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A comparative evaluation of the performance characteristics of a spark ignition engine using hydrogen and compressed natural gas as alternative fuels

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Abstract

The basic intent of the present work is to evaluate the potential of using a clean-burning fuel such as hydrogen for small horsepower spark ignition engines. Since compressed natural gas (CNG) has already been used as an alternative fuel for internal combustion engines, an effort has been made in the present work to compare hydrogen fuelling with CNG operation. The engine was operated separately either with hydrogen or compressed natural gas using an electronically-controlled, solenoid-actuated injection system developed in the Engines and Unconventional Fuels Laboratory of the Indian Institute of Technology, Delhi. A comparative analysis of the performance and combustion characteristics of the engine system has been made with respect to both the gaseous fuels.

1. Introduction

It is well known that fossil fuel reserves are becoming exhausted at an alarming rate. Moreover, the combustion of such fuels results in the emission of noxious pollutants which threaten the very survival of life in this planet. The role of existing internal combustion engines needs to be reviewed now in the context of these two major crises.

In view of the versatility of internal combustion engines, they will continue to dominate the transportation sector. There is a considerable limitation for the battery and fuel-cell powered vehicles with regard to range and acceleration, as shown in Fig. 1 [1]. It has also been demonstrated that, despite the conversion losses, the power to weight ratio of the internal combustion engine (including the tank and the fuel) exceeds that of the battery powered or fuel-cell operated vehicles (Fig. 1). Under such circumstances it becomes essential that environment-friendly technologies should be developed and alternatively-fuelled internal combustion engines be designed to ensure safe survival of the existing engine technology. Apart from the limited life period, the other problem with the unrestricted combustion of fossil fuels is the level of CO_2 emission into the Earth's atmosphere. There are various alternative fuels that are being seriously investigated in several parts of the world. As is evident in Fig. 2 [1], the currently used hydrocarbon fuels release about the same amount of CO_2 per amount of heat produced, and even hydrocarbon fuels with a greater hydrogen content do not lead to substantial improvement. Hydrogen shows the distinctive features of a

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practically acceptable carbon-free fuel. Since the present work is based on evaluating only hydrogen and CNG for engine application, no discussion is made here on the characteristics of other alternative fuels, such as methanol, ethanol, electricity, liquified petroleum gas (LPG), biogas, producer gas, and vegetable oils.

1.1. CNG as an alternative engine fuel

At this point it would perhaps be appropriate to discuss the potential of CNG as an alternative fuel for the S.I. engine. The difference between the operation of the conventional gasoline fuelled and CNG engine system arises from the physical and chemical properties of the two fuels. It is well-known that petroleum fuels are liquid at room temperature and CNG remains in a gaseous state at much lower temperatures (−161°C). Moreover CNG has a lower density as compared to gasoline. Due to some of its favourable physio-chemical properties CNG appears to be an excellent fuel for the S.I. engine. CNG has a very high octane number (120–130) compared to that of gasoline (83–93). The engine can be operated at a relatively higher compression ratio, without any abnormal combustion problems, e.g. detonation. Higher self ignition temperature (SIT) of CNG (540°C) compared to gasoline (257°C) results in a lower risk of inflammation or explosion in the event of leakage. Since CNG is a gas, it requires an altogether different approach of fuel induction mechanism at all normal temperatures and pressures. CNG has been routinely used as a fuel for S.I. engines, which are designed to run on petroleum fuels. Considerable operating experience with CNG-operated engines does already exist in a variety of applications [2]. CNG has been successfully used to power vehicles of various ranges, starting from light delivery trucks to full size urban buses [3]. All these applications have generally been based upon conversions of existing engines to run on both gasoline and CNG. Similarly several investigators of hydrogen fuelling of S.I. engines have carried out some research and development work. A detailed discussion on all aspects of such studies is beyond the scope of this paper. In spite of excellent combustion characteristics (Table 1) of both the gaseous fuels (CNG and hydrogen), it has been observed that they often pose some problems like backfiring during suction, knocking at a higher compression ratio with advanced spark timing [4]. The problem of backfiring acquires significance particularly with the hydrogen-operated engine.

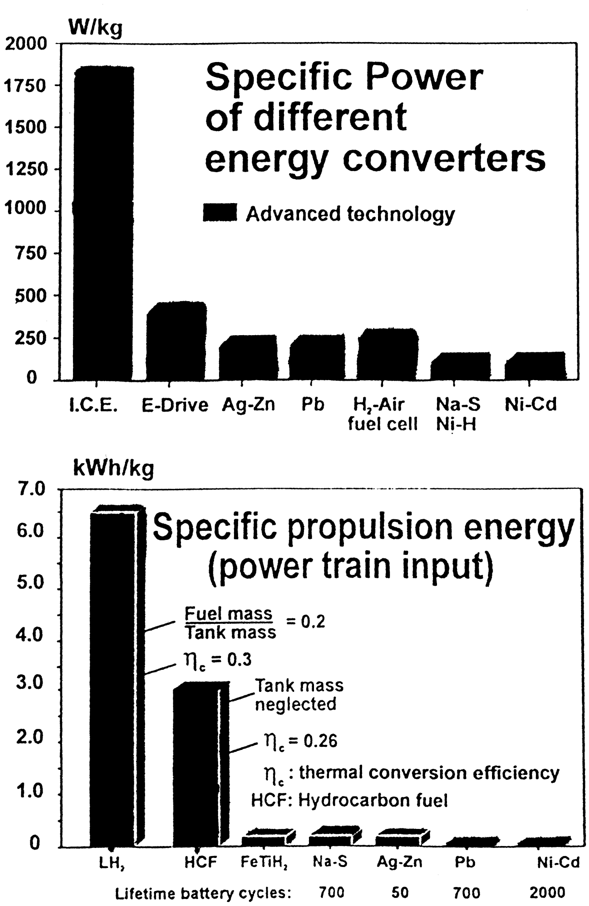

Fig. 1. Power-to-mass and energy-to-mass ratio of vehicular propulsion. Fuel mass, drive engine, fuel storage and energy converter included.

1.2. Hydrogen as an alternative engine fuel

In the history of engine development, hydrogen has been tried several times as an alternative fuel chiefly from the point of view of shortage of fossil fuels.

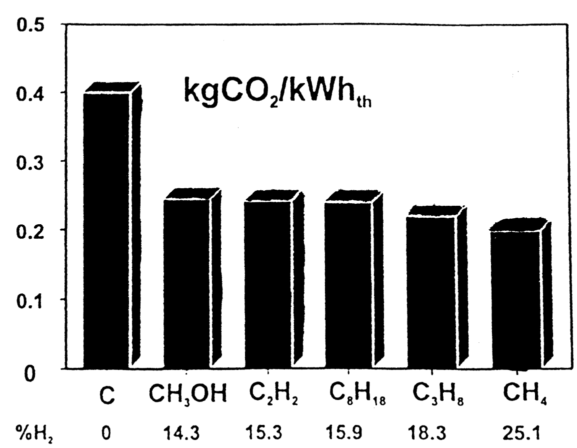

Fig. 2. CO_2 emission of conventional fuels.

Table 1
Physico-chemical properties of CNG, gasoline and hydrogen (generally accepted values from the literature)

		Natural gas (%)	Hydrogen	Gasoline
1.	Compositions	Methane 82.2; ethane 6.1; propane 2.4; isobutane 1.0; isopentane, n-butane 0.4; nitrogen 7.7; CO_2 and oxygen 0.2		C_8H_{18}
2.	Stoichiometric composition in air, vol. %	9.48	29.53	1.76
3.	Lower calorific value, MJ/kg	44.24	119.93	43
4.	Auto ignition temperature, °C	540	585	257
5.	Diffusion velocity in NTP air, cm/s	< 0.51	< 2.00	< 0.17
6.	Adiabatic flame temperature, K	2148	2318	2470
7.	Quenching gap in NTP air, cm	0.203	0.064	0.200
8.	Minimum energy required for ignition in air, MJ	0.29	0.02	0.24
9.	Volumetric efficiency	Less	More	More
10.	Storage and handling	Difficult	More	Easier
11.	Availability	Abundant diverse reserve		Limited
12.	Renewability	Renewable, can be obtained from sewage and biomass, shale oil and other sources		Not renewable

Hydrogen does not experience problems associated with liquid fuels, such as vapour lock, cold wall quenching, inadequate vaporization, poor mixing, and so forth. The other significant feature of hydrogen in the present day context is the "clean-burning" characteristics of the fuel. When hydrogen is burned in air, the main product is water. Hydrogen combustion does not produce toxic products such as hydrocarbons, carbon monoxide, oxides of sulphur, organic acids and carbon dioxide. Acid rain and the CO_2 greenhouse effect are eliminated. Some oxides of nitrogen are generated and our experiments show that it is possible to get the concentration of NO_x drastically reduced by monitoring the engine operation. In today's world, where the effect of global warming turns out to be a crucial problem, the basic advantage of hydrogen combustion is that the greenhouse gas carbon dioxide (CO_2) is not formed at all when hydrogen is burned. This clean-burning property promises an accelerated entry of hydrogen into the existing transportation sectors, as well as several energy consuming sectors, of the developing countries. Like CNG, hydrogen engine fuelling also needs an entirely different approach from that of liquid fuelling. Therefore, a common system of gaseous fuel injection forms the major activity of hardware developed for this work.

2. System hardware development

Research and development work related to hydrogen operated engines has been in progress in IIT, Delhi for over 15 years [5]. In the course of these investigations, it has been observed that the mode of fuel induction plays a critical role in the performance and emission characteristics of the spark-ignited version of the hydrogen engine. A similar experience was observed during the test rig development related to CNG operation. It was observed that abnormal combustion problems, such as backfire and rapid rate of pressure rise, are greatly influenced by the technique of fuel formulation, particularly in the context of system development for hydrogen operation [6,7]. Keeping in view the stringent requirement of hydrogen operation, several fuel induction methods, such as carburetion, continued manifold injection, timed manifold injection, and low pressure direct cylinder injection, were experimentally evaluated for operating the engine with CNG as well as hydrogen. Carburetion and continuous manifold injection were observed to give rise to backfiring under some operating conditions with CNG fuelling [8]. The intensity and frequency of backfire were substantially lower with CNG operation, whereas this tendency of backfire was very severe and uncontrollable with hydrogen fuelling. Through a series of experimental investigations, it was observed that the source of high thermal energy responsible for causing backfiring could be either the spark plug, exhaust valve or some deposits acting as hot spots in the combustion chamber. Timed manifold injection (TMI) was observed to be a very effective technique, particularly for hydrogen operation. Our experimental activities demonstrated that undesirable combustion phenomena, such as backfire, rapid rate of pressure rise etc., cannot be eliminated in a carburetted hydrogen engine. The hydraulically operated and cam actuated injection systems developed earlier were exhaustively tested. The cam actuated injection system was found to be a very effective mechanism and much experimental data were generated with this configuration. Since TMI proved so effective for a temperamental fuel like hydrogen [9], it was therefore adopted also for CNG operation.

3. Injection system developed

The two designs of injection system, as described above, were built for a research engine where adequate in-built facilities existed for the actuation mechanism of the injector implemented. However, it was essential that the technique of fuel injection, conveniently adopted by the small horsepower utility engine, could be operated with gaseous fuels such as hydrogen and CNG. An electronically controlled solenoid-actuated injection system was developed (Fig. 3) for this purpose. After a series of modifications using various mechanisms of actuation, the present system shown in Fig. 3 was found to be the most appropriate for operation with the gaseous fuels. The present system constituted designing a pulse width modulated choked flow gas injection system. The term "choked flow" in this context signifies that the injector nozzle works at choked flow conditions when gas inlet pressure is kept at more than critical pressure. In this type of injection system, changing the pulse width of the control pulse given to the injector (Fig. 4) regulates the fuel. The important functional components of the injection system comprise three parts: (i) optical encoder circuit; (ii) control circuit; and (iii) solenoid injector.

The optical encoder circuit is further classified into two sections, Optical encoder disk and Infrared photo sensor-emitter circuit. The optical encoder disk is made from a circular transparent plastic sheet having 360 black radial marks separated by alternate transparent spaces and one black mark extending at the center of the disk. The radial black marks are used for the angle signal and extended black mark for the reset signal. The optical encoder disk is coupled to the crank of the engine between a pair of infrared photosensors and a photo emitter. The mounting of a pair of sensors was carried out meticulously so that they were in perfect alignment and the vibration level experienced by the disc as well as the sensors was minimal. The rotation of the disk between the sensors causes the infrared beam to be blocked by the black radial marks on the disk, resulting in on/off type signals. These signals are very weak, so they have to be amplified before feeding them to the solenoid.

The control circuit is the most important part of the electronic gas injection unit. It takes the input signal from the optical encoder circuit, processes it and sends the signal in the form of pulses to the solenoid to actuate the plunger lift for a desired duration. The control unit requires two signals from the thumb wheel switches, namely the crank angle values for controlling the injection duration. It gives the output as one when

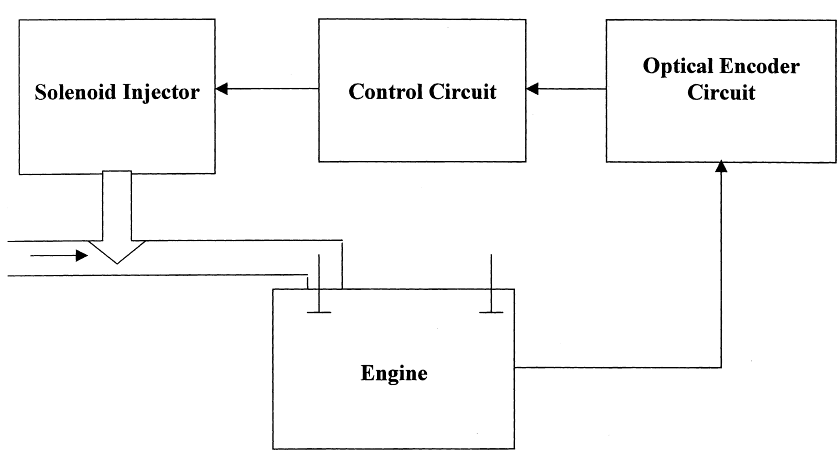

Fig. 3. Electronically controlled injection system.

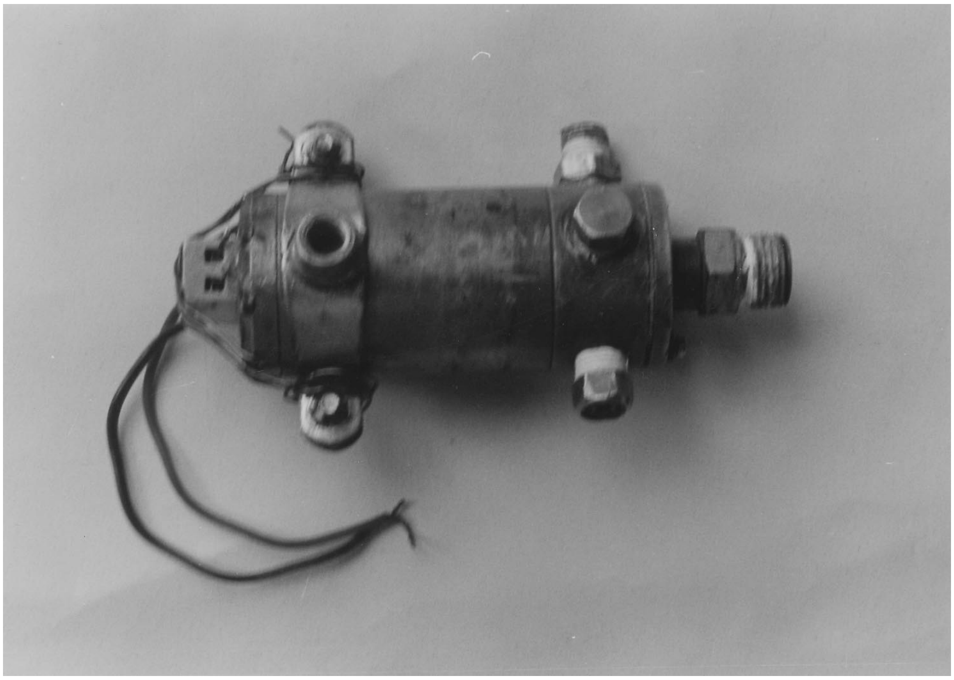

Fig. 4. Injector.

the crank angle, as read by the encoder unit, has a value between the limiting values on the thumb wheel switches and gives the value otherwise as zero. Three 4-bit presettable Binary Coded Decimal (BCD) decade up/down counters are used for counting the black marks encountered during rotation. The angle signal coming from the encoder circuit is fed to every counter. The counting proceeds in a continuous fashion from units to hundreds. Counting in tenths remains paralysed unless the units attain zero value. Similarly the hundreds counter counts only when the value in tenths becomes zero. All three counters are cleared by the reset signal, which comes at each rotation of the crankshaft. The angle signal fed by the encoder unit not being in the proper form required by the counter has to be conditioned. This is accomplished by using a signal conditioning circuit. Thus we get the same signal, but in better form, resembling a square wave and being compatible with the counters. Three counters thereafter give the BCD output for each digit, which are then fed to two sets, each of three comparators, each set thus getting a complete three digit angle count. The crank angle values between which the valve is to be opened are manually set on two sets of thumb wheel switches. The pulses obtained from the control circuit have to be amplified before they are fed to the solenoid, so that sufficient power is transferred to the solenoid. This is carried out in two stages: (i) pre-amplifier stage; (ii) solenoid driving stage. The output of pre-amplifier stage is fed to the base of power transistor (2N3055), which gives a maximum current Ic of 15 A. Transistor 2N3055 is a complementary silicon high power transistor. The power base complementary transistors are designed for high power audio, stepping motor and other linear applications. These devices can also be used in power switching circuits like we are using in solenoid driving circuits. The current gain bandwidth product $Ic = 1.0$ A dc and safe operating area rated to 60 V and 120 V for NPN and PNP, respectively. The solenoid coil is put between the collector of the power transistor and DC source. The emitter of the power transmitter has been grounded. The collector has been grounded though a zener diode of 24 V so that the induced emf developed in the coil (when switched on or off) does not damage the transistor.

3.1. Injector part

The physical configuration of the injector developed is such that its needle is pressure balanced and acts as a valve upon the injector nozzle. It is connected to the electrical solenoid along the pulling rod. When the solenoid is energized the needle opens the valve and the gas is injected into the engine cylinder.

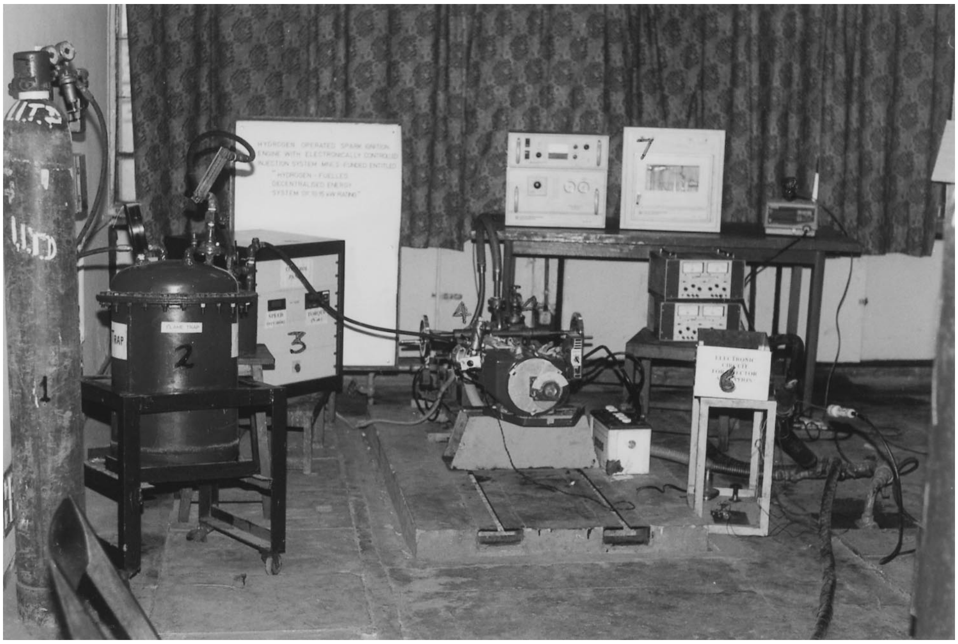

Fig. 5. Hydrogen operated SI engine with electronically controlled injection system. 1. Hydrogen cylinder; 2. flame trap; 3. control panel; 4. SI engine coupled with hydraulic dynamometer; 5. injector; 6. electronic mechanism for injector actuation; 7. chemiluminescent No_x analyzer; 8. non-dispersive infrared CO-HC gas analyzer.

4. Test procedure

The experimental activities were carried out on a single cylinder, 4-stroke, spark ignition engine with the injection system installed. A hydraulic dynamometer was coupled to the engine. Safety devices such as flame traps, pressure regulators, non-return valves etc. were incorporated at specific points in the system. Fig. 5 shows the experimental test rig.

5. Performance tests

Since the experiments were carried out on a typical petrol engine, it was thought desirable to generate the baseline data with petrol for a comparative assessment of the fuel-specific characteristics of the system. The engine was made to run at various speeds, namely 2000, 2200, 2400, and 2600 rpm. It was observed that the requirements of the injector are relatively less stringent, particularly with respect to tendency of backfire. Tests with the hydrogen operated engine were carried out with the throttle kept wide open. The flow was regulated through the hydrogen–gas supply system. Conditions for exhaustive tests were fixed from our preliminary experimental activities. Performance tests on the hydrogen-fueled engine were carried out with the following operating conditions: spark advance/timing 25° before TDC; supply pressure = 0.1 MPa; injection duration = 290° crank angle; injection timing 20° after TDC. The injection timing was fixed taking into consideration the spark advance and injection duration. The effect of the compression ratio was already tested in our research engine where the facility of altering the compression ratio did exist. So the CR was not changed here and all the data were generated with CR 8. This set of conditions was observed to be the most satisfactory with respect to an accurate injector response and smooth running of the engine with hydrogen without any symptoms of undesirable combustion phenomenon. The same set of operating conditions was used with CNG fuelling, except that the injection timing was fixed at TDC.

The fuels were induced using a timed manifold injection on the same injector and under similar operating conditions. The performance characteristics of the engine were determined and the relevant parameters were graphically correlated. It was observed throughout the entire range of operation that backfiring and undesirable combustion phenomena were not present in the case of hydrogen. However, the performance of the engine using hydrogen was limited due to speed and load conditions. The maximum speed obtained was 3500 rpm for hydrogen operation, whereas speeds close to 4000 rpm were achieved for CNG operation. Figs. 6–13 show graphs correlating various operating

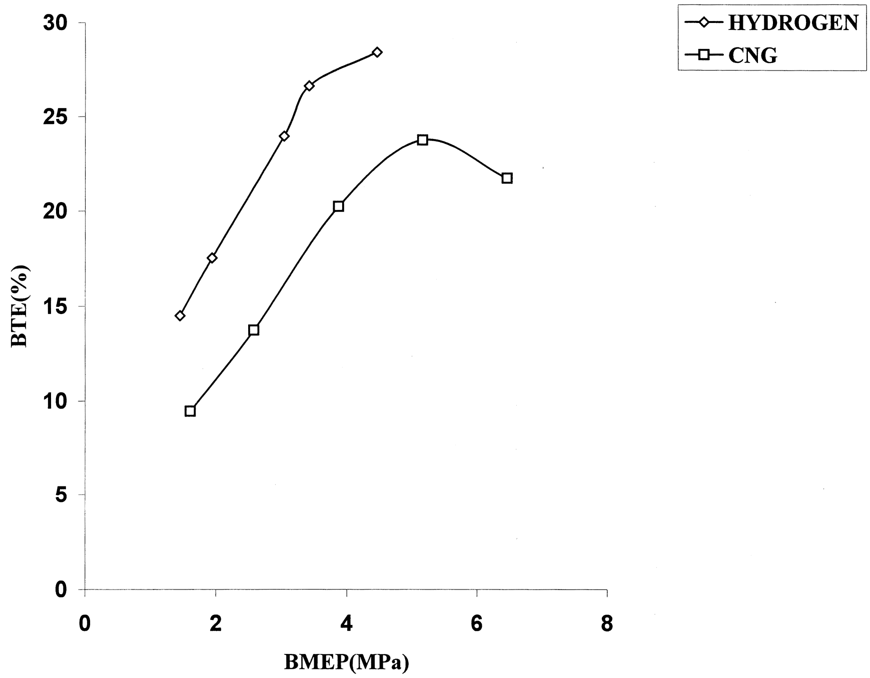

Fig. 6. Variation of brake thermal efficiency with brake mean-effective pressure at 2000 rpm.

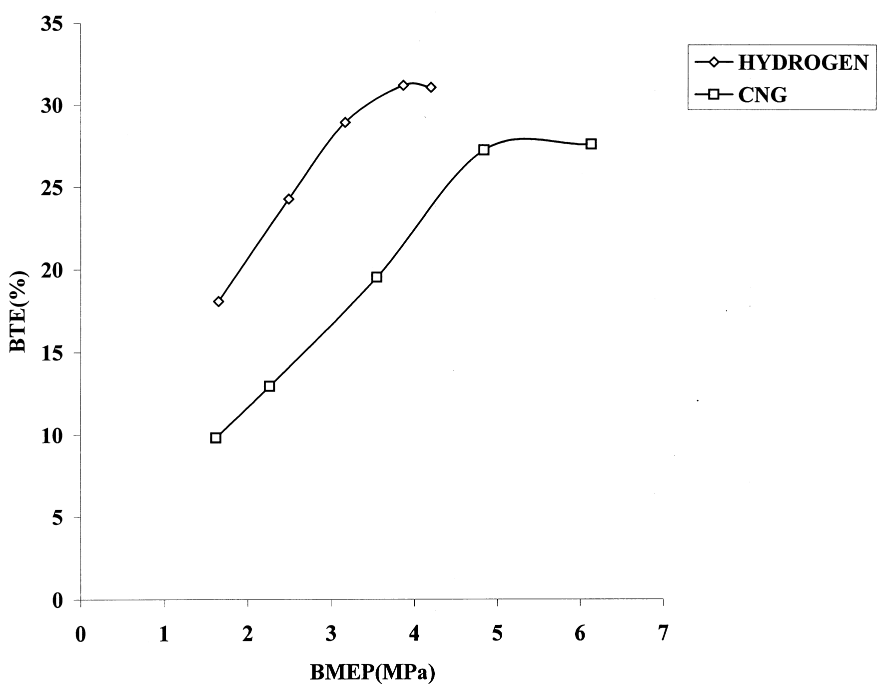

Fig. 7. Variation of brake thermal efficiency with brake mean-effective pressure at 2200 rpm.

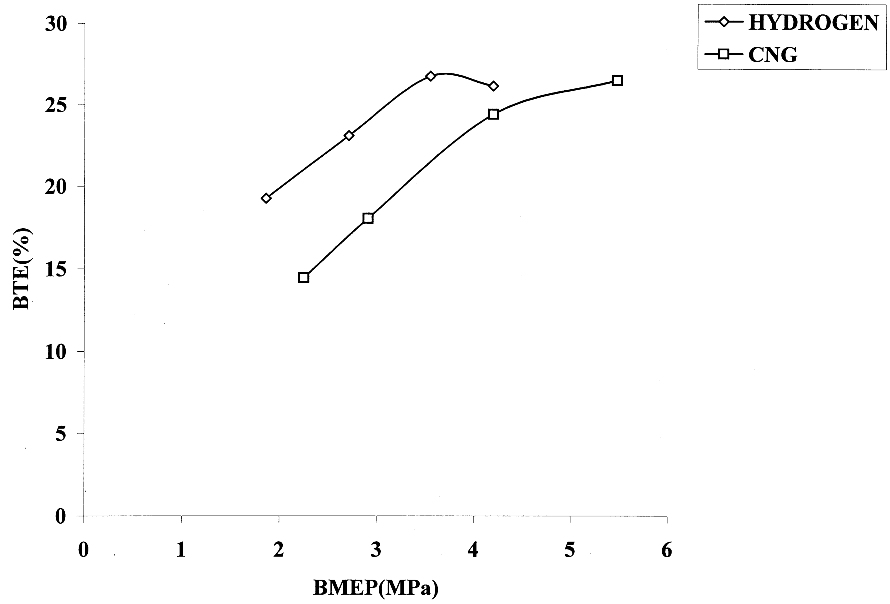

Fig. 8. Variation of brake thermal efficiency with brake mean-effective pressure at 2400 rpm.

parameters. From these figures it can be seen clearly that brake thermal efficiency (BTE) obtained in the hydrogen operated engine is higher than that achieved from CNG over its entire range of operation. The wide range of flammability of hydrogen permits quality regulation, which consists of controlling engine power by varying the fuel rate without throttling the flow of intake air. The gain in BTE for the hydrogen engine is a consequence of the combined effect of lean operation and quality governing abilities. Optimum performance of the injection system was observed at 2000 rpm. Brake-specific fuel consumption (BSFC) was also low for the hydrogen operated engine. As is evident from the figures, the BSFC decreases with the increase in power output. The point at which it becomes minimum is referred to as the "best economical mixture" point.

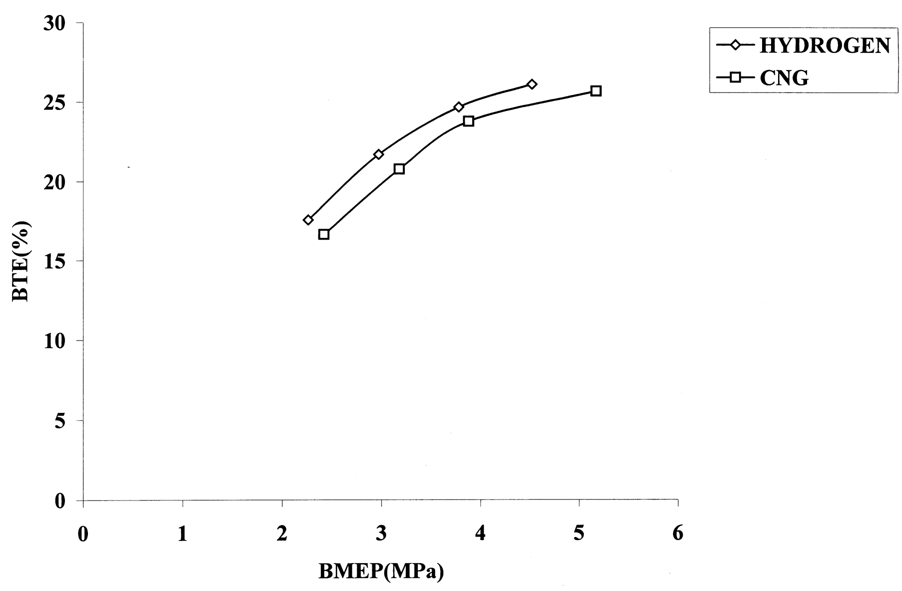

Fig. 9. Variation of brake thermal efficiency with brake mean-effective pressure at 2600 rpm.

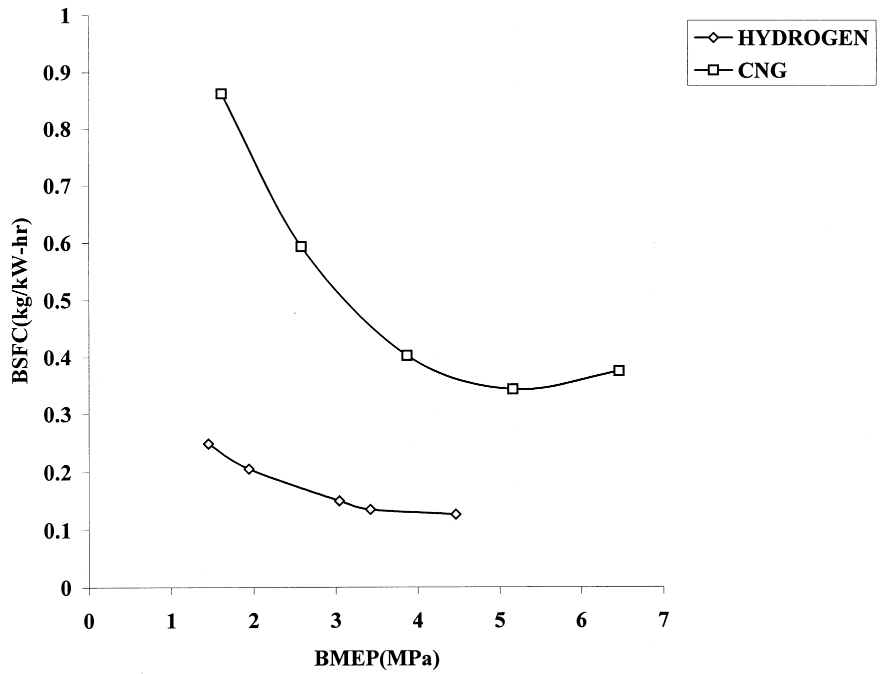

Fig. 10. Variation of brake-specific fuel consumption with brake mean effective pressure at 2000 rpm.

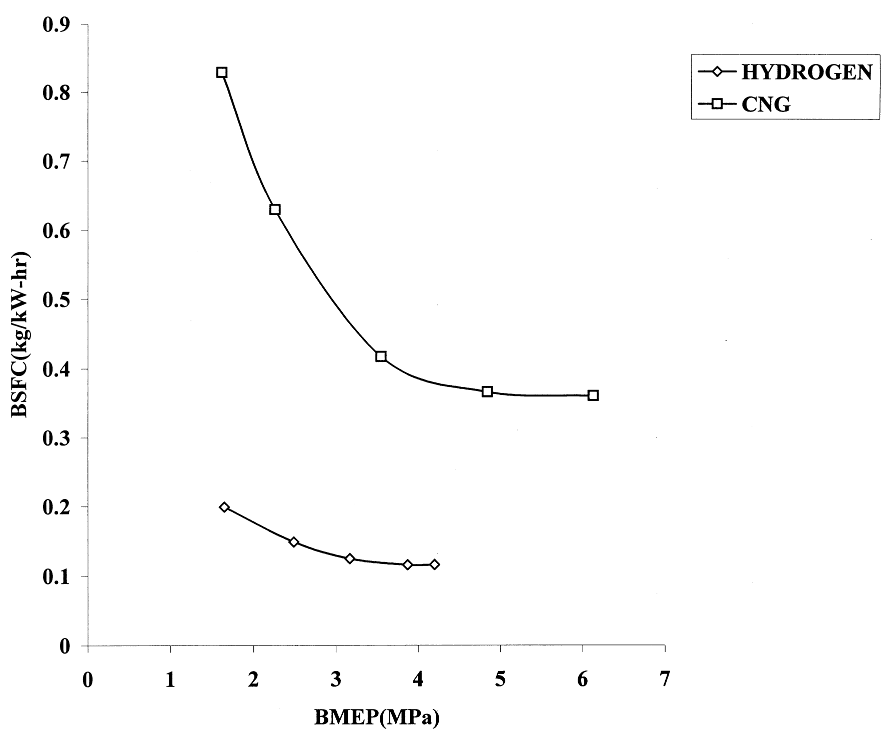

Fig. 11. Variation of brake-specific fuel consumption with brake mean effective pressure at 2200 rpm.

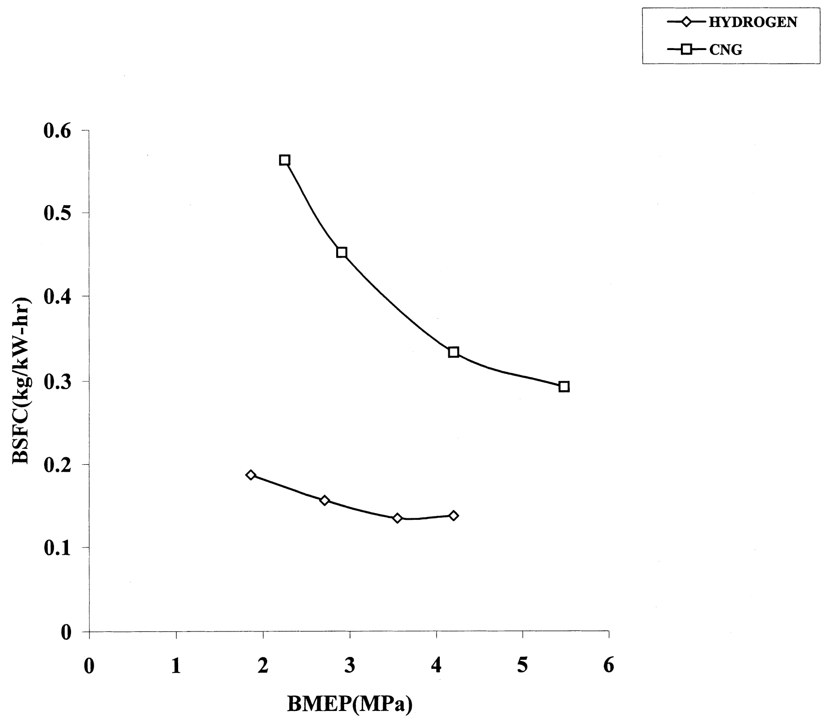

Fig. 12. Variation of brake-specific fuel consumption with brake mean effective pressure at 2400 rpm.

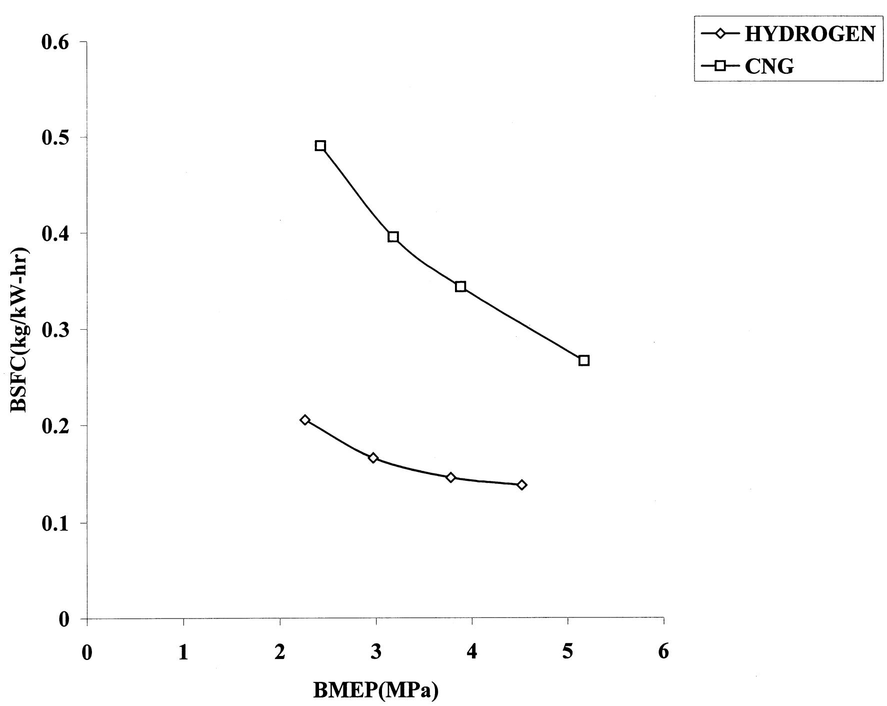

Fig. 13. Variation of brake-specific fuel consumption with brake mean effective pressure at 2600 rpm.

6. Conclusion

From these experiments it is observed that an appropriately designed solenoid-actuated electronically controlled injection system can be adopted for engine operation with both hydrogen and compressed natural gas without any major alteration to the hardware of the system. However, some additional safety features should be adopted for hydrogen operation because of the low minimum ignition energy and the high flame speed of the fuel. It has been observed that the brake-specific fuel consumption was reduced and the brake thermal efficiency improved with hydrogen operation compared to systems running on compressed natural gas. The brake thermal efficiency was as high as 31.19% for hydrogen operation compared to that of 27.59% for CNG.

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