of CO_2 and 1119 ppm of NO. Using the mixture at 5 m/s (Figure 7.2.4) results in emissions of 53.4 ppm of PM, 0.05% of CO, 10 ppm of HC, 2.60% of CO2, and 1165 ppm of NO. Finally, at 6 m/s (Figure 7.2.5), the emissions include 47.5 ppm of PM, 0.07% volume of CO, 16 ppm of HC, 4.00% volume of CO_2 and 1863 ppm of NO.

3.2. P- θ CUREVS

Figure 7.3.1 shows a curve of cycle maximum pressure versus crank angle. It inclines from 300°CA to the peak at 373°, then declines to 500°CA, reaching a maximum pressure of 63.17 bar. Figure 7.3.2 plots a curve between the maximum pressure of the cycle and the angle of rotation, demonstrating an increase of 300 degrees to the peak of 371 degrees, followed by a decrease of 500 degrees. The maximum pressure reaches 81.06 bar, indicating a 28.32% increase compared to using only diesel when hydrogen is added at 3 m/s. Figure 7.3.3 shows a similar curve, with an incline of 300 degrees to the peak at 371 degrees and a subsequent decline. Adding hydrogen at 4 m/s results in a peak pressure of 81.15 bar, which represents a 28.46% increase compared to using only diesel. In Figure 7.3.4, the curve also shows an incline from 300 degrees to the peak of 371 degrees, followed by a decline. Adding hydrogen at 5 m/s results in a peak pressure of 81.43 bar, which represents a 28.90% increase compared to using only diesel. Figure 7.3.5 presents a curve with a similar pattern, inclining from 300 degrees to the peak at 371 degrees and declining afterward. Adding hydrogen at 6 m/s results in a peak pressure of 81.55 bar, which represents a 29.09% increase compared to using only diesel.

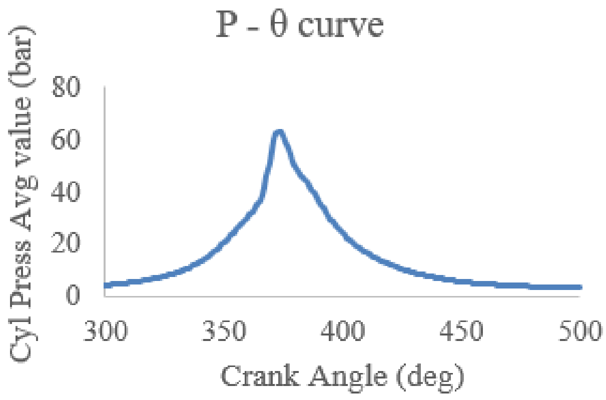


Figure 7.3.1. peak cycle pressure for Diesel

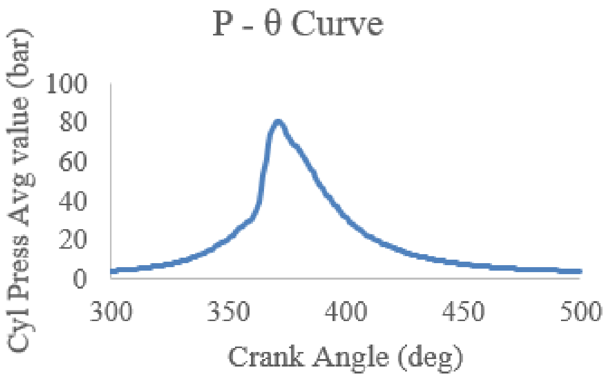


Figure 7.3.2. peak cycle pressure diesel with hydrogen 3ms

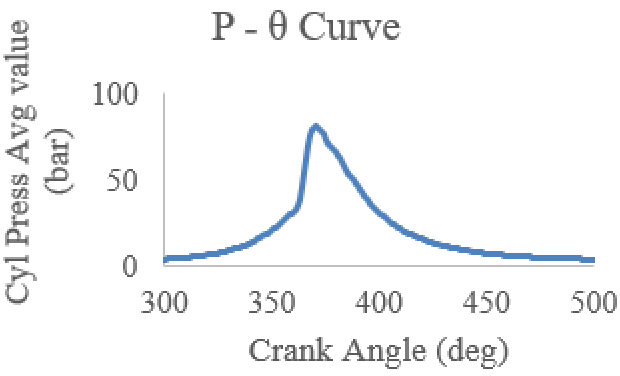


Figure 7.3.3. peak cycle pressure diesel with hydrogen 4ms.

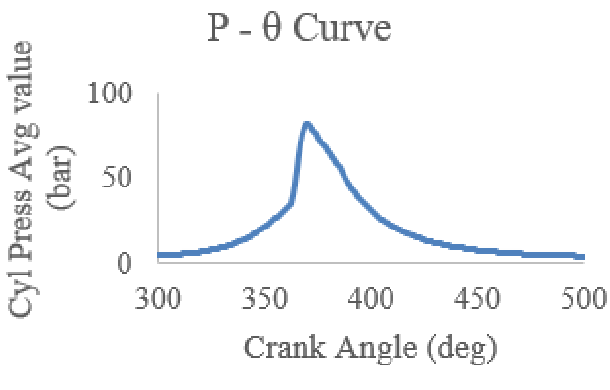


Figure 7.3.4. peak cycle pressure diesel with hydrogen 5ms.

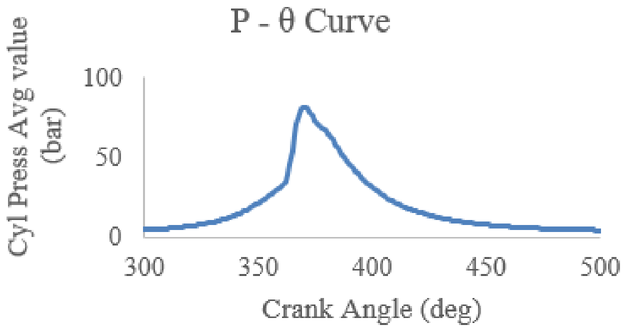


Figure 7.3.5. peak cycle pressure diesel with hydrogen at t 6ms.

3.3. Net heat release

From Figure 7.4.1 the curve typically starts with a gradual rise as the fuel-air mixture ignites and combustion begins. The flame front propagates through the combustion chamber, causing a rapid increase that peaks at a crank angle of 368 degrees. After reaching peak at 63.23 J/deg, the curve gradually declines as the combustion process completes and the exhaust gases begin to exit the cylinder. From figure 7.4.2 the curve typically starts with a gradual rise as the fuel-air mixture ignites and combustion begins. The flame front rapidly increases as it propagates through the combustion chamber, gaining a crank angle of 363 degrees. After reaching the peak at 86.6 J/deg, the curve gradually declines as the combustion process completes and the exhaust gases begin to exit the cylinder. From Figure 7.4.3 the curve typically starts with a gradual rise as the fuel-air mixture ignites and combustion begins. The flame front propagates through the combustion chamber, causing a rapid increase that peaks at a crank angle of 364 deg. After reaching the peak at 88.91 J/deg, the curve gradually declines as the combustion process completes and the exhaust gases begin to exit the cylinder. From Figure 7.4.4 the curve typically starts with a gradual rise as the fuel-air mixture ignites and combustion begins. The flame front rapidly increases as it propagates through the combustion chamber, eclipsing at a crank angle of 364 degrees. After reaching a peak at 90.81 J/deg, the curve gradually declines as the combustion process completes and the exhaust gases begin to exit the cylinder. The curve of figure 7.4.5 typically starts with a gradual rise as the fuel-air mixture ignites and combustion begins. The flame front propagates through the combustion chamber, causing a rapid increase that peaks at a crank angle of 364 deg. After reaching a peak at 92.41 J/deg, the curve gradually declines as the combustion process completes and the exhaust gases begin to exit the cylinder.

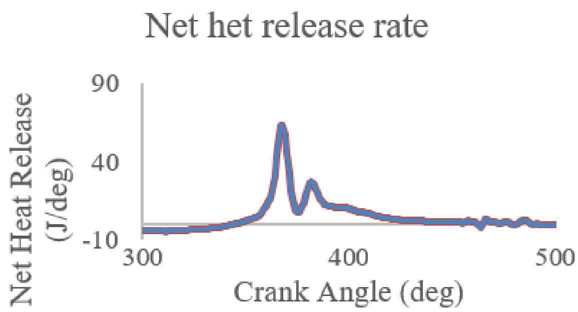


Figure 7.4.1. for Diesel only

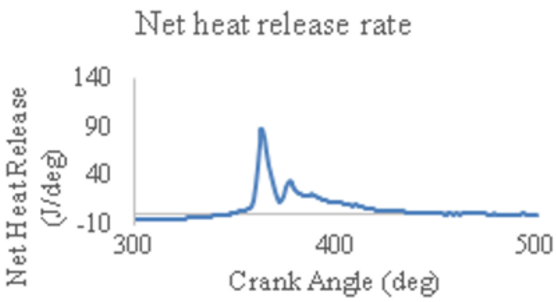


Figure 7.4.2. Diesel with hydrogen at 3 ms

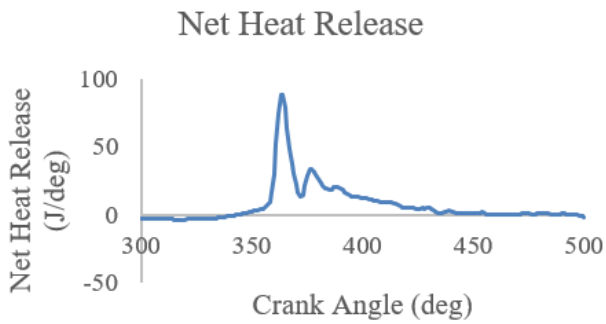


Figure 7.4.3. Diesel with hydrogen at 4 ms.

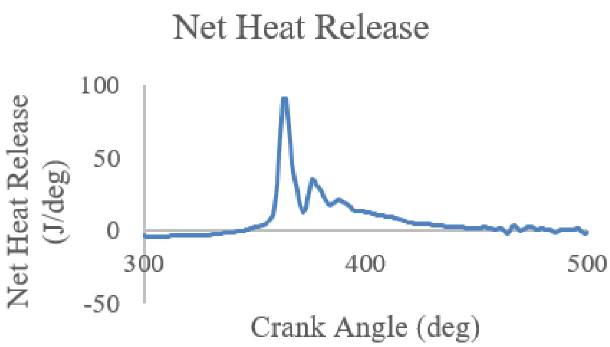


Figure 7.4.4. Diesel with hydrogen at 5 ms

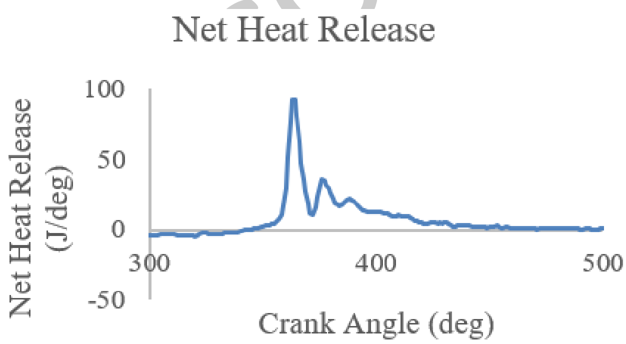


Figure 7.4.5. Net Heat Release vs. Crank Angle for Diesel + H_2 at 6ms

The research innovations are

Reduction in pollutants NO and soot which are reduced simultaneously to some extent which is not possible except by split injection. As, we try to reduce NO, soot will increase and vice versa. Amount of Diesel was reduced to the mass of hydrogen using look up tables.

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