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PERFORMANCE AND COMBUSTION CHARACTERISTICS OF A TYPICAL MOTOR BIKE ENGINE OPERATED ON BLENDS OF CNG AND HYDROGEN USING ELECTRONICALLY CONTROLLED SOLENOID ACTUATED INJECTION SYSTEM

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ABSTRACT

This paper discusses the development of an electronically controlled gas injection system for hydrogen supplemented single cylinder Enfield engine. In view of its typical combustion characteristics, the fuel induction technique plays a very dominant and sensitive role in the performance as well as the combustion characteristics of hydrogen supplemented CNG engine. The designed system should have adequate flexibility to provide the appropriate mixture into the engine at the appropriate point in the engine cycle operation. The motor bike engine was fuelled with neat CNG and mixtures of hydrogen in natural gas (HCNG) of 5, 10, 15 and 20% by energy. The designed Electronic Fuel Injection System ensured successful operation of engine running on different fuel blends over a wide range of load and speed without causing any undesirable combustion phenomena such as backfire or pre-ignition. The performance and combustion characteristics were determined under various operating conditions.

Keywords: motor bike engine, CNG, hydrogen, HCNG, injection, combustion characteristics, emissions.

1. INTRODUCTION

Today's energy and transportation system, which is based mainly on fossil energy carriers, can in no way be evaluated as sustainable. Given the continued growth in the world's population as well as the progressive industrialization of developing nations, the demand for energy is expected to continue to increase in the coming decades - by more than 50% until 2030, according to the International Energy Agency (IEA) - with fossil fuels continuing to dominate global energy use. The internal combustion engines which are designed to run on petroleum fuels are faced with two major crises due to depletion of fossil fuels as well as the environmental degradation caused due to the combustion of these petroleum-based fuels. Under such circumstances, much effort has been focused on the utilization of alternative fuels in engines. Natural gas is considered as a potential alternative fuel due to its higher octane number, low emissions, low price, and abundant reserve. The combustion of natural gas produces less emission than that of gasoline and diesel fuels due to its simple chemical structure and absence of fuel evaporation. The high octane number of natural gas gives the engine high anti-knocking capability and allows it to operate at even high compression ratio, leading to further improvement of both power output and thermal efficiency.

Lean burn is widely accepted as an effective approach to simultaneously improve engine's thermal efficiency and decrease exhaust emissions [1, 2, 3]. Specifically, improvement in combustion efficiency, reduction in heat transfer and increase in the ratio of specific heats ($k = Cp/Cv$), all of which would help to bring down fuel consumption could be realized by lean burn. Furthermore, NOx emissions and the likely hood of knock could be reduced by the decreased cylinder temperature resulting from dilution. However, as the natural gas engine runs close to the so-called lean limit, problem of misfiring occurs. The reason for this is the slow burning speed and higher ignition energy of natural gas. Intensifying turbulence and increasing either spark energy or the number of spark plugs are usually included in the conventional ways to deal with these shortcomings. Unfortunately, the effects are always limited and sometimes they bring with them other penalties for example increasing ignition energy will shorten the life of the spark plug [4] and heavy turbulence is detrimental to volumetric efficiency. Hence there is a need to enhance the combustion of natural gas without bringing the above mentioned drawbacks. Hydrogen has been considered as a good add-on fuel to enhance some specific combustion properties and is an effective and applicable way to increase the lean burn characteristics [5]. It has been used along with fuels like gasoline, natural gas, ethanol, vegetable oil, biogas, LPG, etc. to improve combustion characteristics. [6-10]. Owing to hydrogen's fast burning velocity and low ignition energy, its addition results in increasing the flame speed and reducing ignition energy which is beneficial to both engine efficiency and combustion stability. Normally, cycle-to-cycle variations occur in the engines operating with very lean mixtures. But, with hydrogen addition, these variations are much less compared to that of engines powered by other hydrocarbon fuels [11].

2. FUEL INDUCTION TECHNIQUES

The fuel induction techniques have been found to play a very dominant and sensitive role in determining the performance characteristics of an I.C. Engine. The 'FIT' for an S.I. engine can be classified into following categories:

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2.1 Carburetion system

2.2 Injection system

2.2.1 Inlet manifold/port injection

- Continuous Injection
- Timed Injection

2.2.2 In-cylinder injection (direct injection)

- Low Pressure Direct Injection (LPDI)
- High Pressure Direct Injection (HPDI)

These conventional methods of 'FIT' could also be applied to engine operation with a non-conventional alternative fuel, such as natural gas and hydrogen. Of these methods; carburetion by the use of a gas carburetor has been the simplest and the oldest technique. However, the carbureted version of engine system apart from developing low power output compared to equivalent gasoline fuelled engines also exhibited severe irregular combustion problems due to pre-ignition, backfire and combustion knock.

With injection system the quality governing for the engine operation can be easily achieved due to independence of the fuel delivery rate from the air intake rate. This ability of the injection system to adopt quality governing makes it possible to operate the engine at the lowest equivalence ratio for a given power output which in turn results in high thermal efficiencies, lower combustion temperatures and low levels of NOx. In inlet manifold injection system; the injector is located in the manifold to inject the fuel upstream to the air for the better mixing of air and fuel. The manifold injection gives more time for the fuel to get mixed properly with air in the manifold before entering into the combustion chamber. In comparison to this, the fuel in the port injection system is injected into the inlet valve of each cylinder through an injector placed close to the upstream side of the intake valve. In direct injection, the intake valve is closed when the fuel is injected, completely avoiding premature ignition during the intake stroke. Consequently, the engine cannot backfire into the intake manifold.

The continuous inlet manifold/port injection was tried experimentally but major disadvantage is that it is more susceptible to irregular combustion due to pre-ignition and backfire. The in-cylinder injection technique was not tried. Entire experimentation was done by adopting timed manifold injection technique. In timed injection, there is a sufficient time for the fuel to properly mix and form a homogeneous mixture. Moreover, in this system, the fuel induction can be delayed to reduce the temperature of hotspots responsible for backfire and other undesirable combustion phenomena.

3. DESIGN AND DEVELOPMENT OF ELECTRONIC FUEL INJECTION SYSTEM (EFIS)

For the present work, timed injection of the gaseous fuel was executed by the electronic fuel injection system. It is a pulse width modulated gaseous fuel injection system. The basic requirements of EFIS are as given below:

- Solenoid Actuated Gaseous Fuel Injector
- Electronic Control Unit and Proximity Sensor

3.1 Solenoid actuated gaseous fuel injector

The main part of the injector consists of a solenoid through which fuel is metered. When electric current is applied to the injector coil, a magnetic field is created, which causes the armature to move upward. This action pulls a spring-loaded ball or “pintle valve” off its seat. Then, fuel under pressure can flow out of the injector nozzle. The shape of the pintle valve causes the fuel to be sprayed in a cone-shaped pattern. When the injector is de-energized, the spring pushes the ball onto its seat, stopping the flow of fuel. However as per as the process of injection is concerned, it can be classified based on the location of injector and sequence of injection as already described earlier.

For the present work, two fuel injectors i.e., CNG injector (model SP-051 manufactured by Clean Air Power, USA) and Hydrogen injector (manufactured by Quantum Technologies) were used. The injectors used are shown in Figure-1. The start of injection and duration of injector were controlled by the electronic control unit and proximity which are described in the following section.

CNG Injector Hydrogen Injector

Figure-1. View of injectors.

3.2 Design and development of electronic control unit (ECU)

The Electronic Control Unit is the main stage of the EFIS. The purpose of the ECU is to control the fuel injection during the opening period of intake valve for a pre-selected duration of injection. The ECU should have the capability of varying the fuel injection duration as per the user requirement. The ECU can be of two types:

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a) Time based electronic control unit
b) Angle based electronic control unit

In time based ECU, the duration of injection is varied in terms of time (ms) of the engine crank revolution. In angle based ECU, the ECU controls the fuel injection duration based on the instantaneous position of the crank angle. In the present study, time based ECU was designed and used for experimentation. In the time based ECU, the speed of the shaft is sensed by the proximity sensor which was mounted on the shaft. It gives output pulses (train of pulses), as per the speed of the engine. The start of injection was selected by adjusting the metallic pointer pointing towards the proximity sensor manually. Processor will sense each pulse and will generate time based output pulse which is used as an input to the injector driving circuit which drives the solenoid injector. Hence, ECU provides a very precise control over the fuel injection parameters. Output time is predefined in processor memory which is set from key board input. ECU has basically following four sections:

a) Input section
b) CPU (Central processing unit)
c) Output section
d) Power supply section

A schematic layout of the time based ECU with all the above mentioned stages is shown in Figure-2.

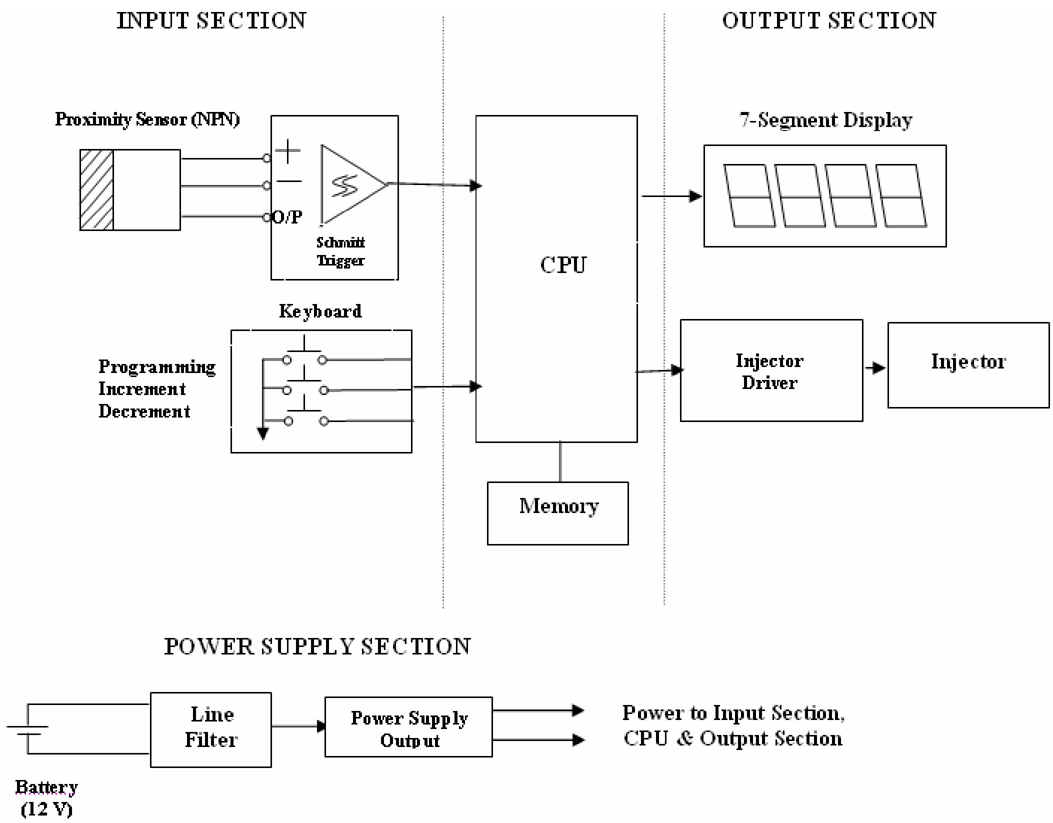

Figure-2. Block diagram of time based ECU.

3.2.1 Input section

The input section consists of two parts as shown in the block diagram.

Proximity sensor (NPN): Proximity sensor is mounted on the engine. The pointer is mounted on shaft so that in one complete cycle, it will give one pulse to the CPU section.
Key board: Three keys are used to set output pulse width for injector (Figure-3).

- Program key: To enter in main menu.
- Increment key: To increase the value of output pulse.
- Decrement key: To decrease the value of output pulse.

3.2.2 CPU (Central processing unit)

CPU section consists of micro-controller IC (P89V51RD2). P89V51RD2 is an 8051 microcontroller. It has its own ROM memory in which program is written in assembly language. There is a Memory chip in which output pulse width timing are saved, which is set by key board. Memory Chip used for this section is AT 24c32. This is EEPROM (Electrical Erasable Memory). Microprocessor 8051 mounted on PCB of ECU is shown in Figure-4.

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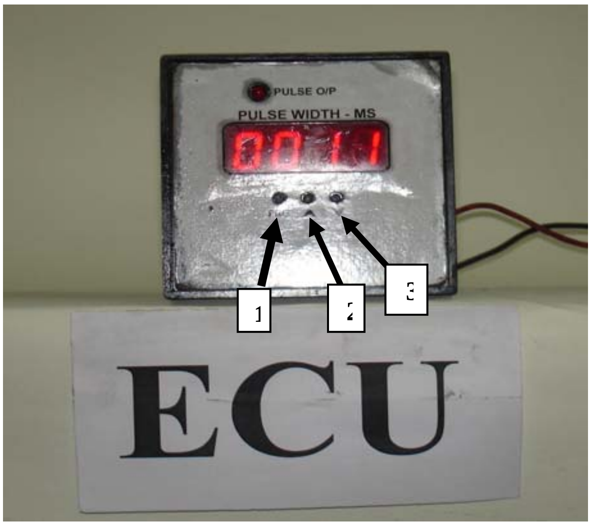

1. Program Key; 2. Increment Key; 3. Decrement Key

Figure-3. View of ECU.

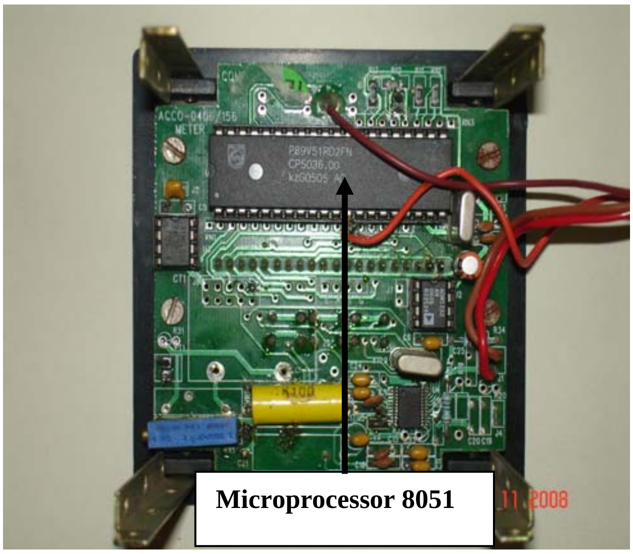

Figure-4. Microprocessor 8051 mounted on PCB of ECU.

3.2.3 Output section

Output section consists of following two parts:

- Display section; and
- Fuel injector driver.

Display section: Display screen is used for user interface to set on time of injector. Micro-controller drive this 7 segment display to display the set value of on time of fuel injector.

Fuel injector driver: Microcontroller cannot drive high current rating coil of injector. So, to increase the capacity, high current rating transistor (TIP 122) is used. Microcontroller will pass command (on and off time) to the transistor. As per on and off time fuel injector will get on and off.

3.2.4 Power supply section

In Power supply section line filter and power supply regulator are used. It supplies constant voltage (+5V) to controller and its associate circuit. Line filter is used because when injector and EHT coil operates, it generates noise which is harmful to controller. So line filter filters this noise and smoothens the operation.

Ganesh RH *et al.*, [12] have worked on the electronic fuel injection system for a hydrogen engine. A solenoid operated gas injector was used to inject hydrogen into the inlet manifold at the specified time. An electronic circuit was used to trigger the injector. The injection timing and injection duration were varied using the potentiometers in the circuit. They suggested reducing the injection duration to over come the problem of backfiring at higher outputs.

Similarly Das LM *et al.*, [13] developed electronically controlled gas injection system for a small horsepower utility hydrogen engine. It mainly constituted designing a pulse width modulated choked flow gas injection system. In this injection system, changing the pulse width of the control pulse given to the injector regulated the fuel. This system proved to be very successful in providing appropriate mixture to the engine and led to smooth operation of engine without any problem of backfire, knocking or rapid rate of pressure rise.

4. EXPERIMENTAL SETUP TEST PROCEDURE

The experiments were conducted on a modified single cylinder Enfield engine with a bore x stroke of 69.874 x 90 mm and a compression ratio of 7.25:1. The engine details are given in Table-1. Figure-5 is a schematic of the experimental setup.

Table-1. Engine Specifications.

Parameter	Specifications
Type	Vertical single cylinder , air cooled, 4-stroke with overhead valve gear
Bore	69.874 mm
Stroke	90 mm
Swept volume	346 c.c.
Compression ratio	7.25 : 1
Maximum power	13.23 kW at 5625 rev./min
Maximum torque	26.8794 Nm at 2875 rev./min

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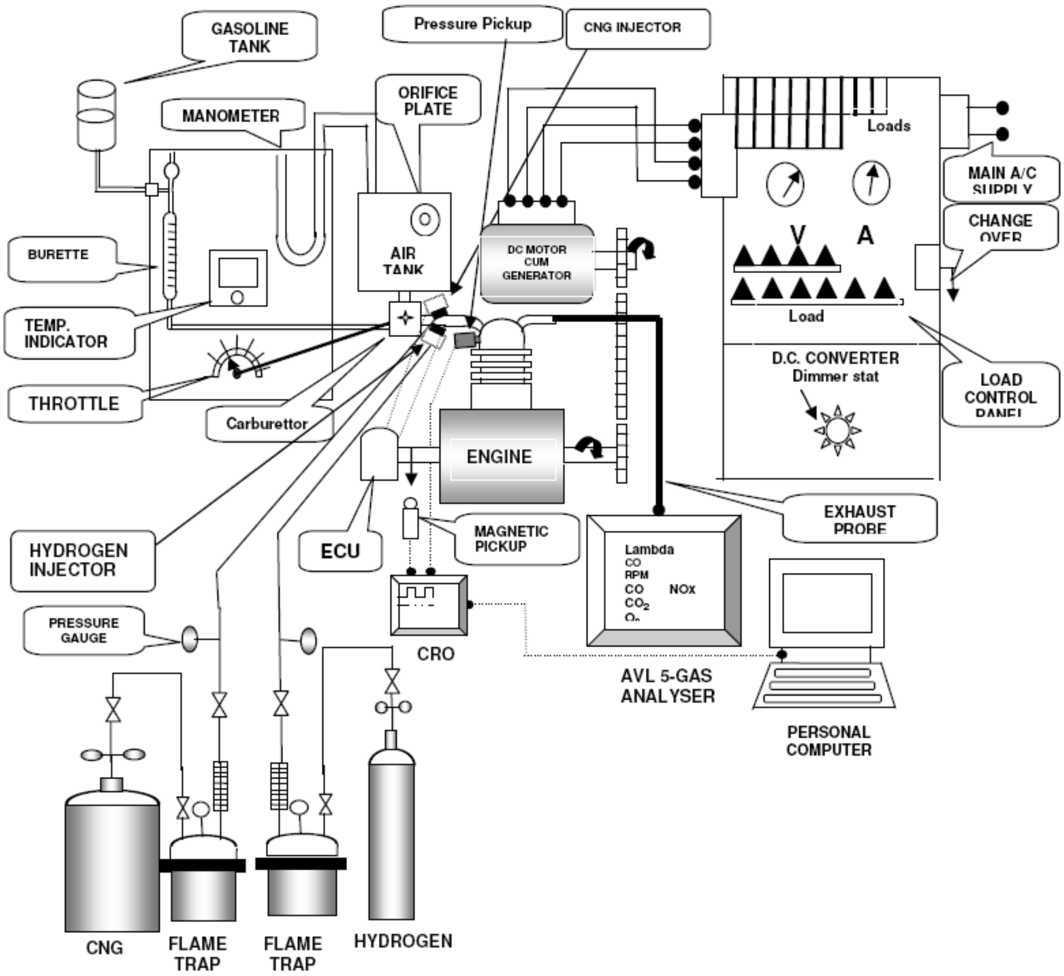

Figure-5. Schematic of experimental setup.

All the research work was conducted in the Engines and Unconventional Fuels Laboratory in the Centre for Energy Studies at the Indian Institute of Technology Delhi. The tests were conducted by varying the equivalence ratio at a constant speed of 2800 r/min and constant spark timing of 25° BTDC. The CNG-H_2 supplying system of the engine consisted of CNG and hydrogen tank, pressure regulators, flame traps, Electronic Control Unit (ECU) and two different injectors for injecting CNG and hydrogen. The flow rate was metered by Proline Promass 80 A04 micro-motion flow meters which use the Coriolis Effect for a direct measure of mass flow the hydrogen used in this study has a purity of 99.99%, while the constitution of natural gas is listed in Table-2. Table-3 gives the fuel properties of natural gas and hydrogen.

Table-2. Composition of natural gas.

Item	CH_4	C_2H_6	C_3H_8	I-C_4H_{10}	N-C_4H_{10}	I-C_5H_{12}	N_2	CO_2	Hexanes
Volumetric Fration, (%)	96.1	2.571	0.359	0.05	0.09	0.01	0.598	0.14	0.06

In this study, four fractions of natural gas-hydrogen blends were studied. The fractions of hydrogen in the natural gas-hydrogen blends are 0%, 5%, 10%, 15%, and 20% by energy, respectively.

4.1 In-cylinder transducer pressure measurement

The engine crank angle was measured by magnetic pickup, make “Electro” model No. 3010AN. The needle was fitted on the shaft coming out of the engine. While the magnetic pickup was fixed, the needle fitted on shaft rotated. While rotating, it cut the magnetic field and generated pulses. These pulses were fed into the Cathode Ray Oscilloscope (CRO).

The in-cylinder pressure was measured with water cooled piezoelectric Kistler 701A pressure transducer. The pressure transducer was mounted over the cylinder head in the threaded hole provided by manufacturer for pressure release valve or decompression

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valve (while experimentation it was used for fitting second spark plug or dummy spark plug). The output of the quartz transducer, which consists of electrical charge, is proportional to the pressure in the cylinder. With the charge amplifier warmed up and the transducer coolant water flowing, the engine was motored and the signal by transducer was directed through an AVL 3059 HICF charge-voltage amplifier to produce a voltage proportionate to the pressure in the cylinder. This was recorded on a storage oscilloscope. Simultaneous reading of two signals i.e., TDC and cylinder gas pressure signal were recorded by the use of a Tektronix TDS 2014 four channel digital storage Cathode Ray Oscilloscope (CRO). RS 232 Interface was used as a communication protocol between Cathode Ray Oscilloscope and personnel computer. Using this interface, the data was transferred from CRO to personnel computer. Personnel Computer was used for analyzing the acquired data from CRO by software (wave star). This acquired data can be opened in any of the data processing software and various combustion calculations were made.

Table-3. Fuel properties of hydrogen and natural gas.

Property	Hydrogen	Natural gas
Density at 1 atm and 300 °K (kg/m^3)	0.082	0.754
Mass lower heating value (MJ/kg)	119.930	43.726
Stoichiometric Air/ Fuel mass ratio (kg/kg)	34.20	17.19
Volumetric lower heating value at 300k and 1 atm (MJ/m^3)	9.82	32.97
Equivalence ratio of lean-burn limit in 293 k and 1 atm	0.1	0.53
Volumetric fraction of fuel at stoichiometric A/F ratio (%)	29.0	9.5
Molar carbon to hydrogen	0	0.25
Quenching gap at NTP (mm)	0.64	2.03
Laminar flame speed (m/s)	2.90	0.38
Adiabatic flame temp (°K)	2318	2148
Minimum ignition energy (mJ)	0.02	0.29
Flammability limits (% by volume)	4–75	5.3–15.0
Conductivity at 300 k and 1 atm (mW /m^{2}k)	182	34
Octane number	130+	127

4.2 Calibration of pressure transducer

Before experimentation, the pressure transducer was calibrated using a dead weight pressure gauge tester and a Tektronix TDS 2014 four channel digital storage CRO. The output of the quartz transducer, which consists of electrical charge, is proportional to the pressure in the cylinder. This signal was directed through an AVL charge-voltage amplifier to produce a voltage proportionate to the pressure in the cylinder. An example calibration curve of pressure transducer and charge amplifier output is shown in Figure-6.

5. PERFORMANCE TESTS

The fuel blends with different fractions of natural gas-hydrogen were used. Experiments were carried out with the CH_4/H_2 fraction ratios of 100/0, 95/5, 90/10, 85/15 and 80/20 at varying excessive air ratios and engine speed of 2800 r/min at wide open throttle (WOT). The quantity of gaseous fuel supplied to the engine was regulated by varying the duration of injection of injector through ECU. It was observed during the entire experimentation that there was neither any backfire nor any trend of any undesirable combustion phenomena.

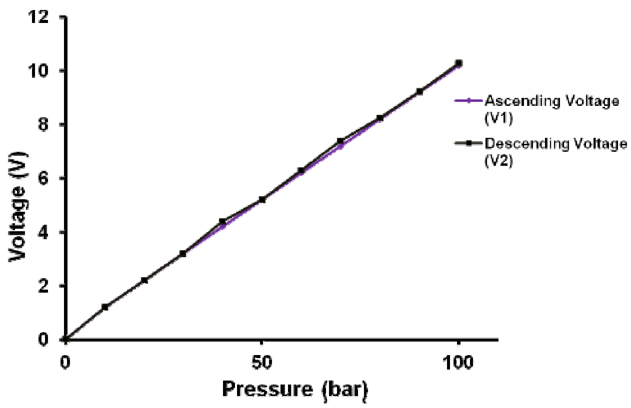

Figure-6. Calibration curve for piezo electric pressure pick-up and charge amplifier.

5.1 Brake thermal efficiency

Figure-7 shows the BTE versus the equivalence ratio. These plots show that the brake thermal efficiency increases from lean to rich reaches the maximum and then starts decreasing as the mixture becomes richer. The maximum Brake Thermal Efficiency was observed around 0.8 to 0.93 equivalence ratio. For the same equivalence ratio, with the increasing percentage of hydrogen, the brake thermal efficiency increased. The difference in BTE

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between HCNG and CNG increases with the decreasing equivalence ratio. The increase in Brake Thermal Efficiency can be attributed to higher flame speed of hydrogen. In the case of rich mixtures, combustion is not complete. As complete combustion does not occur, the BTE decreased when equivalence ratio exceeded 0.98. Similar trend in thermal efficiency were reported in Ref [14].

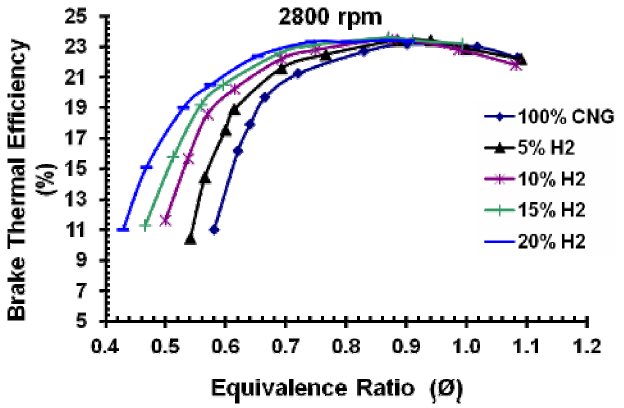

Figure-7. Brake thermal efficiency as a function of equivalence ratio for various hydrogen blends at constant speed of 2800 r/min.

5.2 Combustion characteristics

The combustion analysis of neat CNG and its blends with hydrogen were conducted and the results obtained are as below:

5.2.1 Pressure crank angle diagrams

Figure-8 and Figure-9 reflects the cylinder pressure of mixtures with different hydrogen fractions at an equivalence ratio of 0.82 and 0.96, respectively. It can be interpreted from these figures that when hydrogen is added to CNG, the maximum peak pressure is increased and is found to be close to the top dead centre. The hydrogen's fast burn speed advances the time when maximum pressure occurs.

At 2800 rpm, the maximum peak pressure values are obtained at 15º and 13º ATDC for neat CNG at 0.82 and 0.96 equivalence ratios. The corresponding maximum peak cylinder values are obtained at 14º, 13.5º, 13º and 12º respectively for 5/95, 10/90, 15/85 and 20/80 H_2/CH_4 proportions at equivalence ratios of 0.82. Similarly, the maximum peak cylinder values for equivalence ratio of 0.96 are obtained at 13º, 12.5º, 12º, 11º and 11º respectively for 5/95, 10/90, 15/85 and 20/80 H_2/CH_4 proportions. Generally, the engine can reach its maximum efficiency, when the maximum peak pressure occurs 10-15 degree CA ATDC.

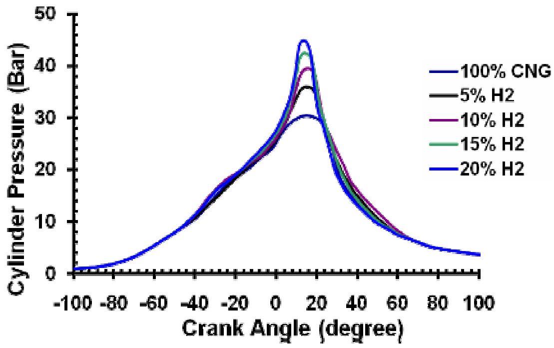

Figure-8. Variation of cylinder pressure with crank angle at 2800 rpm, equivalence ratio of 0.82 and spark advance of 25º CA.

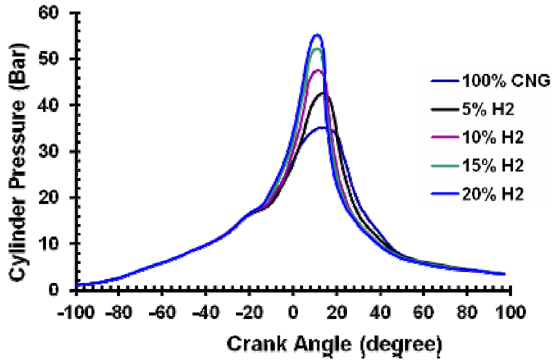

Figure-9. Variation of cylinder pressure with crank angle at 2800 rpm, equivalence ratio of 0.96 and spark advance of 25º CA.

5.2.2 Heat release rate

The heat release rate diagram (Figures 10 and 11) show that maximum heat release rate increases with the increase in substitution of hydrogen in CNG. More over with increasing percentage of hydrogen, combustion takes smaller time to complete as compared to neat CNG. The reason for this is due to fast burn speed of hydrogen. Due to this combustion proceeds faster. This interesting effect qualitatively agrees with the observation of Sierens [14].

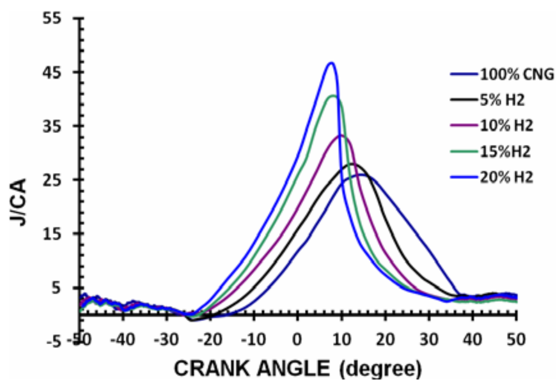

Figure-10. Variation of heat release with crank angle at 2800 rev/min, equivalence ratio of 0.82 and spark advance of 25º CA

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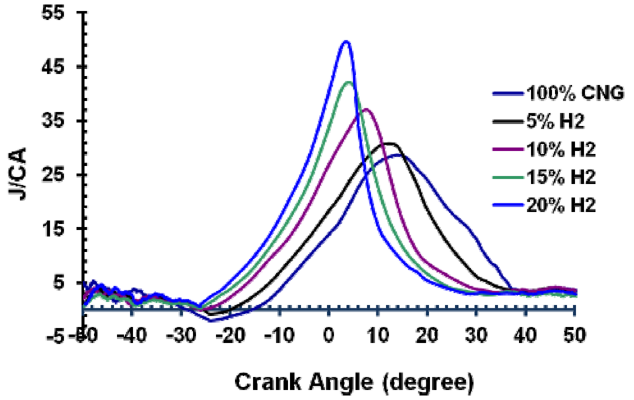

Figure-11. Variation of heat release with crank angle at 2800 rev/min, equivalence ratio of 0.96 and spark advance of 25º CA.

6. CONCLUSIONS

- The timed manifold injection through electronic fuel injection is very essential for the smooth operation of the engine.
- The BTE increase with the increasing hydrogen percentage. This increase in BTE is more pronounced in the leaner region.
- The cylinder pressure increased with the increase in equivalence ratio.
- In general cylinder pressure, heat release, increase with hydrogen addition.
- The experiments gave results coherent with the literature data.

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Nomenclature

BTDC	Before top dead centre
BTE	Brake thermal efficiency
CNG	Compressed natural Gas
CO_2	Carbon dioxide
ECU	Electronic control unit
FIT	Fuel induction technique
HCNG	Hydrogen enriched compressed natural gas
H_2	Hydrogen
NOx	Nitrogen oxide
WOT	Wide open throttle