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HYDROGEN ADDITION ON COMBUSTION AND EMISSION CHARACTERISTICS OF HIGH SPEED SPARK IGNITION ENGINE- AN EXPERIMENTAL STUDY

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Abstract

The present article aims at characterizing the combustion and emission parameters of a single cylinder high speed SI engine operating with different concentrations of hydrogen with gasoline fuel. The conventional carburetted SI engine was modified into an electronically controllable engine, wherein ECU was used to control the injection timings and durations of gasoline. The engine was maintained at a constant speed of 3000 rpm and wide open throttle position. The experimental results demonstrated that heat release rate and cylinder pressure were increased with the addition of hydrogen until 20%. The CO and HC emissions were reduced considerably whereas NO_x emission was increased with the addition of hydrogen in comparison with pure gasoline engine operation.

Keywords: SI Engine, Hydrogen addition, Combustion, Emission.

1. Introduction

The fast depleting fuel reserves, increasing fuel demands and stringent emission standards gave rise to a need of alternatives for fossil fuels. The potential of high efficiency and zero emissions of hydrogen made us to use as an alternative to gasoline for the spark ignition engines. Hydrogen has good combustion properties and wide flammability range in comparison to other fuels. As a result, hydrogen can be combusted in an SI engine over a wide range of fuel-air mixtures. In

Nomenclatures

Greek Symbols

θ_{IVC}	Crank angle at IVC, deg.

Abbreviations

bTDC	Before top dead centre
CO	Carbon monoxide
CO_2	Carbon dioxide
ECU	Electronically controllable unit
HC	Hydrocarbon emissions
IVC	Inlet valve close
N	Nitrogen
NO_x	Oxides of nitrogen
rpm	Rotations per minute
SI	Spark ignition
UBHC	Unburned hydrocarbons
WOT	Wide open throttle

addition, hydrogen has a very low ignition energy, which is helpful for an engine to run on a lean mixture and ensures prompt ignition.

Hydrogen has a fast burning flame velocity which permits high speed engine operation, results in better efficiency and power output. The short combustion period of hydrogen produce lesser exhaust gas temperature. Additionally, hydrogen depletes the emissions like unburned hydrocarbons, carbon monoxide and carbon dioxide due to the absence of hydrocarbons in the fuel. Though many research group question about the issues like safety of the fuel, proper design of storage and transportation systems, still hydrogen can effectively replace gasoline [1-5].

These are some distinctive features of hydrogen fuel, which are of great practical relevance to automobile applications. The use of hydrogen as a fuel in engines has been the subject of study for different authors in the last decades with various degrees of success [6-9]. Changwei and Wang [10, 11] conducted experiments on a modified hydrogen fuel operated SI engine equipped with an ECU controlled port system for hydrogen injection. The experimental results showed the increment in cylinder peak pressure and temperature, while reduction in flame development and propagation durations with the increase of hydrogen addition. Also they revealed that there was decrease in HC and CO emissions and increase in NO_x emissions with increased engine load and hydrogen blending level. Erol Kahraman [12] found that hydrocarbon emissions from hydrogen-enriched SI engine were lower than the original gasoline engine. Escalante Soberanis and Fernandez [13] reported that the emissions of air - hydrogen mixture consist mainly of carbon dioxide and nitric oxides. Higher levels of emission of NO_x are observable due to the higher flame velocity and combustion temperature of hydrogen. Andrea [14] explored the effect of various equivalence ratios and engine speeds on a hydrogen operated SI engine. The experiment results indicated that the nitrogen emission increases and the combustion duration decreases with the increase of hydrogen fraction in the fuel blend.

There is comprehensive information available in the area of utilization of hydrogen as a fuel. But there was limited studies found related to hydrogen fuelled high speed single cylinder SI engines with multipoint fuel injection system. Therefore, the present investigation aimed to investigate the effect of hydrogen addition on a modified high speed gasoline engine with electronically controlled unit.

2. Experimental Setup and Procedure

2.1. Experimental setup

The current investigation aims at analyzing the combustion and emission characteristics of hydrogen enriched high speed SI engine with ECU controlled injection system. The tests were performed on high speed single cylinder Lombardini make LGA-340 gasoline engine. Table 1 gives detailed engine specifications. The test bench consists of an eddy current dynamometer, exhaust gas emission analyzer, fuel metering device, and other auxiliary equipment's. Figures 1 and 2 illustrate the schematic diagram and photographic view of the test rig, respectively. The compressed hydrogen gas at 200 bar is stored in steel cylinder. The hydrogen flow rate was controlled with two stage regulator, which also consists of pressure indicators for hydrogen supply and cylinder pressure. The flame trap was situated between the hydrogen cylinder and engine which comprises of rotameter with control valve. The hydrogen from the cylinder passes to the flame trap and then supplies to the engine via rotameter which regulates the determined quantity of hydrogen with the help of control valve.

The existing gasoline engine was modified to work on hydrogen by adding continuous injection system and replacing carburetor with fuel injector for gasoline injection. The developed ECU was interfaced with the computer by using RS-232 port. AVL's exhaust gas analyzer was used to determine the engine exhaust emission which was placed in the way of engine exhaust system. The engine was equipped with Kistler's integrated cylinder pressure sensor and crank angle encoder. The National instruments data acquisition system was used to acquire data from the Kistler charge amplifier with a Lab VIEW program. The air measurement is done with Bosch make air measurement sensor. Abnormal combustion such as knock, backfire and pre-ignition of hydrogen enrichment fuel were taken care by established engine control parameters.

Table 1. Engine specifications.

Engine parameter	Details
Bore	82 mm
Stroke	64 mm
Displacement	338 cm^3
Compression ratio	8:1
Max rpm at no-load	6200 rpm
Power rating	9kW @ 4400 rpm
Maximum torque	20.2 Nm @ 2800 rpm

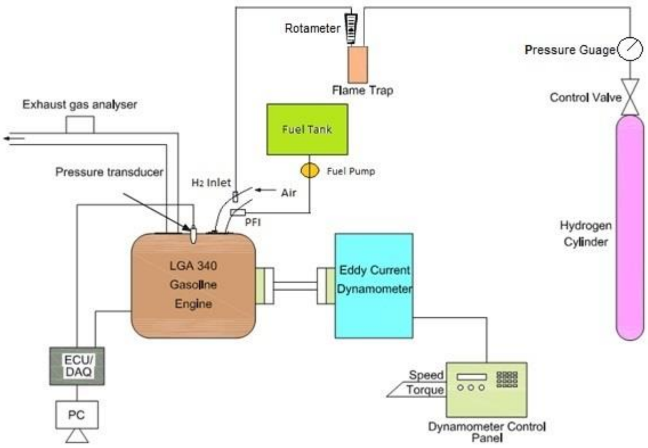

Fig. 1. Schematic diagram of experimental setup.

Fig. 2. Photographic view of the engine setup.

Parts: **1**. Hydrogen cylinder **2**. Flame trap **3**.Dynamometer control panel **4**.Dynamometer**5**. Engine **6**. Data Acquisition system **7**. Hydrogen pressure regulator **8**. Hydrogen flow regulator (Rotameter) **9**. Pressure indicator

2.2. Experimental procedure

All the experiments were conducted with a constant speed of 3000 rpm and wide open throttle position where the engine delivered maximum torque with pure gasoline fuel engine operation. The spark timing used for all testing conditions was roughly kept at 14 deg. bTDC.

At specified engine speed, experiments were conducted initially with pure gasoline and thereafter, hydrogen being added gradually with the help of hydrogen regulator to permit the hydrogen fraction in the total fuel to be raised from 0% to 25% in step of 5%. For all testing conditions, the in-cylinder pressure for 100 consecutive cycles were recorded and analysed through the cylinder measurement system to obtain profiles of cylinder pressure against crank angle and exhaust emissions recorded with the use of exhaust analyser.

2.3. Rate of heat release analysis

This analysis is carried out according to the first law of thermodynamics during the closed part of the engine cycle. The basis for the majority of the heat-release models is the first law of thermodynamics, i.e. the energy conservation equation. The simplest approach was to consider the cylinder contents as a single zone, and modeling as represented by average values. The first law of thermodynamics is applied by considering cylinder contents as a single open system, whose thermodynamic state and properties are being uniform throughout the cylinder and are specified by:

$$\frac{dQ}{dt} - p\frac{dV}{dt} + \sum_i m_i h_i = \frac{dU}{dt} \tag{1}$$

here, Q represents heat transferred in Joules, p denotes pressure in Pascal, V is the volume m^3, m_i is the mass of fuel injected in kg/s, h_i is the enthalpy in J/kg, and U represents internal energy in J.

Assuming that the internal energy and enthalpy are sensible terms (at room temperature) and only the mass transferred from the system is the injected fuel. Rewriting the above equation as:

$$\frac{dQ}{dt} = p\frac{dV}{dt} + \frac{dU}{dt} \tag{2}$$

The heat transfer through the system boundary presents a problem only at the end of combustion when the temperatures have risen. If we further assume the contents of the cylinder as an ideal gas, then we can alter the Eq.2 as follows:

$$\frac{dQ}{dt} = p\frac{dV}{dt} + mC_v\frac{dT}{dt} \tag{3}$$

here, C_v is the specific heat at constant volume.

Differentiation of the perfect gas law with R assumed constant, provides a means of eliminating the temperature term which is generally unavailable in pressure analysis to give

$$\frac{dQ_{Net}}{dt} = \left(1 + \frac{c_v}{R}\right)p\frac{dV}{dt} + \left(\frac{c_v}{R}\right)V\frac{dp}{dt} \tag{4}$$

substituting the specific heat ratio γ, provides the final equation used in the analysis with the result being equally valid when substituting the independent variable θ or crank angle, for time t, then the net heat release combustion model of Krieger and Borman is obtained [15]

$$\frac{dQ_{Net}}{d\theta} = \frac{\gamma}{\gamma - 1}p\frac{dV}{d\theta} + \frac{1}{\gamma - 1}V\frac{dp}{d\theta} \tag{5}$$

where, γ is the ratio of specific heats, Q_{Net} is the net heat release rate in Joules per degree, p is the in-cylinder pressure in Pascal, and V is the in-cylinder volume in m^3.

Calculating the cylinder volume (V) from crank angle for a slider-crank mechanism as follows [16].

$$V = V_c + \frac{\pi B^2}{4}\left(l + R - R\cos\theta - \sqrt{\left(l^2 - R^2\sin^2\theta\right)}\right) \quad (6)$$

where, V_C is clearance volume at TDC in cubic meter, B is bore in meter, l is connecting rod length in meter, R is crank throw in meter (= stroke/2), θ is crank angle measured from the beginning of the induction stroke in radians.

Specific heat at constant pressure is given as:

$$C_p = \frac{R}{1 - 1/\gamma} \quad (7)$$

A temperature dependent equation for specific heat ratio γ obtained from experimental data is used [16].

$$\gamma = 1.338 - 6x10^{-10}T + 1x10^{-8}T^2 \quad (8)$$

where T is the mean charge temperature found from pV=mRT state equation. Since the molecular weights of the products and the reactants are similar, the mass m and gas constant R can be assumed as constants. If all thermodynamic states (p_{ref}, T_{ref}, V_{ref}) are known or evaluated at a given reference condition such as inlet valve close (IVC), then the mean charge temperature *T* is calculated as

$$T = pv\frac{T_{ref}}{p_{ref}V_{ref}} \quad (9)$$

The cylinder volume at IVC is computed using the cylinder volume given in the above equation for θ_{IVC} and is therefore considered to be known. The two other states at IVC (P_{IVC}, T_{IVC}) are considered unknown and have to be estimated.

3. Results and Discussions

3.1. Combustion characteristics

Cylinder pressure

Figure 3 shows the effect of hydrogen addition on cylinder pressure with respect to the crank angle at 3000 rpm where engine attains maximum torque at WOT. As shown in Fig. 3, the increase in hydrogen addition fraction distinctly raises the cylinder pressure. Addition of the hydrogen also results to bring the peak of the pressure rise gradually shifting towards the TDC. This indicates that combustion in the cylinder takes place relatively at high pressure and temperature, due to the high adiabatic flame temperature and high flame speed of hydrogen [17]. This improves the combustion process of the mixture with shorter combustion duration. This improvement is found noticeably up to 20% of the hydrogen only. However, for the 25% hydrogen addition, the cylinder pressure decreased due to improper combustion and reduced volumetric efficiency.

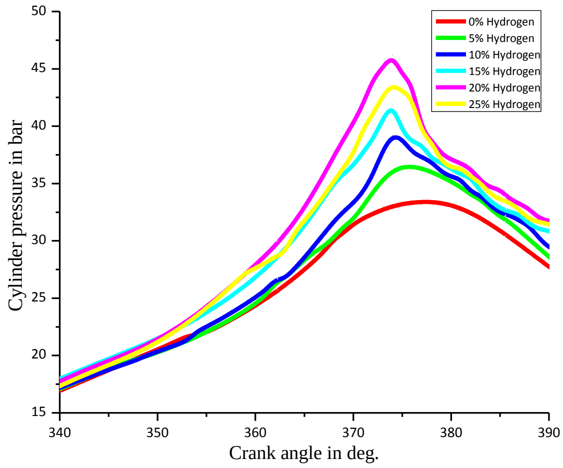

Fig. 3. Variation of cylinder pressure with various hydrogen fractions.

Heat release rate

Figure 4 shows net heat release rate versus crank angle for different hydrogen addition. The graph reveals that the rate of heat release increases with the hydrogen addition. This was mainly due to faster flame front propagation of hydrogen and high rate of combustion. Hydrogen addition improves combustion efficiency due to shorter period of combustion and hence, extreme amount of heat release occur nearer to TDC position and also availed easing of cyclic variations [18, 19]. The maximum rate of heat release of about 43.5 J is observed at 20% hydrogen fraction which is comparatively much more than pure gasoline engine operation. For the 25% hydrogen fraction, the rate of heat release decreased mainly due to reduction in volumetric efficiency resulting in lower combustion temperature and pressure.

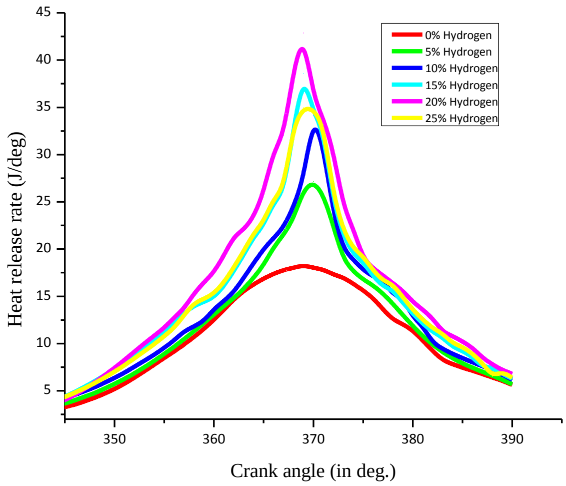

Fig. 4. Variation of net heat release with various hydrogen fractions.

3.2 Exhaust emissions

SI engine suffers from poor combustion and maximum rate of toxic emissions due to high residual gas fraction and low combustion temperature. As hydrogen has better combustion qualities than gasoline, the engine emissions performance seems to be better with the addition of hydrogen. Figures 5, 6 and 7 show the major engine pollutant emissions for hydrogen addition from 0% to 25% with gasoline fuel.

Hydrocarbons emission

Figure 5 indicates the variation of HC emission with different hydrogen addition with gasoline in a SI engine. It was found that HC emission decreased with the addition of hydrogen fraction in the fuel blend. The improved chain reaction among hydrogen and gasoline accelerates the formation rate of OH radical by hydrogen addition. High flame speed and high diffusivity property of hydrogen facilitates the formation of a more uniform and homogenous fuel air mixture. This helps in complete combustion of gasoline-hydrogen mixture and releases less HC emissions than gasoline. The shorter quenching distance of hydrogen than that of gasoline also helps in reducing HC emission with the increase of hydrogen addition level at a specified speed [11, 20].

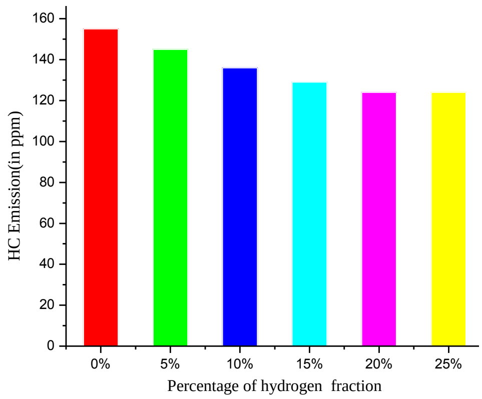

Fig. 5. Variation of HC emission with various hydrogen fractions.

Nitrogen oxide emission

Figure 6 shows the result of hydrogen addition on nitrogen oxide emission at specified speed condition. From the graph, it is observed that the emission of NO_x increases with the addition of the hydrogen fraction.

At higher temperatures, N_2 breaks down to monatomic N, which is more reactive with oxygen and water vapour. The outcome of these reactions leads to the formation of NO_x. The higher the combustion reaction temperature, more dissociation takes place & more NO_x is formed [17, 21]. Progressively continuous increment in NOx emission was observed until 20% hydrogen addition wherein marginal increment was found for 25% hydrogen addition. This is mainly attributed towards the higher speed and low density of the hydrogen which displaces air causing fuel rich mixture thus increasing NO_x emissions though in cylinder temperature was lower.

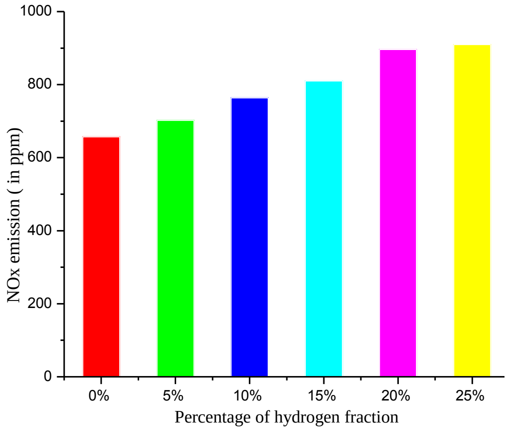

Fig. 6. Variation of NO_x emission with various hydrogen fractions.

Carbon monoxide emission

Figure 7 shows the effect of hydrogen addition on CO emission at specified speed condition. From the figure, it was observed that CO emission decreases, as the percentage of hydrogen blend increased. With increase in hydrogen addition, the gasoline flow content reduces, thus reducing carbon content in the fuel blend. Hydrogen possesses a high flame speed and wide flammability range thus the fast combustion of hydrogen quickly consumes the adjacent air, thus producing shorter post combustion period than gasoline, so that the cylinder temperature and necessary time for CO oxidation reaction decreases causing reduction in CO emission [10, 11]. There is a decrement of 8%, 16%, 22%, 29% and 33% for 5%, 10%, 15%, 20% and 25 % hydrogen addition respectively compared to pure gasoline engine operation.

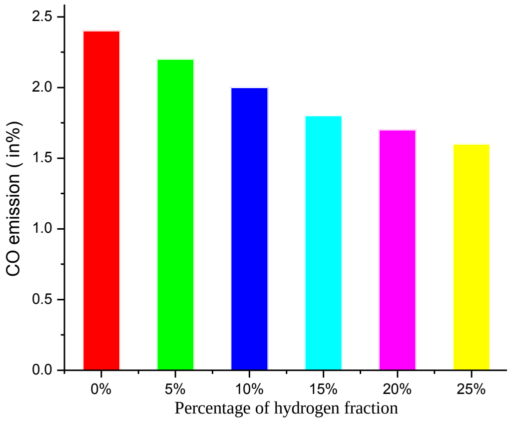

Fig. 7. Variation of CO emission with various hydrogen fractions.

4. Conclusions

An experimental study investigated the effect of hydrogen addition on high speed single cylinder gasoline engine in order to explore the combustion and emission characteristics at maximum torque attained engine speed of 3000 rpm. The main conclusions are:

- The addition of hydrogen tends to increase the engine cylinder pressure. Increase of engine cylinder pressure was observed for a hydrogen fraction up to 20%. Beyond this, the cylinder pressure declines due to reduction engine brake torque.
- The addition of hydrogen with gasoline increases the net heat release rate. Hydrogen blending improves the combustion efficiency hence, the maximum rate of heat release occurs nearer to TDC.
- The CO and HC emissions are reduced drastically with the addition of hydrogen due to improved combustion and shorter post combustion period.
- Hydrogen enrichment increases the NO_x emission due to high rate of combustion pressure and temperature.

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