International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:6, No:10, 2012

Hydrogen and Diesel Combustion on a Single Cylinder Four Stroke Diesel Engine in Dual Fuel mode with Varying Injection Strategies

Probir Kumar Bose, Rahul Banerjee, and Madhujit Deb

***Abstract*—**The present energy situation and the concerns about global warming has stimulated active research interest in non-petroleum, carbon free compounds and non-polluting fuels, particularly for transportation, power generation, and agricultural sectors. Environmental concerns and limited amount of petroleum fuels have caused interests in the development of alternative fuels for internal combustion (IC) engines. The petroleum crude reserves however, are declining and consumption of transport fuels particularly in the developing countries is increasing at high rates. Severe shortage of liquid fuels derived from petroleum may be faced in the second half of this century. Recently more and more stringent environmental regulations being enacted in the USA and Europe have led to the research and development activities on clean alternative fuels. Among the gaseous fuels hydrogen is considered to be one of the clean alternative fuel. Hydrogen is an interesting candidate for future internal combustion engine based power trains. In this experimental investigation, the performance and combustion analysis were carried out on a direct injection (DI) diesel engine using hydrogen with diesel following the TMI(Time Manifold Injection) technique at different injection timings of 10 degree,45 degree and 80 degree ATDC using an electronic control unit (ECU) and injection durations were controlled. Further, the tests have been carried out at a constant speed of 1500rpm at different load conditions and it can be observed that brake thermal efficiency increases with increase in load conditions with a maximum gain of 15% at full load conditions during all injection strategies of hydrogen. It was also observed that with the increase in hydrogen energy share BSEC started reducing and it reduced to a maximum of 9% as compared to baseline diesel at 10deg ATDC injection during maximum injection proving the exceptional combustion properties of hydrogen.

***Keywords*—**Hydrogen, performance, combustion, alternative fuels.

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I. Introduction

With higher rate of depletion of non-renewable fuels the quest for an appropriate alternative fuel has gathered a great momentum. Therefore to sustain the present growth of civilization a non-depletable clean fuel must be expeditiously sought.

In this century, it is believed that the crude oil and petroleum products will become very scarce and costly. Nowadays fuel economy of engine is getting enhanced and will continue to get better. However, massive increases in number of vehicles have created the demand for fuel. Gasoline and diesel will become inadequate and most costly in the near future.

With increased use and the reduction of fossil fuels, alternative fuel technology will become more common in the coming decades. The hunt for an alternative fuel, which promises a sweet correlation with sustainable development, energy conservation, management, efficiency, and environmental preservation, has become highly pronounced in the present context. Many researches have been directed towards the development of alternative fuels to achieve this goal. Among the various probable alternative fuels, hydrogen is found to be the most promising due to its clean burning and better combustion properties [1]-[4]. Interest in hydrogen [7,8] as a potential alternative automotive fuel has grown due to need of reducing greenhouse gases, CO_2 emissions and to minimize dependence on fossil fuels. Hydrogen has, for years, been recognized for its extremely high energy potential.. Diesel can be displaced completely by using alternative fuels like vegetable oils with some changes in the basic components of the engine or retrofitting the engine , while the dual-fuel operation needs only peripheral changes in the diesel engine. Therefore it is more convenient and economical to operate the engine on the dual-fuel mode.

Dual-fuel engine works on the basis of diesel cycle where diesel acts an ignition source for the gaseous fuel like hydrogen. In the present experimental investigation hydrogen was injected into the intake manifold and ignited with diesel injected in the conventional manner. The amount of hydrogen injected should be restricted up to a certain limit since the hydrogen will replace the air, thereby reducing the air available for diesel combustion [9]. Lee et al.[10] suggested that in dual injection, the stability and maximum power could be obtained by direct injection of hydrogen. However the maximum efficiency could be obtained by the external mixture formation in hydrogen engine. The use of hydrogen in dual fuel mode with diesel by Masood et al. [11] showed the highest brake thermal efficiency of 30% at a compression ratio of 24.5. Das et al. [12] have carried out experiments on continuous carburetion, continuous manifold injection, timed manifold injection and low pressure direct cylinder injection. Lee et al.[13] studied the performance of dual injection hydrogen fueled engine by using solenoid in-cylinder injection and external fuel injection technique. In this paper, a continuous induction of hydrogen in the air inlet manifold of a single cylinder, compression ignition engine is adopted to investigate engine combustion and performance experimentally under different modes of hydrogen injection strategies. A.P. Roskilly et al.[14] has presented his findings of an experimental investigation into the operation of a compression ignition (CI) engine in homogeneous charge compression ignition (HCCI) mode using hydrogen fuel.

Factors that were investigated include engine efficiency, emissions and mechanical loads. Hydrogen was found to be a possible fuel for operation of a CI engine in HCCI mode. The heat release rate is extremely high, which leads to high ignition timing control requirements. The ignition timing was controlled using heating of the inlet air, and satisfactory performance was demonstrated using this method. J. D. Naber et al. [15] studied the auto ignition and combustion of hydrogen were investigated in a constant-volume combustion vessel under simulated direct-injection (DI) diesel engine conditions. The parameters varied in the investigation included: the injection pressure and temperature, the orifice diameter, and the ambient gas pressure, temperature and composition. The results showed that the ignition delay of hydrogen under DI diesel conditions had a strong dependence on temperature; however, the dependence on the other parameters examined was small.

II. COMBUSTION CHARACTERISTICS OF HYDROGEN

Hydrogen (H_2) is a colorless gas that has no direct environmental or health impact but can play a role in a number of reactions in emission control catalysts. Hydrogen has significantly different combustion characteristics than other hydrocarbon fuels. Hydrogen has wider flammability limits of 4–75% by volume in air compared to diesel of 0.7–5% by volume. One of the significant advantages of hydrogen is that the engine can be theoretically operated up to an equivalence ratio of 0.1[16]. The minimum energy required for ignition of hydrogen–air mixture is 0.02 mJ only. This enables hydrogen engine to run well on lean mixtures and ensures prompt ignition. However, this creates the problems of premature ignition and flashback due to hot spots present in the cylinder that can serve as a source of ignition. Backfire can be eliminated by avoiding hot spots in the combustion chamber, and intake manifold that acts as an ignition source for hydrogen and by exhaust gas recirculation or water injection [17,18].The density of hydrogen is 0.0837 kg/m3, which is lighter than air that it can disperse into the atmosphere easily. Hydrogen has the highest energy to weight ratio of all fuels. The flame speed of hydrogen is 270 cm/s that may cause a very high rate of cylinder pressure rise. The diffusivity of hydrogen is 0.63 cm^2/s. As the hydrogen self-ignition temperature is 858 K, compared to diesel of 453 K, it allows a larger compression ratio to be used for hydrogen in internal combustion engine [19].

III. EXPERIMENTATION

In this experimental investigation a single cylinder, four-stroke diesel engine is used whose specification is shown in table 1. The engine is operated at a constant speed of 1500rpm on dual-fuel mode, using diesel as the pilot fuel and hydrogen as the main fuel. A solenoid-operated hydrogen gas injector was fixed onto the engine cylinder head. The hydrogen injector was positioned just above the intake valve at a some distance from the intake valve seating position [20,21]. The hydrogen stored in a high-pressure storage tank at a pressure of 140 bar at 32 ^{0}C was reduced to a pressure of 1.2 bar by a CONCOA pressure regulator. A flow regulator in the hydrogen circuit helps to regulate the volume flow rate of hydrogen in the hydrogen circuit according to ones desire to quantify the amount of hydrogen to be inducted per computational cycle. A flame arrestor that also acts as a non-return valve was provided to suppress any possible fire hazard in the system. In addition a bubbler tank is included in the circuit to dampen out any pressure fluctuations in the hydrogen supply line.

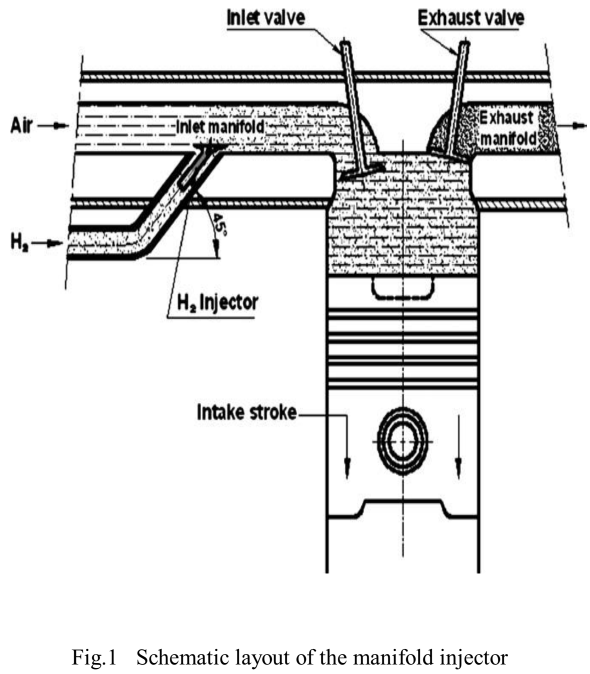

Fig.1 Schematic layout of the manifold injector

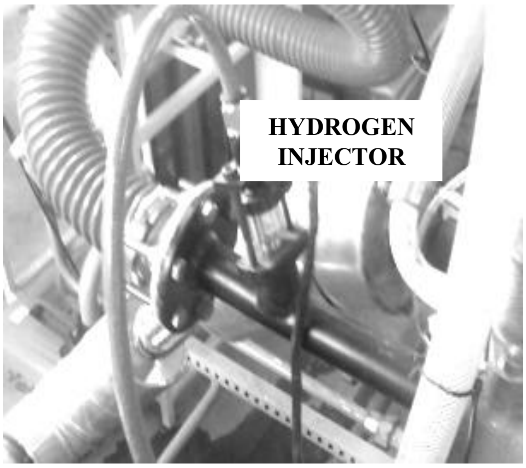

Fig. 2 Photographic view of the manifold injector

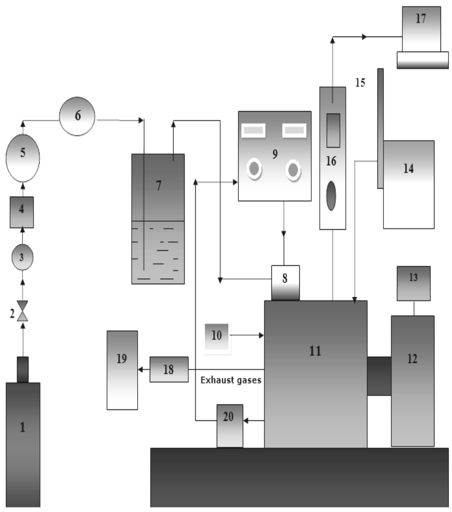

Fig. 3 Schematic layout of the experimental setup

1. Hydrogen cylinder 2. Pressure regulator 3. Pressure gauge. 4. Flame arrester 5. Pressure reducer 6. Gas flow meter. 7. Water bubbling tank 8. Gas injector 9. DAQ station with injector driver & DAQ card and PC 10. Air filter. 11. VCR engine 12. Electrical dynamometer 13. Loading device 14. Fuel tank 15. Burette 16.Engine control panel with sensors 17.Computer panel 18. Exhaust Gas Calorimeter. 19. Gas Analyzer. 20. Crank Angle Encoder.

In the present work the three injection timing was chosen to gauge the impact of injection timing on the performance and combustion parameters of the dual fuel engine. The consumption of diesel is measured by using a graduated burette. A dynamometer has been used for the measurement of brake power. The engine is initially operated with 10% diesel and at a constant speed of 1500rpm and at six different loads (2kg,4kg,6kg,8kg,10kg and12kg). The injection duration was chosen on the basis of the time interval available during the inlet valve opening period corresponding to its injection angle and speed. This total duration is divided into three equal intervals and was set by the operators desire through the pc based DAQ(Data acquisition) program developed on DAQ factory. At each injection timing the quantity of gas injected again varied to realize the impact of quantity of HYDROGEN injected per cycle of the dual fuel operation. The gas injection timing was not chosen arbitrarily, but due consideration was given to develop a homogeneous mixture made available to the pilot charge of diesel at the time of injection . An injection timing of 10 degree, 45 degree and 80 degree of HYDROGEN, after TDC during the IVO(Inlet valve open) to IVC(Inlet valve close) period was chosen.

TABLE I
ENGINE SPECIFICATION

Type	Compression ignition
No. of cylinders	One
Bore	80 mm
Stroke	120 mm
Speed	1500 rpm
Rated power	5.2 kW at 1500 rpm
Compression ratio	17.5:1
Type of cooling	Water cooled
Injection timing	23^{0}BTDC static

IV. RESULTS AND DISCUSSIONS

Initially the engine was operated with pure diesel at a constant speed of 1500rpm at six different loads i.e at 2kg, 4kg, 6kg, 8kg, 10kg and 12kg. At each load various combustion and performance parameters have been evaluated and plotted. Then the engine is switched to dual-fuel mode of operation with hydrogen as the main fuel and diesel as the pilot fuel under the same operating conditions. Some of the typical combustion parameters like brake power, rate of change of pressure w.r.t crank angle , mean gas temp, net heat release etc. and performance parameters like volumetric efficiency, brake thermal efficiency, brake specific energy consumption etc. have been evaluated during experimentation.

From the observations made with the experimentation with the existing engine the maximum value of peak pressure is observed to be 63.89 bar for 10degree ATDC with first injection strategy of hydrogen under full load with an 18% increase as shown in fig.4 compared to base diesel only at all the injection strategies of hydrogen-diesel blend which may be due to the fact that at with the introduction of hydrogen the combustion becomes more homogeneous .

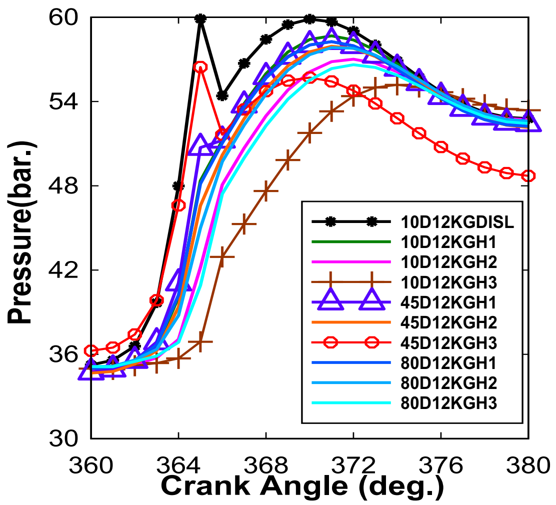

Fig. 4 Pressure vs crank angle at full load

In fig.5 it can be viewed that the rate of pressure rise w.r.t crank angle is highest for first injection strategy of 9 exp(+3) microseconds of hydrogen at full load condition which is of 7.87 bar for 10degree ATDC per crank angle at 365 degree crank angle with an increase of 17% compared to base diesel. This increase in the pressure rise is due to high flame speed of hydrogen which promotes better combustion as compared to other injection strategies.

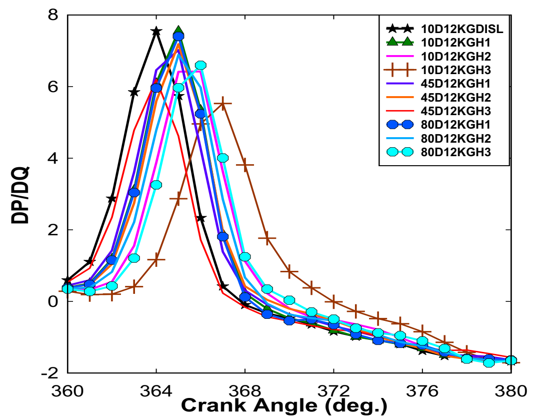

Fig.5 Rate of change of pressure (DP/DQ) w.r.t crank angle

From fig. 6 it can be observed that the net heat release of 91KJ is maximum for the case of hydrogen injection strategy at 10degree ATDC with first injection duration strategy at full load condition with an increase of 21% compared to base diesel which gives an indication of bulk release of fuel energy with hydrogen participation.

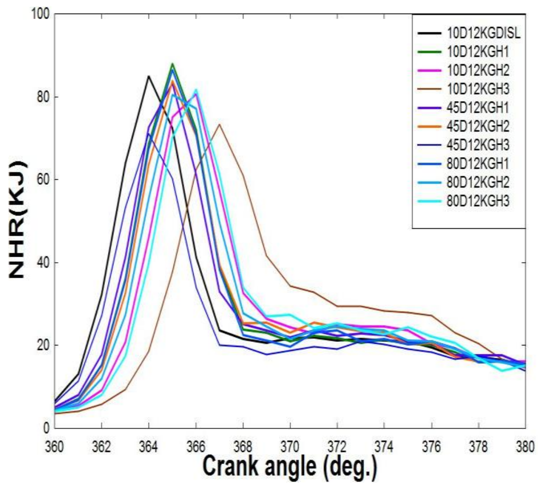

Fig. 6 Neat heat release (NHR) vs crank angle at full load

In fig.7 it can be observed that the maximum mean gas temp (MGT) is 1599.87K in case of 10degree ATDC with first injection strategy of hydrogen at 365 crank angle at full load condition with an increase of 10% compared to base diesel which is an indicative higher flame propagation accompanied with better combustion.

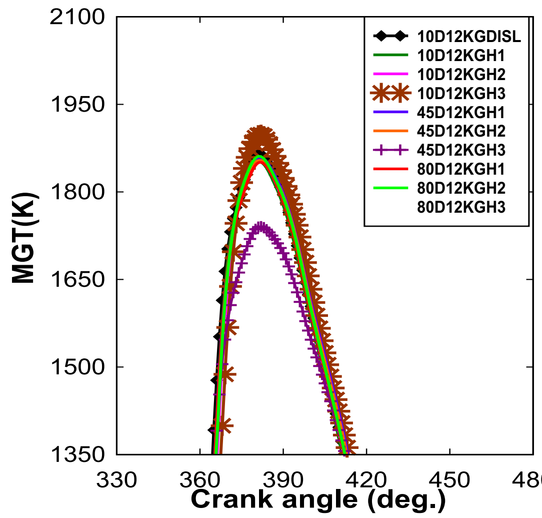

Fig. 7 Mean gas temperature (MGT) vs crank angle at full load

Fig. 8 shows that the percentage of hydrogen energy share is increases with the lean mixture which is maximum of 70% at 10 degree injection timing strategy at lower loads but as the load increases the mixture is becoming rich so there gradual decrease in hydrogen energy share.

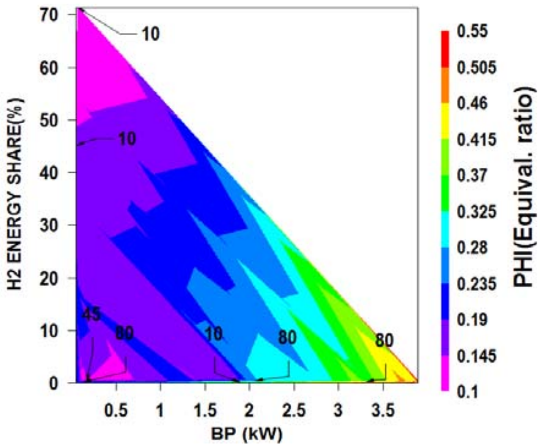

Fig. 8 Break power(BP) vs H2 energy share vs PHI (Equivalance ratio)vs injection timing

It can be observed from fig. 9 that With the increase in load the brake specific energy consumption (BSEC) decreases and it reaches to a minimum value of 10800KJ/KW-hr at full load during injection timing of 10 degree ATDC. The increase in brake specific energy consumption (BSEC) is observed at low load conditions with 80 degree ATDC hydrogen injection strategy which may be due to better mixing of fuel mixture with air caused by hydrogen which results in more efficient burning process of fuel mixture. This increases engine power.

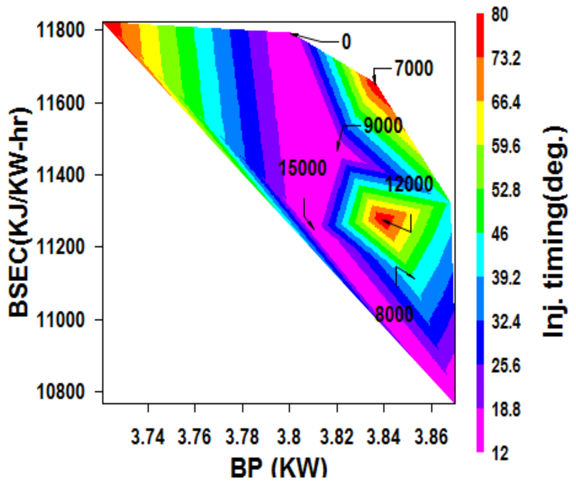

Fig. 9 Break power(BP) vs BSEC vs injection timing vs injection duration

From fig. 10 it can be observed that the brake thermal efficiency(BTHE) increases with increase in load at all injection strategies of hydrogen. This may be due to the improvement of combustion process caused by the presence of hydrogen since the presence of hydrogen improves mixing process of fuel mixture with air . Also the presence of hydrogen reduces the duration of combustion process.

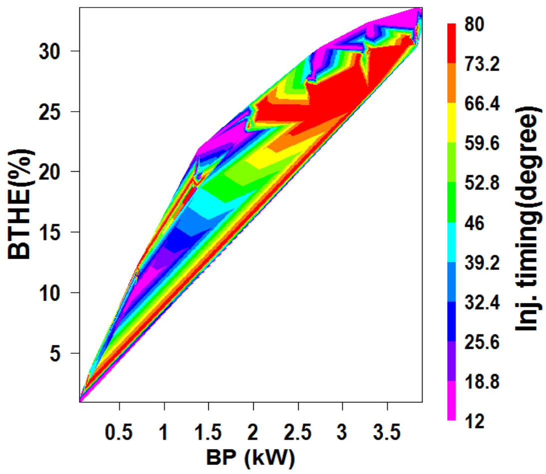

Fig. 10 Break power(BP) vs BTHE (Brake thermal efficiency)vs injection timing

It can be observed from fig.11 that the volumetric efficiency decreases with load with increase in hydrogen mass flow rate for constant speed. This is due to the effect of hydrogen which reduces air flow through the inlet manifold.

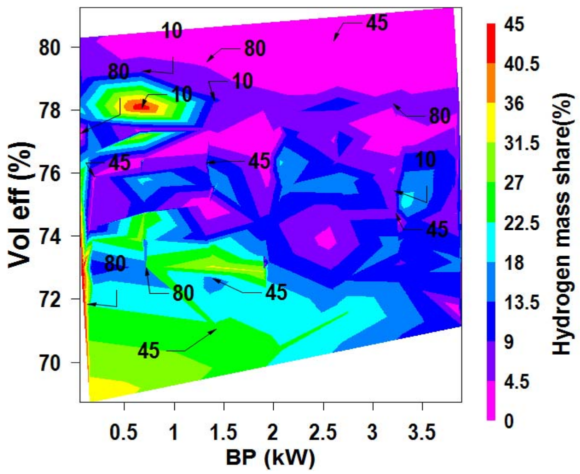

Fig. 11 Break power(BP) vs volumetric efficiency vs hydrogen mass share vs injection timing

V. Conclusion

In a single cylinder compression ignition engine the experiment was done successfully using hydrogen–diesel blend. The following conclusions are made on the basis of investigation.

1. The combustion process is improved as the hydrogen blending ratio increases.

2. The adopted TMI system with gas injector was successful in operating the existing diesel engine without any flashback phenomena.

3. The maximum mean gas temp for the 10 degree ATDC injection was observed to be 1924K for maximum load in the 21exp(+3)micro seconds hydrogen induction window.

4. The maximum net heat release was observed to be 88.04KJ at 6 exp(+3) microseconds hydrogen induction window for the 10 degree ATDC injection at a crank angle of 365 degree for maximum load.

5. Overall equivalence ratio decreased appreciably for all hydrogen enrichment with maximum reduction of 90% as compared to baseline diesel operation at 2kg load under 10 deg ATDC of injection, thereby enabling engine operation extremely leaner than diesel operation.

6. With the increase in load the brake specific energy consumption (BSEC) decreases and it reaches to a minimum value of 10800KJ/KW-hr at full load during injection timing of 10 degree ATDC.

7. Volumetric efficiency reaches to maximum of 81.5% at mid load conditions at 10 degree ATDC injection strategy and reaches to a minimum value of 71.8% at 45 degree injection strategy with 9exp(+3) microseconds.

8. The brake thermal efficiency increases with increase in load at all injection strategies of hydrogen which is maximum of 15% increase compared to base diesel.

9. The maximum value of peak pressure is observed to be 63.89 bar for 10degree ATDC with first injection strategy of hydrogen under full load with an 18% increase compared to base diesel only at all the injection strategies of hydrogen-diesel blend.

10. The rate of pressure rise w.r.t crank angle is maximum for first injection strategy of 9 exp(+3) microseconds of hydrogen at full load condition which is of 7.87 bar for 10degree ATDC per crank angle at 365 degree crank angle with an increase of 17% compared to base diesel.

11. The net heat release of 91KJ is maximum for the case of hydrogen injection strategy at 10degree ATDC with first injection duration strategy at full load condition with an increase of 21% compared to base diesel

Acknowledgment

This research at National Institute of Technology, Agartala, Tripura, India has been done in collaboration with Legion Brothers, Bangalore, India.

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