EFFECT OF HYDROGEN ADDITION ON COMBUSTION AND EMISSIONS PERFORMANCE OF A HIGH SPEED SPARK IGNITED ENGINE AT IDLE CONDITION

by

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The fuel depletion and environmental pollution have pushed studies on improving the combustion and emission characteristics of internal combustion engines with several alternative fuels. Expert studies proved that hydrogen is one of the prominent energy source which has exceptional combustion qualities that can be used for improving combustion and emissions performance of gasoline-fueled spark ignition engines. This paper introduced an experiment conducted on a single cylinder high speed gasoline engine equipped with a hydrogen injection system to discover the combustion and emissions characteristics with various hydrogen gasoline blends at idle condition. For this purpose, the conventional carburetted high speed spark ignition engine was modified into an electronically controllable engine with help of electronic control unit which dedicatedly used to control the ignition timings and injection duration of gasoline fuel.

Key words: *spark ignition, hydrogen addition, emissions, idle*

Introduction

Fast depletion of fossil fuels and their detrimental effect to the environment is demanding an urgent need of alternative fuels for meeting the demand of sustainable energy with minimum environmental impact. Expert studies indicate that among all the alternative fuels hydrogen is a promising energy source for the future because of its superior combustion qualities and availability. Hydrogen has a wide flammability range in comparison with all other fuels. As a result, hydrogen can be combusted in an internal combustion engine over a wide range of air/fuel mixtures. Hydrogen can run on a lean mixture and ensures prompt ignition due to its low ignition energy [1]. The combustion of hydrogen produces only water as a product, thus reduction in toxic pollutants except oxides of nitrogen compared to gasoline fuel combustion [2]. Fast burning characteristics of hydrogen permit high speed engine operation with maximum power output and efficiencies.

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The use of hydrogen as an engine fuel has been attempted on very limited basis with varying degrees of success by numerous researchers over many decades and much information about their findings is available in the open literature. It has been proved by several successful experiments that hydrogen in many aspects is much better than existing automotive fuels [3-9]. D'Andrea *et al.* [10] investigated the effect of hydrogen addition on combustion characteristics of a spark ignition (SI) engine. The experiment results revealed that the duration of combustion is decreased and the nitrogen emission increased with the increase in hydrogen addition. Ma *et al.* [11, 12] carried out experiments on idle performance of a hydrogen-enriched SI engine. The experiment results showed that engine pollutants such as HC and CO emissions were reduced as the addition of hydrogen increases at idle conditions. Ji and Wang [13] investigated effect of hydrogen on a modified hybrid hydrogen gasoline engine equipped with an electronically controlled hydrogen port injection system at various load. The experimental results demonstrated that the engine brake thermal efficiency increases with the addition of hydrogen. They also observed that the engine peak cylinder pressure and temperature increases with the hydrogen addition. HC and CO emissions were decreased and NO_x emissions were increased with the increase of hydrogen blending level. Escalante Soberanis and Fernandez [14] reported in their technical paper that the hydrogen-gasoline combustion gave rise to NO_x increment due to higher temperature and flame velocity compared with gasoline. Ji *et al*. [15] and Ji and Wang [16] investigated the idle performance of a spark ignited gasoline engine with hydrogen addition. The research results show that, with the increasing of hydrogen enrichment levels, the engine idle speed remains approximately at its original target. The flame development, propagation durations and coefficient of variation of IMEP are reduced with the increasing hydrogen fraction. Since hydrogen has a wide flammability and fast burning velocity, the CO and HC emissions are reduced with the hydrogen enrichment at idle and lean conditions.

The spark-ignited engine always suffer low thermal efficiency and expel more toxic emissions at idle condition due to the high residual gas fraction, low engine speed, high variation in the intake charge, and decreased combustion temperature. According to previous studies, in some big cities with heavy traffic congestion, automobile engines have to spend 25% and 30% of their total operating time and fuel consumption at idle, respectively [17]. Thus, improving engine idle performance becomes crucial on enhancing engine overall performance. The enrichment of hydrogen with gasoline is a possible solution to improve the engine performance at idle. Since the flame speed of hydrogen is five times higher than gasoline, hydrogen engines can get a high degree of constant volume combustion, which not only benefits the engine performance but also reduces toxic emissions [18-20]. Besides, the low ignition energy of hydrogen also permits hydrogen-air mixture to be easily ignited under idle conditions and helps engines gain a smooth starting process.

The exhaustive information is available in the area of utilization of hydrogen as a fuel. However, only limited studies were related to hydrogen-enriched high speed single cylinder SI engines with multi fuel (hydrogen and gasoline) injection system. The above studies were mainly concentrated on combustion performance and emissions at normal operating conditions rather than at an idle condition. Therefore, experiments have been conducted to investigate the effect of hydrogen addition on modified, electronically controlled high speed engine to evaluate combustion performance and emission at idle condition.

Analysis of net heat release

This analysis is carried out according to the First law of thermodynamics during the closed part of the engine cycle. Net heat release defined as the difference between the energy released through combustion and the energy lost to heat transfer from the system walls. 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 is with regards to the cylinder contents as a single zone, modeled as and 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:

$$\frac{\mathrm{d}Q}{\mathrm{d}t} p\frac{\mathrm{d}V}{\mathrm{d}t} + \sum_i m_i h_i = \frac{\mathrm{d}U}{\mathrm{d}t} \tag{1}$$

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

Assuming that the enthalpy and internal energy are sensible terms (using a baseline of 298 K) and only the mass is transferred from the system is the injected fuel. Thus the above equation can be re-written:

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = p\frac{\mathrm{d}V}{\mathrm{d}t} + \frac{\mathrm{d}U}{\mathrm{d}t} \tag{2}$$

The heat transfer through the system boundary presents a problem only at the end of combustion where the temperatures have raised. If we further assume that the contents of the cylinder can be modeled as an ideal gas, then the eq. (2) can be altered:

$$\frac{\mathrm{d}Q}{\mathrm{dt}} = p\frac{\mathrm{d}V}{\mathrm{dt}} + mC_V\frac{\mathrm{d}T}{\mathrm{d}t} \tag{3}$$

here C_V is the specific heat at constant volume.

Differentiation of the perfect gas law (pv = mRT), eliminates the temperature term which is generally unavailable in pressure analysis to give:

$$\frac{\mathrm{d}Q_{\mathrm{Net}}}{\mathrm{d}t} = 1 + \frac{C_V}{R} p\frac{\mathrm{d}V}{\mathrm{d}T} + \frac{C_V}{R} V\frac{\mathrm{d}p}{\mathrm{d}t} \tag{4}$$

Substituting the specific heat ratio γ ($\gamma = C_p/C_V$), provides the final equation used in the analysis with the result being equally valid when substituting the independent variable crank angle θ, for time t, the net heat release combustion model of Krieger and Borman [21] is obtained:

$$\frac{\mathrm{d}Q_{\mathrm{Net}}}{\mathrm{d}\theta} = \frac{\gamma}{\gamma - 1} p\frac{\mathrm{d}V}{\mathrm{d}\theta} + \frac{1}{\gamma - 1} V\frac{\mathrm{d}p}{\mathrm{d}\theta} \tag{5}$$

where Q_{net} is the net heat release rate in Joules per degree, p – the in-cylinder pressure in Pascal, and V – the in-cylinder volume in m^3.

The cylinder volume from crank angle for a slider-crank mechanism that can be achieved [1]:

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

where R is the crank throw, l – the connecting rod length, V_c – the clearance volume at top dead center, B – the bore, θ – crank angle measured from the beginning of the induction stroke.

The specific heat at constant pressure is given:

$$C_p = \frac{R}{1 - \dfrac{1}{\gamma}} \tag{7}$$

A temperature dependent equation for specific heat ratio γ obtained from experimental data is used [22]:

$$\gamma = 1.338 - 6 \cdot 10^{-10} T + 10^{-8} T^2 \tag{8}$$

where T is the mean charge temperature found from $pV = m\mathrm{R}T$ state equation assuming the total mass of charge mc and the mass specific gas constant R to be constant. Since the molecular weights of the reactants and the products 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, the mean charge temperature T is calculated as:

$$T = pV \frac{T_{\mathrm{ref}}}{p_{\mathrm{ref}} V_{\mathrm{ref}}} \tag{9}$$

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.

Experimental section

Experimental set-up

The current investigation was aimed at analyzing the combustion and emission characteristics of hydrogen enriched high speed SI engine with ECU controlled MPI system. The tests were performed on high speed single cylinder Lombardini make LGA-340 gasoline engine. Detailed engine specifications are given in tab. 1. The test bench consists of an eddy current-type dynamometer, exhaust gas emission analyzer, fuel metering device and other auxiliary equipment. Figures 1 and 2 illustrate the schematic diagram and photographic view of the test bench, respectively. The compressed hydrogen at 200 bar is supplied from 50 kg steel gas cylinder. On the top end of the cylinder, hydrogen flow control system is mounted, which comprises the regulator and pressure indicator for hydrogen supply. The regulator reduces the cylinder pressure of hydrogen to operating pressure. The existing conventional gasoline fuel injection system was modified with continuous hydrogen injection system. The carburetor was replaced with fuel injector for gasoline injection. The flame trap is situated between hydrogen cylinder and hydrogen fuel injection system. The rotameter with flow controlling valve is attached to the flame trap. The flow controlling valve is used to regulate the intake quantity of hydrogen to the engine manifold. The developed electronic control unit is 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

Bore, [mm]	Stroke, [mm]	Displacement, [cm^3]	Compression ratio	Power rating	Max. torque
82	64	338	8:1	9kW at 4400 rpm	20 Nm at 2800 rpm

Experimental procedure

All experiments were started after the engine was fully warmed. The main throttle valve was kept closed to ensure the engine working at idle. The spark timing used for all testing conditions was roughly kept around top dead center of 14° bTDC. At a specified engine idle speed, initially experiments were conducted with pure gasoline and thereafter, hydrogen injection rate was gradually increased with the help of hydrogen regulator to permit the hydrogen energy fraction in the total fuel to be raised from 0% to about 25%. For all testing conditions, the in-cylinder pressure for 50 consecutive cycles were recorded and analyzed through the cylinder measurement system to obtain profiles of cylinder pressure versus crank angle and exhaust emissions recorded with the use of exhaust analyzer.

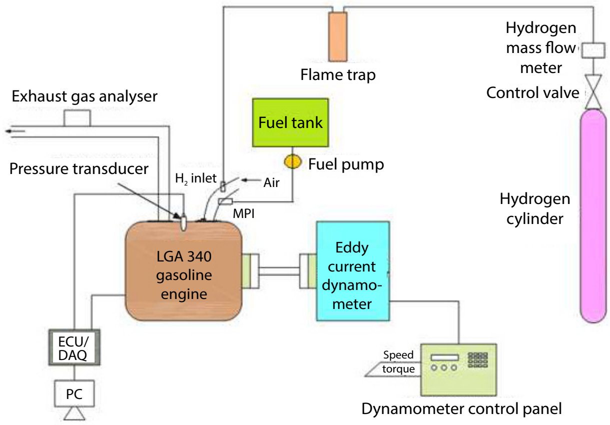

Figure 1. Schematic diagram of experimental apparatus

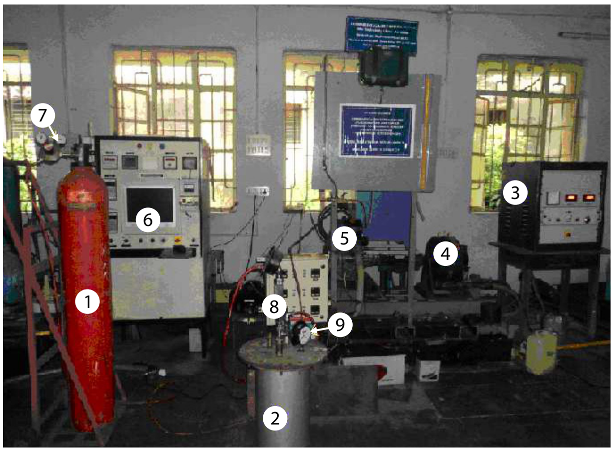

Figure 2. Engine setup; *1 – engine 2 – dynamometer 3 – dynamometer control panel 4 – data acquisition system 5 – hydrogen cylinder 6 – hydrogen pressure regulator 7 – flame trap 8 – hydrogen flow regulator (rotameter) 9 – pressure indicator*

Results and discussion

Combustion characteristics

Cylinder pressure

Figure 3 shows the effect of hydrogen addition on cylinder pressure with respect to the crank angle at idle condition. As shown in fig. 3, cylinder pressure is distinctly raised with the increase of hydrogen fraction. It is also observed that the peak of the pressure is gradually moving towards TDC position as the hydrogen fraction increased except for 25%. This indicates that the combustion in the cylinder take place at relatively high pressure and temperature due to the high adiabatic flame temperature and high flame speed of hydrogen, which improve the combustion process with a shorter combustion duration. Further cyclic variations are continuously decreased with increase in hydrogen fraction as it diffuses much faster than air, which improves the homogeneity of the mixture in turn contributes to the fast and complete combustion of the mixture [1, 23, 24]. But, as the hydrogen enrichment level exceeds to 25% and above, cylinder pressure is decreased due to improper combustion and reduced volumetric efficiency.

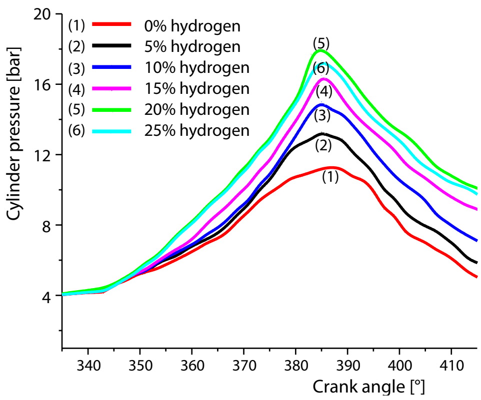

Figure 3. Variation of cylinder pressure with various hydrogen fractions

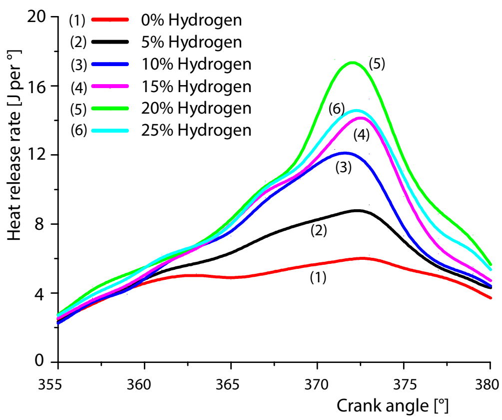

Figure 4. Variation of net heat release with various hydrogen fractions

Heat release rate

The rate of net heat release is plotted against the crank angle as shown in fig. 4 for each state of hydrogen blending. From the graph it can be revealed that the rate of heat release is increased with the hydrogen enrichment. This is mainly due to faster flame front propagation of the hydrogen and high rate of combustion. Hydrogen blending improves combustion efficiency with shorter combustion period and hence, extreme amount of heat release occurs nearer to TDC position and also availed easing of cyclic variations [25]. The maximum rate of heat release of about 16.5 J observed at 20% hydrogen fraction. As the percentage of hydrogen fraction exceeds 25% and above, the rate of heat release decreases due to the reduction in volumetric efficiency which in turn lowers combustion temperature and pressure.

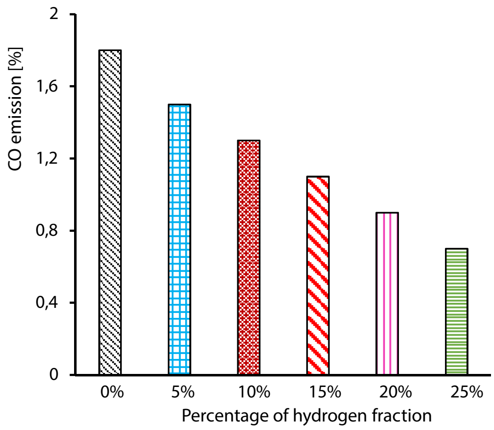

Figure 5. Variation of CO emission with various hydrogen fractions

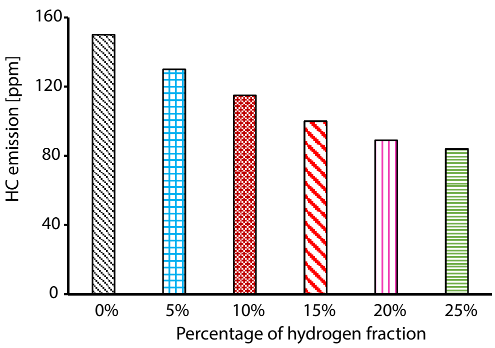

Figure 6. Variation of HC emission with various hydrogen fractions

Exhaust emissions

SI engine suffers poor combustion and maximum rate of toxic emissions at idle condition 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 [26, 27]. Figures 5-7 plot the engine pollutant emissions against hydrogen addition fractions from 0-25% at idle conditions.

Carbon monoxide emission

The effect of hydrogen addition on CO emission at idle condition is shown in fig. 5. From the figure it can be observed that CO emission decreases as the hydrogen percentage in the fuel blend increases. The gasoline flow rate is reduced with increase in hydrogen blends. Due to the improved combustion caused by hydrogen addition and abundant oxygen available, emission of CO is dropped with the increase of hydrogen addition. As the hydrogen possesses a high flame speed and wide flammability range, the hydrogen quickly consumes the adjacent air, thus produces shorter post combustion period than gasoline [15, 25]. Therefore, necessary time for CO oxidation reaction decreases causing reduction in CO emission.

Hydrocarbons emission

Figure 6 indicates the variation of HC emission with hydrogen addition at different hydrogen blending levels. It can be found that HC emission decrease with the increase of hydrogen addition fraction. Due to the improved chain reaction, the formation rate of OH radical is accelerated 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 compared to gasoline. The shorter quenching distance of hydrogen than that of gasoline also helps in reduction of HC emission with the increase of hydrogen addition level at idle condition [17, 28].

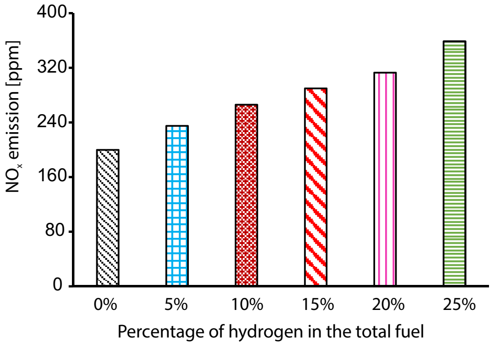

Figure 7. Variation of NO_x emission with various hydrogen fractions

Nitrogen oxide emission

The effect of hydrogen addition on nitrogen oxide emission at idle condition is shown in fig. 7. From the plot it can be observed that the emission of NO_x increased with the addition of hydrogen fraction. As the percentage of hydrogen in the fuel blend increases, the combustion takes place at higher temperature and pressure due to its higher amount of energy content. At high temperatures, N_2 breaks down to monatomic N, which is more reactive with the oxygen and water vapor. The outcome of these reaction leads to the formation of NO_x. The higher the combustion reaction temperature, more dissociation takes place and more NO_x will be formed [29, 30]. The maximum amount of NO_x is observed at 25% of hydrogen fraction, where engine runs with rich hydrogen fraction compared to all other energy fraction.

Conclusions

An experimental study was carried to investigate the effect of hydrogen addition on engine combustion and emission characteristics of high speed SI engine with ECU controlled injection system at idle conditions is presented in this article. The outcomes are listed below.

- The addition of hydrogen tends to increase engine cylinder pressure. An increase of engine cylinder pressure was observed till a hydrogen fraction of 20%. Beyond this, the cylinder pressure is declined due to reduction in volumetric efficiency. It is also observed that the peak pressure is gradually moving towards TDC position as the hydrogen fraction increased except for 25%. The tendency of peak pressure is approaching the TDC as engine running with hydrogen fraction consequences to optimize the ignition angle for optimal engine performance and efficiency.
- The addition of hydrogen with the gasoline up to 20% increased the net heat release rate. This is mainly due to high flame speed and shorter combustion period of hydrogen.
- The emissions of HC and CO were reduced due to improved combustion and shorter post combustion period caused by addition of hydrogen.
- Hydrogen enrichment increases the NO_x emission due to high rate of combustion pressure and temperature.
- Overall the test results revealed that the blends up to 20% hydrogen are suitable as an engine fuel without much compromise in the engine combustion and emission characteristics at idle conditions.

Nomenclature

Greek symbols

θ_{IVC} – crank angle at IVC, [°]

Acronyms

ECU – electronically control unit
IC – internal combustion
IMEP – indicated mean effective pressure
IVC – inlet valve close
rpm – rotations per minute
SI – spark ignition
TDC – top dead centre
UBHC – unburned hydrocarbons
WOT – wide open throttle

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