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Research Paper

HYDROGEN COMBUSTION IN A SINGLE CYLINDER DIESEL ENGINE AND TO STUDY ITS PERFORMANCE AND COMBUSTION PARAMETERS

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The world is presently confronted with the twin crisis of fossil fuel depletion and environmental degradation. Petroleum crude is expected to remain main source of transport fuels at least for the next 20 to 30 years. 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. Energy security is an important consideration for development of future transport fuels. 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 expected to be one of the most important fuels in the near future to meet the stringent emission norms. 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 Time Manifold Injection (TMI) technique at different injection timings of 100, 450 and 800 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 10° ATDC injection during maximum injection proving the exceptional combustion properties of hydrogen.

Keywords: Hydrogen, Performance, Combustion, Alternative fuels

INTRODUCTION

In this century, it is believed that the crude oil and petroleum products will become very scarce and costly. Day- to-day, fuel economy of engine is getting improved and will continue to improve. However, enormous increases in

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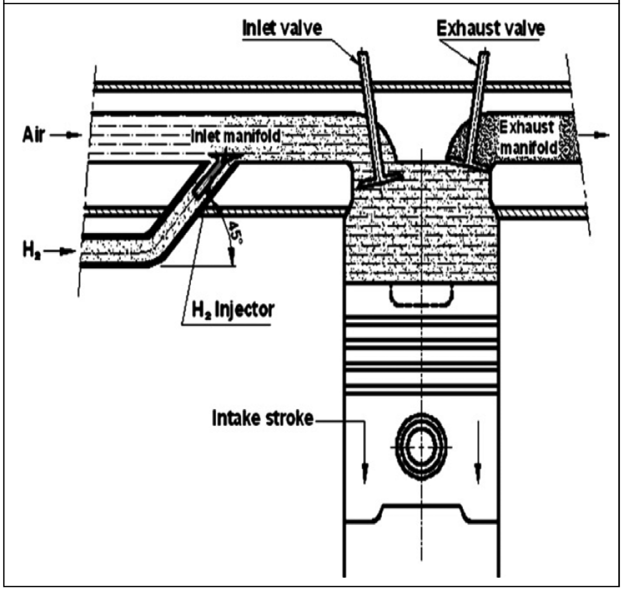
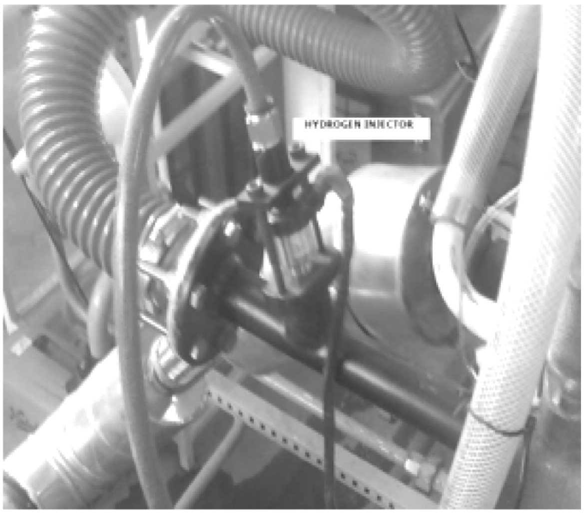
number of vehicles have started dictating the demand for fuel. Gasoline and diesel will become scarce and most costly in the near future. With increased use and the depletion of fossil fuels, alternative fuel technology will become more common in the coming decades. The search for an alternative fuel, which promises a harmonious 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 (Lee *et al.*, 1995; Das, 2002a; Polasek *et al.*, 2002; and Mihaylov and Barzev, 2004). With higher rate of depletion of the non-renewable fuels, the quest for an appropriate alternative fuel (Kukkonen and Shelef, 1994; and Barreto *et al.*, 2003) has gathered great momentum. Therefore, to sustain the present growth rate of civilization, a non-depletable, clean fuel must be expeditiously sought. Interest in hydrogen (Das, 2002a and 2002b) 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 (Figure 1). The

Figure 1: Schematic Layout of the Manifold Injector



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 (Guo *et al.*, 1999). Lee *et al.* (2001) 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.* (2007) showed the highest brake thermal efficiency of 30% at a compression ratio of 24.5. Das *et al.* (2002a) have carried out experiments on continuous carburetion, continuous manifold injection, timed manifold injection and low pressure direct cylinder injection. Lee *et al.* (2002) 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 (Figure 2). Roskilly *et al.* (2008) has presented his

Figure 2: Photographic View of the Manifold Injector



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. Naber *et al.* (1994) 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 compo-sition. 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.

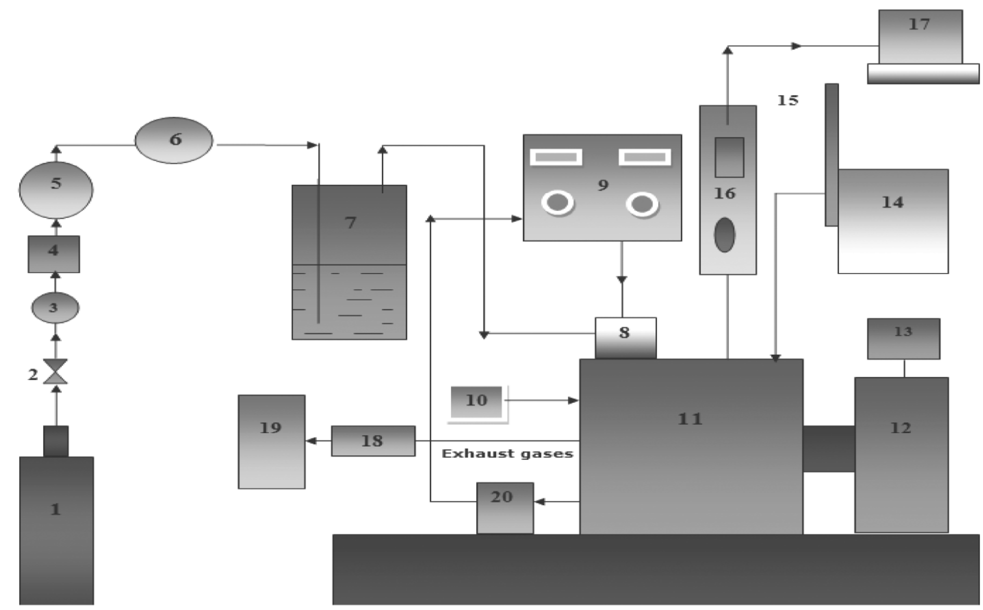
COMBUSTION CHARACTERISTICS OF HYDROGEN

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 (Heffel *et al.*, 1998). 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 (Yamin *et al.*, 2000; and Ma *et al.*, 2003). The density of hydrogen is 0.0837 kg/m^3, 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 (Lee and Kim, 2002).

EXPERIMENTATION

A single cylinder, four-stroke diesel engine is used for this experimental investigation (Figure 3). The specification of the engine is shown in Table 1. The engine is operated at a constant speed of 1500 rpm on dual-fuel mode, using diesel as the pilot fuel and hydrogen as the main fuel. A solenoid-operated hydrogen gas injector was fitted onto the engine cylinder head. The hydrogen injector was placed just above the intake valve at a some distance from the intake valve seating position (Lee *et al.*, 1995; and Norbeck *et al.*, 1996). The hydrogen stored in a high-pressure storage tank at a pressure of 140 bar at 32 °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 of 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

Figure 3: Schematic Layout of the Experimental Setup



Note: 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 and 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; and 20. Crank angle encoder.

Table 1: Engine Specifications

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° BTDC Static

a bubbler tank is included in the circuit to dampen out any pressure fluctuations in the hydrogen supply line. 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 (Saravanan *et al.*, 2008a and 2008b). 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 1500 rpm and at six different loads (2 kg, 4 kg, 6 kg, 8 kg, 10 kg and 12 kg). At each load the following parameters were recorded:

- Air flow rate
- hydrogen consumption
- Diesel consumption
- Water flow rate
- Exhaust gas temperature
- Water inlet temperature
- Water outlet temperature

At each load, the diesel supply is slowly reduced and to maintain the same the hydrogen supply is increased by using the control valve. The above parameters were recorded again at each load conditions under the same operating conditions. Both for pure diesel and dual-fuel operation all the important engine combustion and performance parameters have been evaluated at all loads.

RESULTS AND DISCUSSION

The engine was initially operated on 100% diesel at a constant speed of 1500 rpm at six different loads, i.e., at 2 kg, 4 kg, 6 kg, 8 kg, 10 kg and 12 kg. 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 Figures 4, 5 and 6 it can be observed that 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 which may be due to the fact that at with the introduction of hydrogen the combustion becomes more homogeneous. From Figures 7, 8 and 9 it can be viewed that 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 10° ATDC per crank angle at 365

Figure 4: Pr. vs. Crank Angle @ Low Load

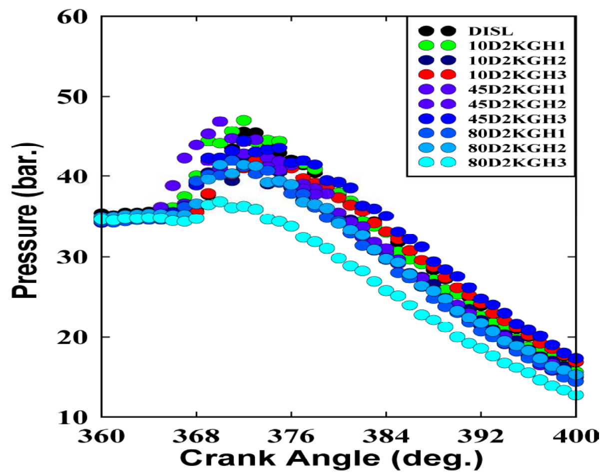


Figure 5: Pr. vs. Crank Angle @ Half Load

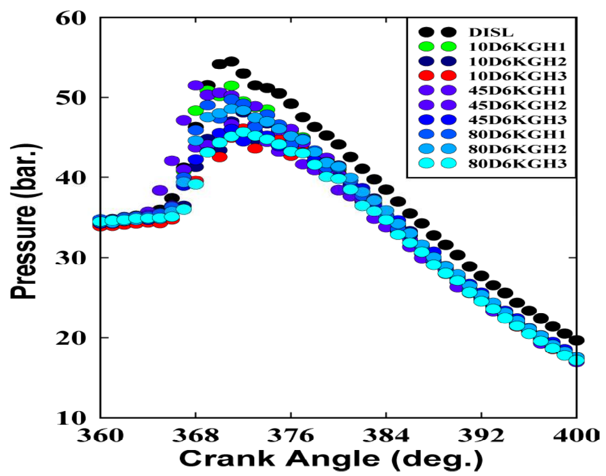


Figure 6: Pr. vs. Crank Angle @ Full Load

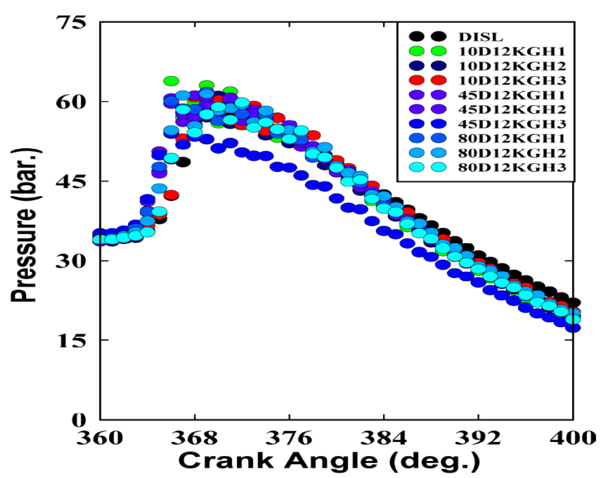


Figure 7: Variation of Pr. w.r.t Crank Angle ($dp/d\theta$) @ Low Load

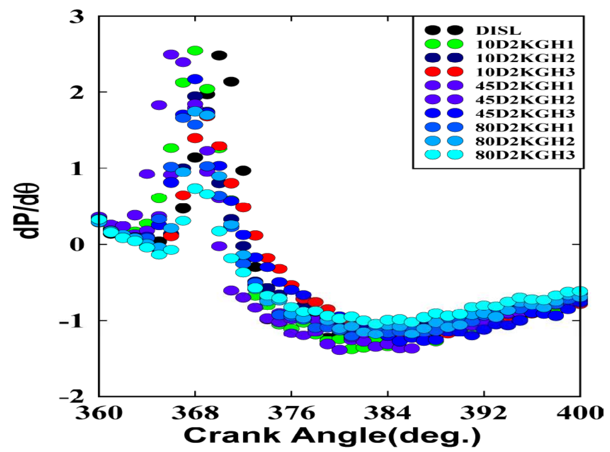


Figure 8: Variation of Pr. w.r.t Crank Angle ($dp/d\theta$) @ Half Load

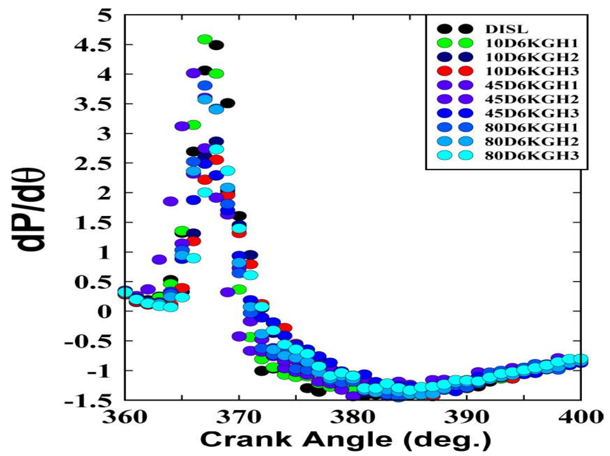
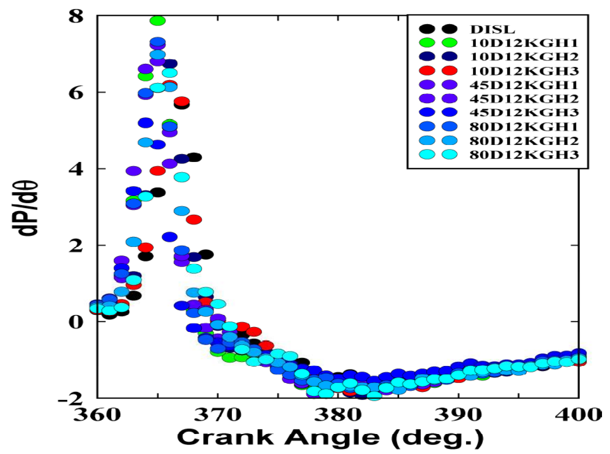


Figure 9: Variation of Pr. w.r.t Crank Angle ($dp/d\theta$) @ Full Load



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. From Figures 10, 11 and 12 it can be observed that the net heat release of 91 KJ is maximum for the case of hydrogen injection strategy at 10° 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. From Figures 13, 14 and 15 is observed that the maximum Mean Gas Temp (MGT) is 1599.87 K 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. Figure 16 shows that the percentage of hydrogen energy share is increases with the lean mixture which is maximum of 70% at 10° injection timing strategy at lower loads but as the load increases the mixture is becoming rich so there gradual decrease in hydrogen energy share. It can be observed from Figure 17 that with the increase in percentage of hydrogen energy share, Brake Specific Energy Consumption (BSEC) decreases 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. From Figure 18 it can be observed that the brake thermal efficiency 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

Figure 10: Net Heat Release (NHR) vs. Crank Angle @ Low Load

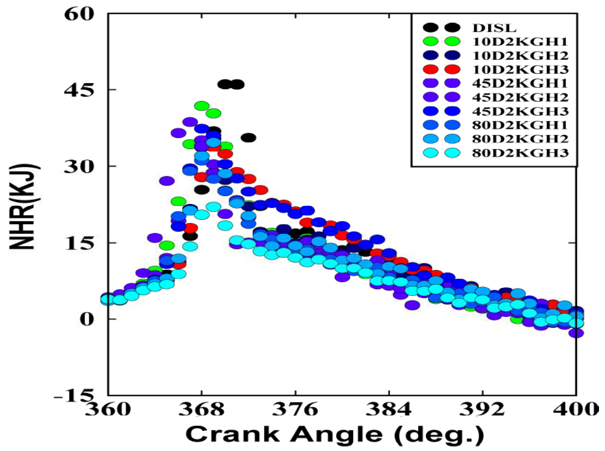


Figure 11: Net Heat Release (NHR) vs. Crank Angle @ Half Load

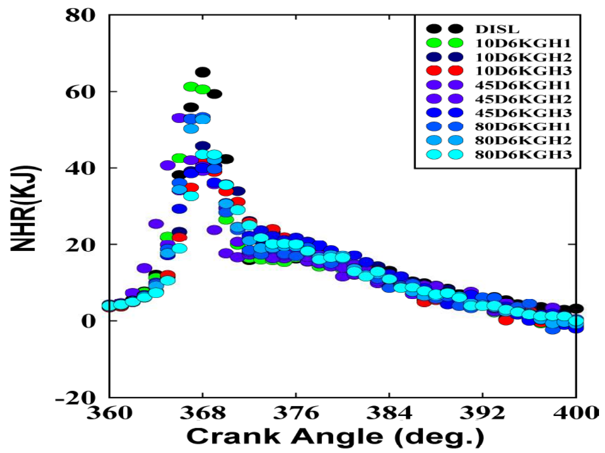


Figure 12: Net Heat Release vs. Crank Angle @ Full Load

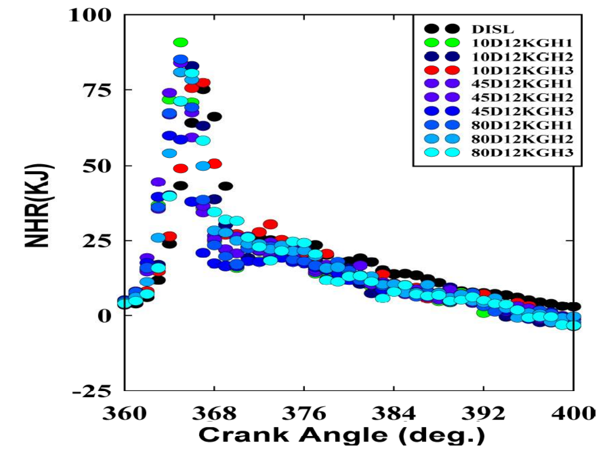


Figure 13: Mean Gas Temp. (MGT) vs. Crank Angle @ Low Load

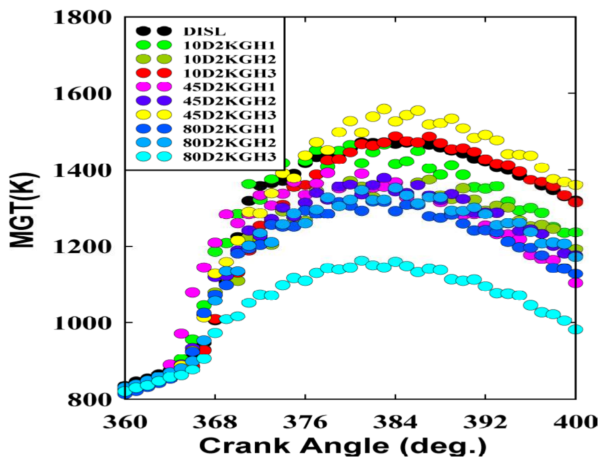


Figure 14: Mean Gas Temp. vs. Crank Angle @ Half Load

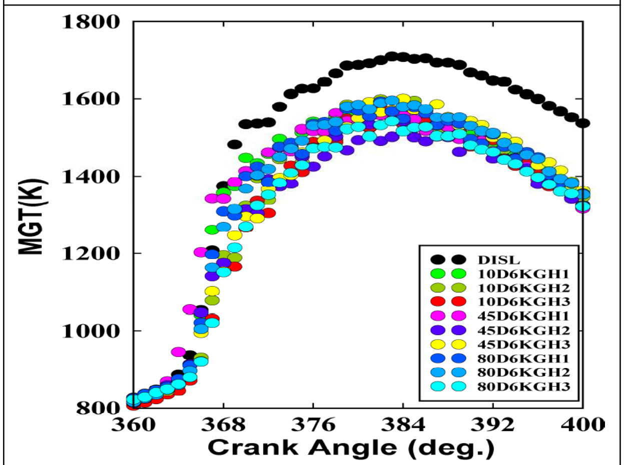


Figure 15: Mean Gas Temp. vs. Crank Angle @ Full Load

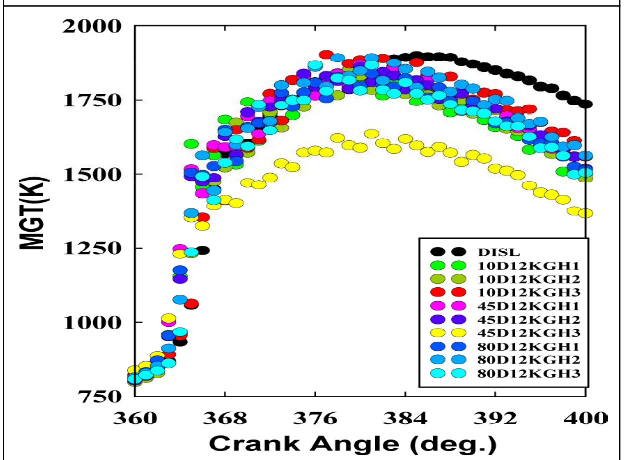


Figure 16: Load vs. H2 Energy Share vs. Equival Ratio (PHI) vs. Inj. Timing

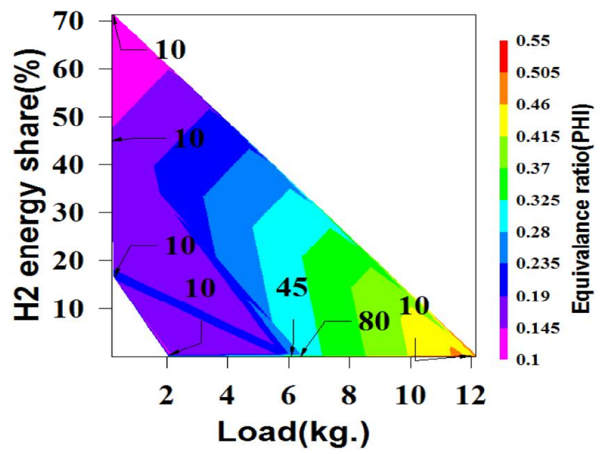


Figure 17: Load vs. H2 Energy Share vs. Brake Specific Energy Consumption (BSEC) vs. Inj. Timing

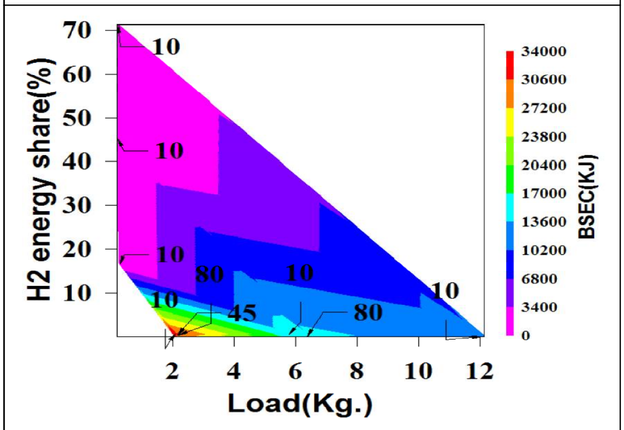


Figure 18: Load vs. H2 Energy Share vs. Brake Thermal Efficiency (BTH) vs. Inj. Timing

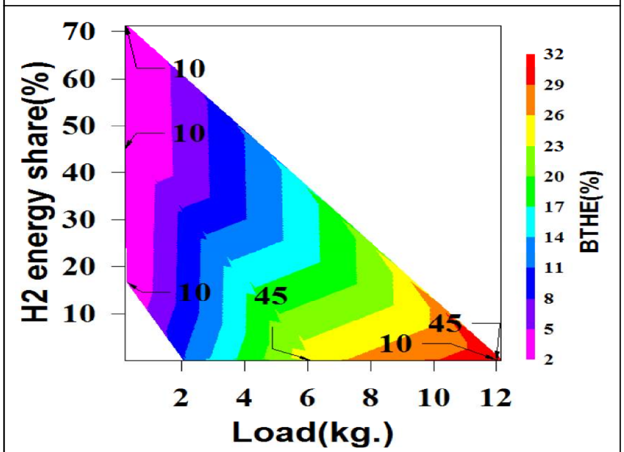


Figure 19: Load vs. Injuction Timing vs. Vol. Eff. vs. Injection Duration

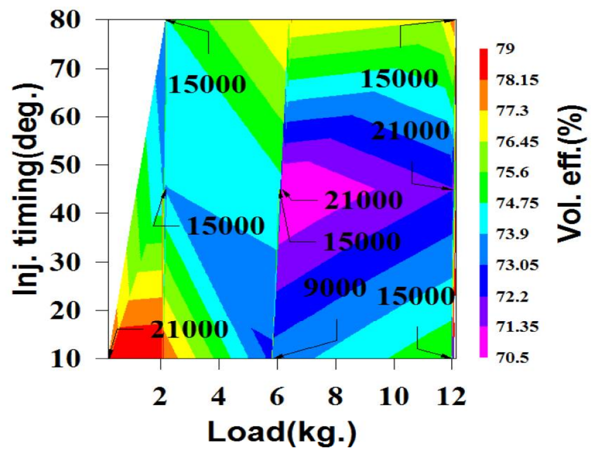


Figure 20: Load vs. Inj. Duration vs. Hydrogen Mass Flow Rate vs. Injection Timing

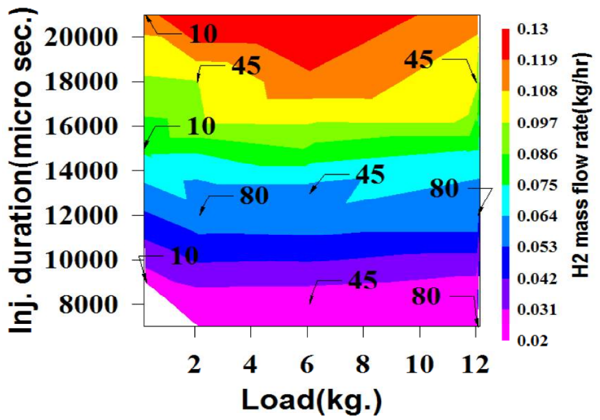
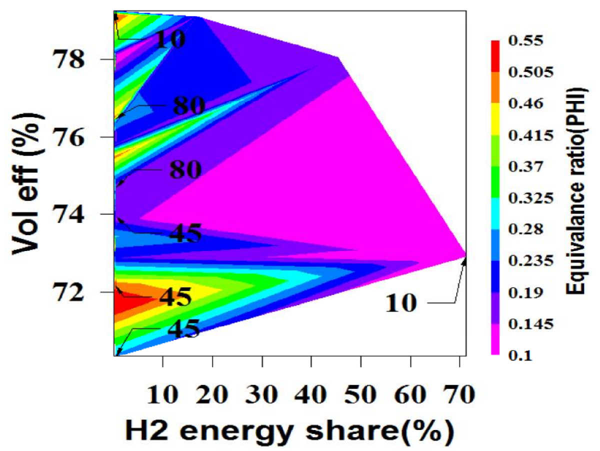


Figure 21: H2 Energy Share vs. Vol. Eff. vs. PHI vs. Injection Timing



presence of hydrogen improves mixing process of fuel mixture with air. Also the presence of hydrogen reduces the duration of combustion process. It can be observed from Figures 19, 20 and 21 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.

CONCLUSION

A single cylinder compression ignition engine was operated successfully using hydrogen-diesel blend. The following conclusions are made on the basis of experimental results.

- The adopted TMI system with gas injector was successful in operating the existing diesel engine without any flashback phenomena.
- The combustion process is improved as the hydrogen blending ratio increases.
- The percentage of hydrogen energy share is increases with the lean mixture which is maximum of 70% at 10° injection timing strategy at lower loads.
- With the increase in percentage of hydrogen energy share, Brake Specific Energy Consumption (BSEC) decreases.
- Volumetric efficiency decreases with increase in load and is minimum at medium load conditions with highest injection strategies of hydrogen, i.e., at 21 exp(+3) microseconds.
- 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.

- The maximum value of peak pressure is observed to be 63.89 bar for 10° 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.
- 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 10° ATDC per crank angle at 365° crank angle with an increase of 17% compared to base diesel.
- The net heat release of 91 KJ is maximum for the case of hydrogen injection strategy at 10° ATDC with first injection duration strategy at full load condition with an increase of 21% compared to base diesel.

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