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Experimental Investigation of the Effect of Hydrogen Addition on Combustion Performance and Emissions Characteristics of a Spark Ignition High Speed Gasoline Engine

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Abstract

Considering energy crises and pollution problems today much work has been done for alternative fuels for fossil fuels and lowering the toxic components in the combustion products. Expert studies proved that hydrogen one of the prominent alternative energy source which has many excellent combustion properties that can be used for improving combustion and emissions performance of gasoline-fuelled spark ignition (SI) engines. This article experimentally investigated the performance and emission characteristics of a high speed single cylinder SI engine operating with different hydrogen gasoline blends. For this purpose the conventional carburetted high speed SI engine was modified into an electronically controllable engine with help of electronic control unit (ECU) which dedicatedly used to control the injection timings and injection durations of gasoline. Various hydrogen enrichment levels were selected to investigate the effect of hydrogen addition on engine brake mean effective pressure (Bmep), brake thermal efficiency, volumetric efficiency and emission characteristics. The test results demonstrated that combustion performances, fuel consumption and brake mean effective pressure were eased with hydrogen enrichment. The experimental results also showed that the brake thermal efficiency was higher than that for the pure gasoline operation. Moreover, HC and CO emissions were all reduced after hydrogen enrichment.

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1. Introduction

In recent years, hydrogen has gained attention as a feasible energy source for the next generation of transportation vehicles because of several reasons. The transportation sector is at present highly dependent on fossil fuels. Oil that accounts for nearly 100% of fuel use in the sector has been cheap and plentiful in the past. However, economic and environmental risks are associated with the sector's reliance on petroleum resources. Furthermore, the supply of crude oil is expected to be exhausted in the course of this century. An option for reducing the petroleum dependence problem of the transportation sector is a change to alternative fuels, like hydrogen.

Hydrogen has a wide flammability range in comparison with all other fuels. As a result, hydrogen can be combusted in an internal combustion (IC) engine over a wide range of fuel-air mixtures. Hydrogen has very low ignition energy. A significant advantage of this is that hydrogen can run on a lean mixture and ensures prompt ignition. Generally, fuel economy is greater and the combustion reaction is more complete when an IC engine runs on a lean mixture [1]. All conventional fossil fuels contain carbon atoms in addition to hydrogen atoms, carbon dioxide (CO₂) is a major product gas formed during the conversion of the fuel to energy. The release of stored chemical energy in hydrogen (H₂) produces only water as a product, thus eliminating CO₂, a significant contributor to climate change as a significant greenhouse gas [2]. Fast burning characteristics of hydrogen permit high speed engine operation allows an increase in power output and efficiencies, relatively. Short time of combustion produces a lower exhaust gas temperature for hydrogen [3].

The use of hydrogen as an engine fuel has been attempted on very limited basis with varying degrees of success by numerous investigators over many decades and much information about their findings is available in the open literature. It has been demonstrated by way of several successful experimental projects that hydrogen in many respects is much better than existing automotive fuels [4-6]. Andrea [7] investigated the effect of various engine speeds and equivalence ratios on combustion of a hydrogen blended gasoline engine. The experiment results showed that the combustion duration decreases and the nitrogen emission increases with the increase of hydrogen blending fraction.

Li et al. [8] found that HC and CO emissions from the hydrogen-enriched gasoline engine were lower than the original gasoline engine. Changwei Ji and Wang SF [9] investigated the effect of hydrogen addition on a gasoline-fuelled SI engine performance at various operating condition. They reported that, engine indicated thermal efficiency and emission were also improved after hydrogen enrichment, except for that HC and CO emissions were slightly increased when hydrogen volumetric fraction in the intake exceeded 4.88%. Rahaman [10] focused on the effect of air fuel ratio and engine rotational speed on the performance of a single cylinder hydrogen fuelled spark ignited engine. The air fuel ratio varied from stoichiometric limit to lean limit and rotational speed from 2500rpm to 4500 rpm. The injector location was considered to be fixed in the middle way of the intake port. The experiment shows the increase in brake mean effective pressure and brake thermal efficiency, but shows the decrease at higher air fuel ratio and higher speed. This is because of low flammability of hydrogen and lower densities and air required for combustion is less. The volumetric efficiency of hydrogen fuelled is a serious problem and reduces the power of hydrogen per unit volume. Changwei Ji and Wang SF [11, 12] carried out the experiments on a modified four-cylinder hybrid hydrogen gasoline engine equipped with an electronically controlled hydrogen port injection system and a hybrid electronic control unit. The experimental results demonstrated that the engine brake mean effective pressure was increased after hydrogen addition only at low load conditions. The engine brake thermal efficiency increases with the addition of hydrogen. The cylinder temperature and the peak cylinder pressure increase, while the flame development and propagation durations reduce with the increase of hydrogen addition. HC and CO emissions were decreased and NO_x emissions were increased with the increase of engine load and with the increase of hydrogen blending level. M.A. Escalante Soberanis and AM Fernandez [13] reported in their technical paper that the emissions of air - hydrogen mixtures consist mainly of carbon dioxide and nitric oxides. In the case of NO_x, higher levels of emissions can be observed, due to the higher temperature and flame velocity of hydrogen compared with other fuels, like gasoline. Emissions of HC are the product of lubricant oil heating and the use of oil derivatives for engine

cooling.

The exhaustive information is available in the area of utilisation of hydrogen as a fuel. However, only limited studies were related to hydrogen-enriched high speed single cylinder SI engines with multipoint fuel injection (MPI) system. On account of this, the experiments have been conducted to investigate the effect of hydrogen addition on modified electronically controlled high speed engine at various engine speeds and hydrogen blending level.

2. Experimental Setup and Procedure

2.1 Experimental setup

The tests were performed on high speed single cylinder Lombardini make LGA-340 gasoline engine. Detailed engine specifications are given in Table1. The laboratory consists of test rig involving an eddy current-type dynamometer, exhaust gas emission analyser, fuel metering device and other auxiliary equipment. Fig.2.1 and Fig.2.2 illustrates the schematic diagram and photographic view of the test rig respectively. The compressed hydrogen at 200 bar is supplied from 50 kg steel gas tank. The hydrogen flow control system is mounted on the top end of the hydrogen cylinder which consists of hydrogen regulator and the hydrogen flow indicator. The hydrogen regulator system regulates the flow of hydrogen to the engine and the amount of hydrogen flow can be determined by hydrogen flow indicator. The gasoline engine is modified to hydrogen operated engine by adding hydrogen continuous injection system with the original gasoline injection system kept unchanged. The flame trap is situated in between the hydrogen cylinder and hydrogen injection system as shown in the figure. The developed electronic control unit (ECU) is interfaced with the computer by using RS-232 port. The exhaust emissions from the test engine are measured by exhaust gas analyser which is placed in the way of engine exhaust system.

2.2 Experimental procedure

The tests were carried out at engine speeds of 2000 to 4000 rpm with an increment of 500 rpm. Hydrogen energy fraction on volume basis of 5%, 10%, 15%, 20% and 25% was adjusted with the help of regulator. The current investigation is aimed at analysing the performance and emission characteristics of hydrogen enriched high speed SI engine with ECU controlled MPI system.

3. Results and discussions

3.1 Performance characteristics

3.1.1 Brake Mean Effective Pressure (Bmep)

The brake mean effective pressure is a parameter that reflects the engine power output. The Fig. 3.1 shows the variations of Bmep with different engine speed at various hydrogen fractions. From the graph it can be revealed that, the Bmep rises as the hydrogen fraction increases compared to pure gasoline operation. The proper explanation for such a trend is, hydrogen has a much wider flammable range, a much faster flame propagation speed and a much higher adiabatic flame temperature than those of gasoline, which help extend the flammable range and accelerate the combustion of gasoline–hydrogen–air mixtures. But at 25% hydrogen addition fraction, Bmep drops due to improper combustion as the air content in the intake is gradually reduced with the increase of hydrogen fraction in the total intake gas. However the maximum value of Bmep obtained at an engine speed of 3000 rpm due to proper combustion and highest torque gained by the engine compared to other operating speeds with all operating blends.

3.1.2 Brake thermal efficiency

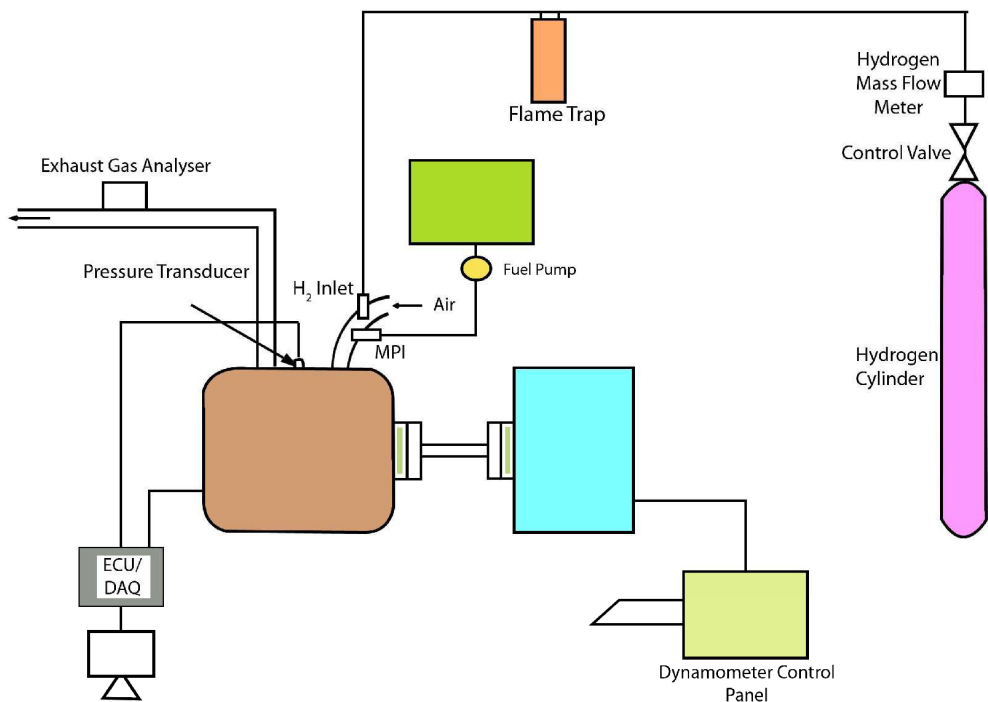


Fig 2.1 Schematic diagram of experimental apparatus



Fig 2.2 Photographic view of engine setup

Table 1 Engine specifications

Bore (mm)	Stroke (mm)	Displacement (cm ³)	Compression Ratio	Power Rating	Max. Torque	Max. rpm at no load
82	64	338	8:1	9kW@ 4400 rpm	20.2 Nm @2800 rpm	6200

Engine thermal efficiency is crucial on evaluating the engine economic and overall performance. It can be improved by either optimizing the combustion system or fuel properties. Engine brake thermal efficiency against various engine speed profiles are shown in Fig. 3.2. As it is seen in Fig. 3.2, brake thermal efficiencies of the hydrogen enriched operation are higher than those of the pure gasoline engine operation at all engine speeds. Moreover, brake thermal efficiency increases distinctively with the increase of hydrogen fraction.

The peak brake thermal efficiency under the test conditions reaches 27.5% for 0% hydrogen addition, 29.4 % for 5% hydrogen addition, 30.5% for 10% hydrogen addition, 32.5% for 15% hydrogen addition, 34.2% for 20% hydrogen addition and 32.8% for 25% hydrogen addition. Since the flame speed of hydrogen is five times as large as that of gasoline and the flammability range of hydrogen is much wider than gasoline, the hydrogen–gasoline mixture will have a faster burning velocity and an extended flame limit than gasoline, which can achieve a shorter burning duration and a more complete burning. Therefore, the faster flame speed of gasoline–hydrogen–air mixture leads to a higher degree of constant volume combustion, meaning that the engine operates much closer to the ideal cycle, and gains a higher brake thermal efficiency than gasoline at all the operating engine speeds. Hydrogen has a much smaller energy density on volume basis. As the percentage of addition of hydrogen increases, hydrogen itself accumulate the cylinder volume which results in reduction in required amount of air for the complete combustion. The collective outcome of these factors lowers brake thermal efficiency of the engine for 25% hydrogen fraction.

3.1.3 Volumetric efficiency

The volumetric efficiency is the ratio of the actual mass of mixture in the combustion chamber to the mass of mixture that the displacement volume could hold if the mixture were at ambient (free-air) density. The Fig. 3.3 indicate the variations of volumetric efficiency for various percentage hydrogen addition at different speeds. As the speed increases there is increase in volumetric efficiency due to reduction in pumping losses.

The maximum volumetric efficiency is attained for pure gasoline of about 70% at 4000 rpm compared to hydrogen gasoline operation. As the percentage of hydrogen blend increases there is a drop in volumetric efficiency due to the density difference between the air and hydrogen. Hydrogen being lighter than air displaces the air. The volumetric efficiency is affected by the fuel being burned in the engine. Liquid fuel takes up very little space in the intake port and the combustion chamber. The hydrogen fuel vapour can take considerably more of this space, leaving less volume for the air being pumped into the cylinder. This causes less amount of mixture density at the inlet of the engine in turn reduction in volumetric efficiency.

3.2 Emission characteristics

3.2.1 Carbon monoxide (CO) emission

The effects of hydrogen addition on CO emission at various engine speeds are shown in the Fig. 3.4. From the figure it can be inferred that CO emission is decreases as the hydrogen gasoline blend percentage increases at all engine speeds. The gradual reduction of gasoline flow rate is enforced with increase in hydrogen blends. CO is dropped with the increase of hydrogen energy fraction due to the enhanced combustion caused by hydrogen addition and abundant oxygen available for the post-oxidation of CO emission. This is because the properly increased hydrogen enrichment fraction helps increase the formation of O and OH radicals which benefit the combustion completeness. The hydrogen possesses a high flame speed and stoichiometric air-to-fuel ratio, the fast combustion of hydrogen is prone to quickly consume the adjacent air, which possibly forms some lean-oxygen zones in the cylinder and blocks CO oxidation in these areas. This produces shorter post combustion period than gasoline, so that the necessary time and cylinder temperature for CO oxidation reaction decreases causing slow reaction kinetics of CO into CO₂. Hydrogen is having higher range of flammability causes the decrease in CO blends.

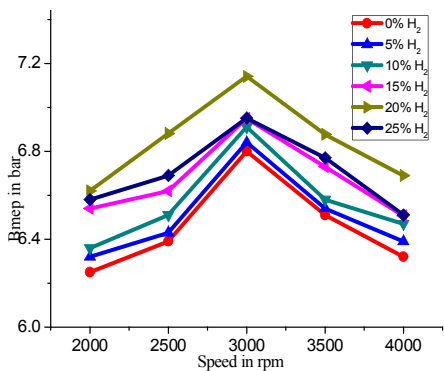


Fig. 3.1 Variation of Bmep with speed for various hydrogen volume fraction

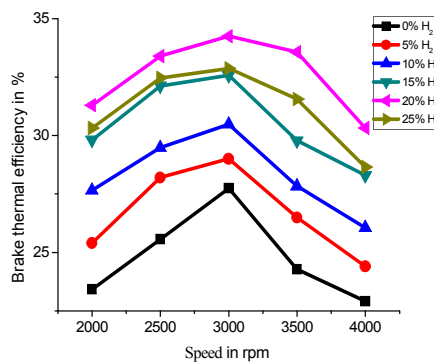


Fig. 3.2 Variation of brake thermal efficiency speed for various hydrogen volume fraction

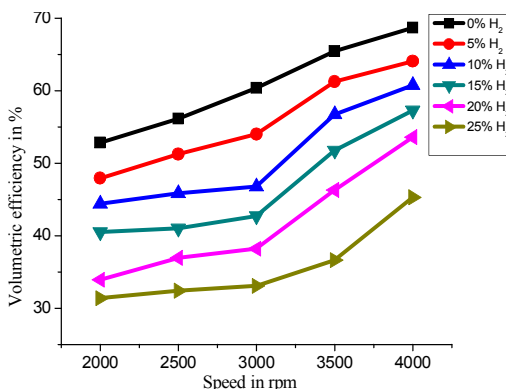


Fig. 3.3 Variation of volumetric efficiency with speed for various hydrogen volume fraction

3.2.2 Hydrocarbons (HC) emission

The Fig. 3.5 indicates the variations of HC emissions with engine speeds at different hydrogen blending levels. It can be found that HC emissions decrease with the increase of hydrogen addition fraction. This can be possibly explained that the formation rate of OH radical is accelerated by hydrogen addition. So gasoline-hydrogen mixture can be more fully burnt and emits less HC emissions than gasoline, due to the improved chain reaction. The shorter quenching distance of hydrogen than that of gasoline is other possible reason for the reduced HC emission. A shorter quenching distance allows the flame to travel closer to the cylinder wall facilitating complete combustion. Another reason is high diffusivity property of hydrogen. It can disperse into the air more easily and this facilitates the formation of a more uniform and homogenous fuel air mixture. Additionally, the high flame speed of hydrogen reduces the combustion duration, and decreases the probability of occurrence of slow-burning and incomplete combustion cycles. The least values of HC emission level observed at an engine speed of 3000 rpm as all the fuel gets burnt with a maximum combustion temperature and pressure.

3.2.3 Nitrogen oxide (NO_x) emission

At very high temperature which occurs in the combustion chamber of an engine, N₂ breaks down to monatomic N which is reactive. Other gases such as oxygen and water vapor also break down at high temperatures leading to the formation of NO_x. The higher the combustion reaction temperature, more dissociation takes place and more NO_x will

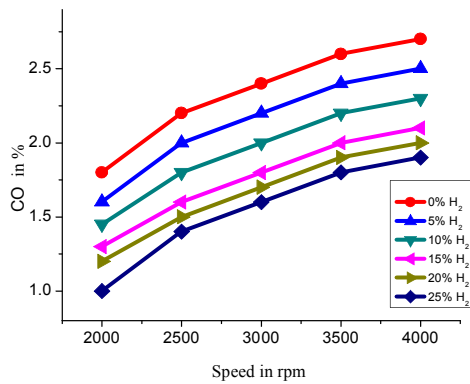


Fig. 3.4 Variation of CO emission with speed for various hydrogen volume fraction

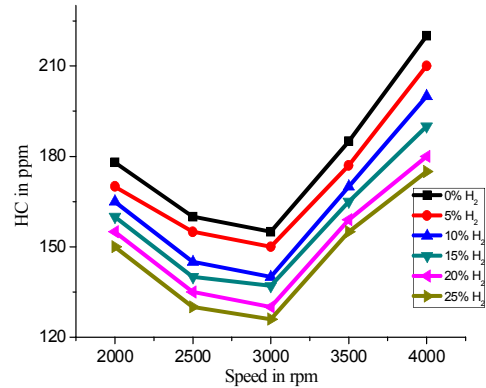


Fig. 3.5 Variation of HC with speed for various hydrogen volume fraction

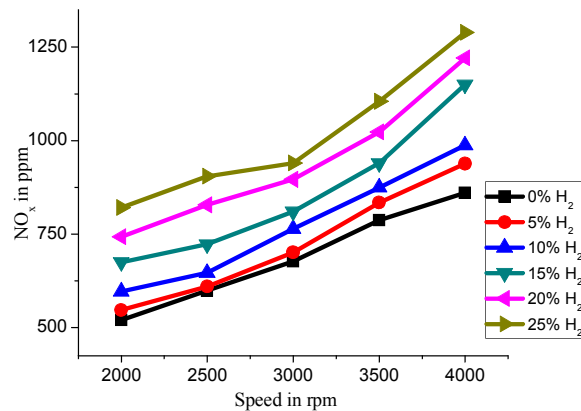


Fig. 3.6 Variation of NO_x with speeds for various hydrogen volume fraction

be formed. The emission of NO_x is increase with the increase of hydrogen addition fraction as shown in Fig. 3.6. The increase in volume of hydrogen blend will lead to rise in combustion temperature. This is due to wide range of flammability. The higher amount of NO_x is observed at 4000 rpm engine speed where engine runs with rich fuel mixture compared to all other engine speeds. At this operating condition, engine attains combustion with highest rate of combustion temperature and in addition, there is an excess of oxygen that can combine with the nitrogen to form various oxides.

4. Conclusions

An experimental study aiming at investigating the effect of hydrogen addition on improving gasoline engine performance under different engine speed was introduced in this article. The main conclusions are listed below:

1. The addition of hydrogen helps in improving Bmep. The maximum Bmep obtained at 20% blend of hydrogen for an engine operating at 3000 rpm speed.
2. The addition of hydrogen is effective on improving engine brake thermal efficiency. An increase of brake thermal efficiency was observed till a hydrogen fraction of 20%. Beyond this, the brake thermal efficiency is declined due to reduction in air quantity.
3. The volumetric efficiency decreases as the percentage of hydrogen increases as hydrogen tends to replace air from the mixture.
4. HC and CO emissions reduces with the increase in percentage of hydrogen mainly due to increase in the cylinder

temperature. NO_x emissions increase with the increase in hydrogen addition. High NO_x values are observed for engine operating at higher speed for all the fuel blends.

5. Overall the test results revealed that the blends up to 20% hydrogen are suitable as an engine fuel without much compromise in the performance and emission characteristics.

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