Applied Thermal Engineering 106 (2016) 850–854

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Experimental investigation on performance of single cylinder spark ignition engine fueled with hydrogen-gasoline mixture

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HIGHLIGHTS

- Performance of spark ignition engine fueled with hydrogen and gasoline mixture was studied.
- The hydrogen percent changed from 24% to 49% of total intake volume.
- Using hydrogen improved engine performance through reducing unburned hydrocarbon percent.
- Emission analysis shows a reduction in unburned hydrocarbon (HC) and carbon monoxide (CO).

ARTICLE INFO

Article history:
Received 23 February 2016
Revised 25 May 2016
Accepted 29 May 2016
Available online 30 May 2016

Keywords:
Hydrogen
Dual fuel engine
Spark ignition engine
Emission
Thermal efficiency

ABSTRACT

In the following an experimental investigation on a single-cylinder four-stroke spark ignition engine operating with gasoline was performed to study the effect of hydrogen addition to fuel on its performance and emissions. The hydrogen was inducted in the air inlet manifold with different volume ratios 24%, 26%, 27%, 28%, 29%, 31%, 35%, 37%, 49% of total intake volume. The combustion analysis was carried out for different percentage of hydrogen additions. The results show that due to the rapid rate of burning of gasoline-air mixture with the addition of hydrogen leads to increase in cylinder pressure. The engine test performance shows an improvement in thermal efficiency as well as reduction in brake specific fuel consumption. The emission analysis shows a reduction in unburned hydrocarbon (HC) and carbon monoxide (CO). Finally, using hydrogen blended with gasoline showed an improvement in efficiency and environmental benefit.

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1. Introduction

During the last decade, the use of alternative fuel in internal combustion engines has received great attention. The uncertainty of petroleum-based fuel availability has created a need for alternative fuels [1]. A lot of research studied improves fuel economy and reducing exhaust emissions. A renewable fuel source as hydrogen is an excellent fuel to meet the environmental controls of exhaust emissions from combustion devices [2].

Broustail et al. [3] carried out an Experiment to study the blends of butanol/isooctane and isooctane/ethanol on pollutants of port-fuel injection SI engine. The results showed the addition of alcohol increase of the fuel consumption, a slight increase in CO_2 emissions and decrease in HC and NO_x emissions. The addition of butanol decreases methane emissions than ethanol. Orhan Akansu et al. [4] made a survey on using natural gas–hydrogen mixtures in engines. It is found that, brake specific fuel consumption, HC, CO_2, and CO emissions decrease with increasing H_2, but NOx emissions increase.

Choi et al. [5] studied the effect of a hydrogen enriched LPG fueled engine on exhaust emission, thermal efficiency and performance. The result shows that there is no merits of the hydrogen enriched LPG engines for break mean effective pressure and thermal efficiency. There is no difference in the CO emissions when hydrogen added, but the amount of oxygen decreases around the rich and theoretical air fuel ratio ranges as hydrogen supplement rate is getting higher but CO_2 emissions increase with the increase of hydrogen supply.

Wang et al. [6] studied experimentally the combustion analysis of hydrogen-enriched ethanol engine. An effect in improving thermal efficiency of an ethanol engine at idle for hydrogen blended was noticed. HC and CO emissions were first reduced and then increased with the increase of the hydrogen blending fraction.

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http://dx.doi.org/10.1016/j.applthermaleng.2016.05.177
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Nomenclature

HC	hydrocarbon	B.P.	brake power watt
CO	carbon monoxide	V	volt
CO_2	carbon dioxide	I	current A
LPG	liquid petroleum gas	BSFC	brake specific fuel consumption, kg/k h
NO_x	nitrogen oxide	C.V.	calorific value, kJ/kg
NTP	normal temperature, pressure (293.15 K, 101.3 kPa)	m	mass flow rate, kg/s
BTDC	before top dead center	η	efficiency

NO_x emissions increase more than ethanol engine at idle and stoichiometric.

The effect of addition hydrogen and ethyl alcohol on performance of a four-stroke spark ignition engine was studied by Al-Baghdadi [7]. The study showed an improvement in engine performance when operating engine with addition of hydrogen and ethyl alcohol. Addition of hydrogen increases the thermal efficiency and NOx but reduces power and CO emission.

Operation of a four stroke spark ignition engine fueled with gasoline, ethanol and hydrogen either pure or blended mathematically was studied by Al-Baghdadi [8]. It was found that ethanol can be used as a supplementary fuel up to 30% of gasoline without major changes, and it improves the output power and reduces NO_x emissions of a hydrogen supplemented fuel engine. The hydrogen added improves the combustion process, reduces the ignition delay, speeds up the flame front propagation, reduces the combustion duration, and retards the spark timing. Blending of ethanol and hydrogen with gasoline reduces CO concentration, but increases NO_x concentration in the exhaust gases.

When hydrogen is burned the main product is water and no toxic products such as hydrocarbons, carbon monoxide, oxides of sulfur, and carbon dioxide, but if it is burned with air it also produced some oxides of nitrogen. The combustion properties of hydrogen as a wide flammability mixture range in air and it requires a low minimum amount of energy to affect ignition with extremely fast resulting flames has an effect on its performance when used as engine fuel [9].

An improvement of break mean effective pressure (BMEP), brake thermal efficiency and maximum BMEP was obtained at 20% blend of hydrogen. Also HC and CO emissions reducing with the increase in percentage of hydrogen but decreasing the volumetric efficiency were noticed through a study performed by Shivaprasad [10] on hydrogen addition at different engine speed.

An improvement in combustion process efficiency and emissions were noticed thorough addition of hydrogen oxygen mixture to the inlet air of a single cylinder direct injection diesel engine experimentally by Mihaylov and Barzev [11] or through Studding the effects of Jatropha hydrogen peroxide emulsion on a direct injection diesel engine by Nguyen [12].

The effect of hydrogen blending on pollutants emission and engine performance of single cylinder spark ignition engine was studied [13,14]. It is found that hydrogen blending improves engine efficiency until a blending ratio of 20% by mass and also the hydrogen blending reduces CO_2, CO and particulate emissions but increases NO_x emission.

An experiment uses an electronic control unit to control the injection timings and injection durations of gasoline with various hydrogen enrichment levels to investigate the effect of hydrogen addition on the performance and emission characteristics of a SI engine. It was found that the combustion performances, fuel consumption and brake mean effective pressure were eased with hydrogen enrichment and also the brake thermal efficiency was higher than that for the pure gasoline operation, HC and CO emissions reduced after hydrogen enrichment [15,16].

Ali Mohammadi et al. [17] studied injecting hydrogen directly into the cylinder of a single-cylinder and effects of injection timing and spark timing on engine performance and NOx emission. The results showed that direct injection prevents backfire, high thermal efficiency and output also NOx emission reduced. The only drawback was that when using hydrogen only as a fuel, the total net power outputs decreased due to its gaseous state which prevents large mass injection process.

Using hydrogen as a blended fuel has much benefits for spark ignition engines by enhancing the combustion process and still needs more investigation for the whole system performance and emissions of CO and UHC. Most of the literatures use it combined with LPG or ethanol. The test percentage of hydrogen not covered a wide range to identify the best percentage of mixture. The aim of the following study is to determine the suitable percentage of hydrogen and gasoline mixture to be used in a single cylinder spark ignition engine and checking the reduction percentage in UHC and CO emissions.

2. Experimental setup

To perform the task, an experimental work carried out on a test rig consists of the following parts: the gasoline engine unit, the hydrogen fueling system, exhaust gas analyzer and various measuring equipment as shown in Fig. 1. A single cylinder four stroke spark ignition engine coupled with a generator (model number (EP6500CXS)) was used as the test engine. The uncertainty of the power output was estimated to be ±0.3 W. The engine specifications are shown in Table 1.

Hydrogen flow rate was measured with gas flow meter. Flow rate of hydrogen was adjusted by a control valve (needle valve) on the gasoline. The uncertainty of the fuel flow rate was estimated to be ±1.7%. The characteristics of hydrogen fuel and gasoline fuel with respect to fuel combustion properties are shown in Table 2.

The tests were performed on two stages. At first stage, the engine was tested with gasoline only. At the second stage, the engine was tested with a mixture of gasoline and hydrogen by changing the amount of hydrogen in the mixture. The test procedure was the following steps:

1. Start the engine and wait till it fully wormed up and reach speed of 3000 rpm. The uncertainty of the speed of engine be ±30 rpm.
2. Hydrogen was injected into the air so to obtain ratio 24%, 26%, 27%, 28%, 29%, 31%, 35%, 37%, 49% by volume in the hydrogen air mixture.
3. The spark timing has been constant at 35° BTDC throughout the tests.
4. The other engine parameters such as the specific fuel consumption and exhaust emissions were recorded. The uncertainty of the exhaust emission be ±0.2% for CO emission and be ±5 ppm for HC emission.

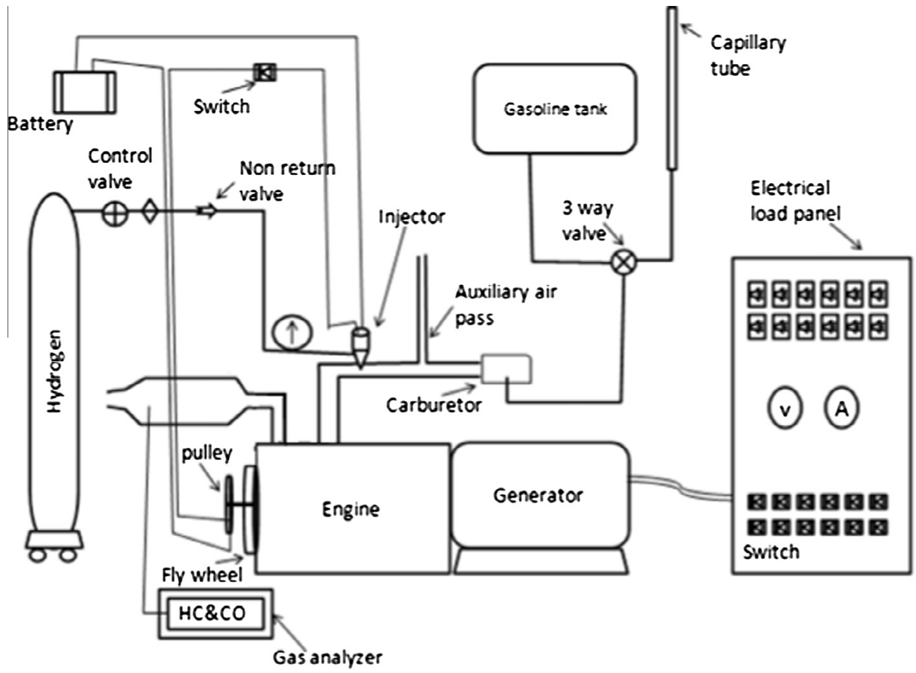

Fig. 1. The experimental test rig.

Table 1
Specifications of the test engine.

Items	Engine
Engine type	Four stroke, overhead valve, single cylinder (Honda)
Bore (mm)	88
Stroke (mm)	64
Fuel system	Carburetor
Cooling system	Air cooling
Ignition system	Transistorized magneto

Table 2
The properties of hydrogen with gasoline.

Properties	H_2	Gasoline
Limits of flammability in air, vol%	4–75	1.0–7.6
Stoichiometric composition in air, vol%	29.53	1.76
Minimum energy for ignition in air, mJ	0.02	0.24
Auto ignition temperature, K	858	501–744
Flame temperature in air, K	2318	2470
Burning velocity in NTP air, cm/s	325	37–47
Quenching gap in NTP air, cm	0.064	0.2
Normalized flame emissivity	1.0	1.7
Equivalence ratio flammability limit in NTP air	0.1–7.1	0.7–3.8

3. Engine performance calculation

The engine power output is determined by measuring the electric current and volt from the generator which is directly connected to load panel (Fig. 1), so the power developed from the engine is calculated using the following equation which was suggested by the generator manufacture:

$$B.P = 1.73 \times V \times I \quad \text{W} \tag{1}$$

The specific fuel consumptions was estimated with the following equation:

$$B.S.F.C = \frac{m_{\dot{Gasoline}} + m_{\dot{Hydrogen}}}{B.P} \quad \text{kg/kW h} \tag{2}$$

The brake thermal efficiency was calculated from the following equation:

$$\eta_{b,th} = \frac{B.P}{(m_{\dot{Gasoline}} \times C.V_{Gasoline}) + (m_{\dot{Hydrogen}} \times C.V_{hydrogen})} \tag{3}$$

4. Results and discussion

The engine performance and emissions have been studied for engine run with gasoline only and with a mixture of gasoline and hydrogen with nine different ratios of hydrogen added to engine (24%, 26%, 27%, 28%, 29%, 31%, 35%, 37%, 49%). The operating parameters such as speed, optimum power output and compression ratio were kept constant during entire test range and the ignition timing was 35° before top dead center (TDC).

The hydrogen has a high flame speed, and the addition of hydrogen enhanced the combustion process characteristics, which has good effect on the fuel consumption of gasoline. It is evident from Fig. 2 that using hydrogen with gasoline improves the devel-

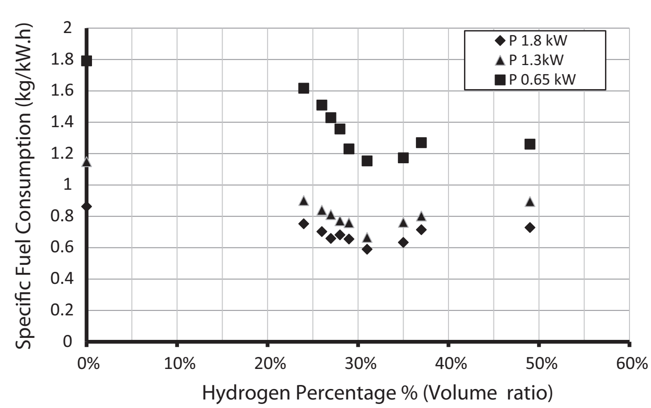

Fig. 2. Effect of hydrogen flow rate on gasoline consumption rate at different load power.

oped power developed more than using gasoline only to operate a engine. This due to the highest flame speed of hydrogen gas. As it has been observed previously, the addition of hydrogen reduces the gasoline fuel consumption for the same power until the hydrogen percentage reached to 31% of total volume of cylinder. After this percentage the increase of hydrogen percentage increases the gasoline consumption again but it is still less than the case of using gasoline alone. This is due to the incompleteness of combustion process because the air percentage is reduced with increase of hydrogen fraction in total intake air.

Brake thermal efficiency is an important parameter, which provides the readily available engine output shaft power and compares the output of the same engine with different blends of hydrogen. Fig. 3 shows a comparison picture between brake thermal efficiency with respect to the brake power for different hydrogen supplementations to engine at constant throttle and spark timing.

Generally, brake thermal efficiency increases with the increase in hydrogen fraction percentage. This is due to high flame speed for gasoline-hydrogen mixture which leads to higher degree of constant volume heat addition process for ideal cycle. This gains a higher brake thermal efficiency greater than using gasoline only at all operating hydrogen fraction [10] but after 31% hydrogen fraction the brake thermal efficiency decreases due to reduction in amount of air required for complete combustion.

The mechanism of hydrocarbons formation is relatively more complicated. The main reason for the formation of hydrocarbons is a distinct combustion in which HCs are formed due to uneven mixture concentration that occurs if the mixture is very lean. These are called unburnt hydrocarbons (UHCs). Hydrocarbon formation also is a function of available air. A better degree of combustion takes place up to the point where there is too little fuel. During the flame quenching, HCs tend to form near the vicinity of metallic surfaces of cylinder walls or cylinder heads which are relatively cooler. At these locations the flame front is quenched and the fuel does not burn. A typical variation of hydrocarbon emission as a function of brake power is shown in Fig. 4. It has been observed, that the amount of HC in exhaust reduced as hydrogen fraction increases due to high flame speed of gasoline-hydrogen mixture which leads to increase the temperature of cylinder wall and reduce the flame quenching, but the amount of HC emission increases again after the hydrogen fraction reaches more than 31% due to reduction in amount of air in the cylinder and the high hydrogen flame speed which consumes more air prior to a gasoline so that the remaining quantity of air will not be sufficient to burn the amount of gasoline which increases amount of unburned hydrocarbon.

Carbon monoxide occurs only in engine exhaust. It is a product of incomplete combustion due to insufficient amount of air in the

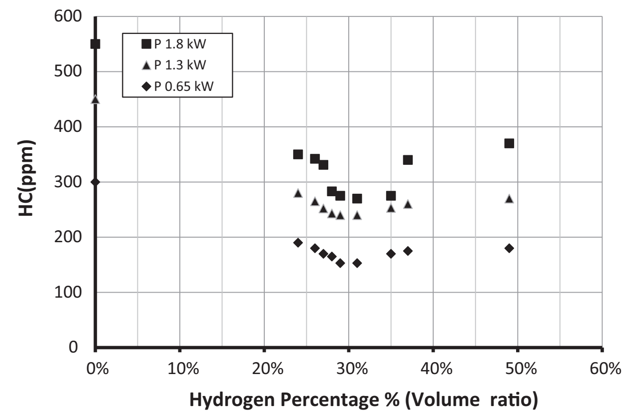

Fig. 4. Effect of hydrogen flow rate on the unburned hydrocarbon at different power.

air fuel mixture or insufficient time in the cycle for completion of combustion. By better mixing of fuel with air, and by providing more air, complete combustion can be achieved. As far as gasoline engine is concerned, it also depends upon the degree of the fuel either vaporized (carbonized or gasified) and thoroughly mixed. Due to this, gasoline engines produce a large portion of CO during the cold start, when the fuel is incompletely vaporized and poorly mixed, where the mixture is poor in quantity or air. The hydrogen mixing with air is an easy task because it is gaseous fuel. So the engine runs leaner than gasoline and gives lower level of CO.

The variations of CO exhaust emissions as a function of brake power for various hydrogen flow rates are shown in Fig. 5. It has been observed, that the increase in hydrogen fraction reduces the amount of CO in the exhaust for the same power due to high flame speed of gasoline–hydrogen mixture and high temperature but after the hydrogen fraction 31% the CO emission increases again due to insufficient combustion low energy flow rate and low temperature.

A comparison between the result and another experimental result [10] is shown in Figs. 6a–c, and the comparison was made with results of Ref. [10] at the same engine speed 3000 rpm. The experiments in Ref. [10] ranged from 5% up to 25%, the present experiment result was done starting from 25% up to 47% and this covers a wide range of hydrogen percentage. The plot of data was normalized using data for no hydrogen as reference point for both data from Ref. [10] and present experiments.

Comparing results shows an improvement in thermal efficiency and reduction in HC and CO emission which is presented in Figs. 6a–c. The best hydrogen percent was 31% volume ratio of total

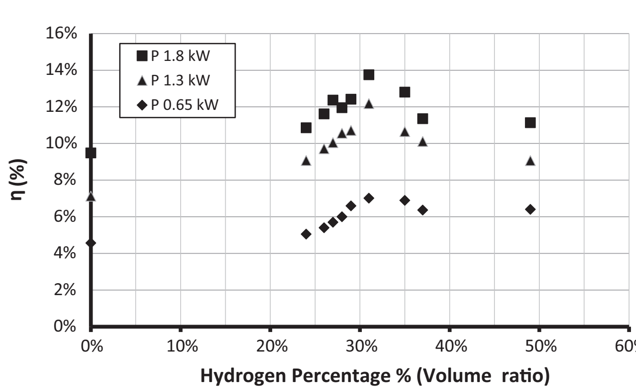

Fig. 3. Effect of hydrogen flow rate on break thermal efficiency at different power.

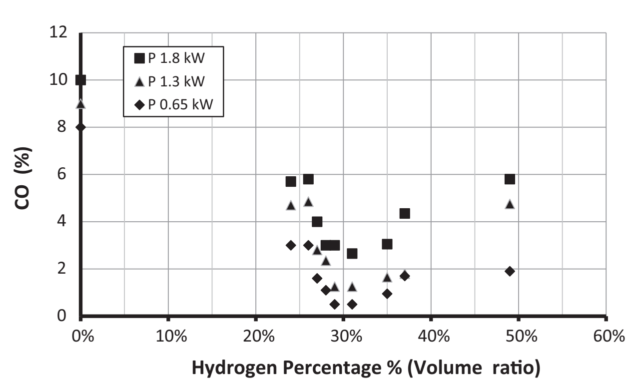

Fig. 5. Effect of hydrogen flow rate on concentration of CO in exhaust at different power.

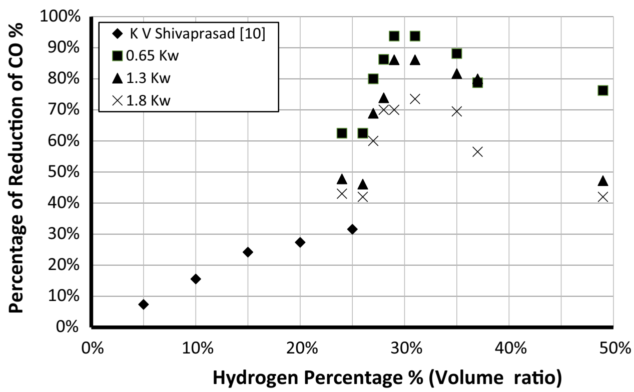

Fig. 6a. Percentage of reduction versus Hydrogen percentage ratio compared with experimental data Ref. [10].

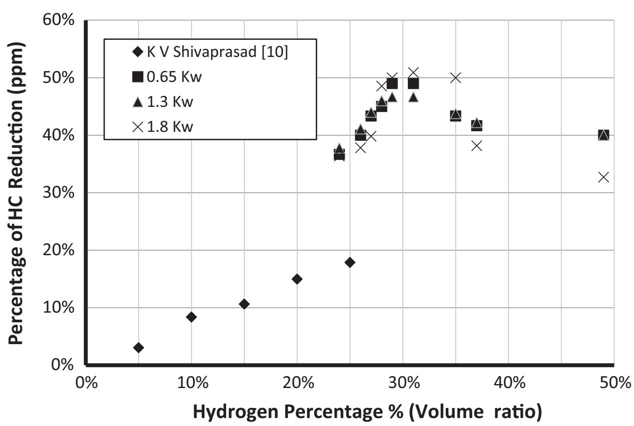

Fig. 6b. Percentage of HC reduction compared with experimental data Ref. [10].

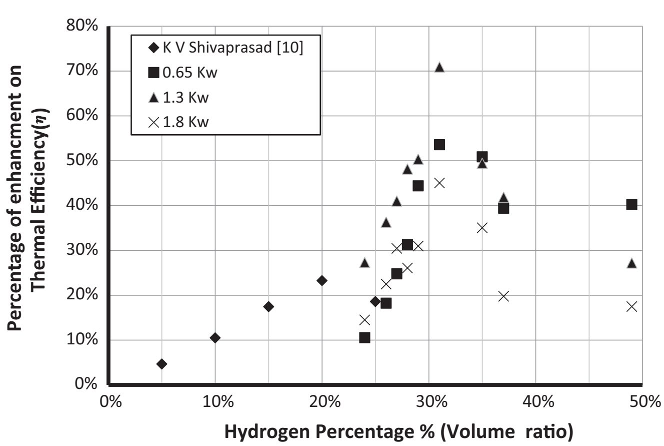

Fig. 6c. Percentage of increased thermal efficiency (η) compared with experimental data Ref. [10].

intake and the comparison shows that the present experiment is consistent with data from Ref. [10] at the same engine speed.

5. Conclusions

An experimental study was performed to explore the effect of hydrogen addition to gasoline fuel in a stationary spark ignition engine to bring out the optimum conditions for a better performance under different load conditions. The results showed that the addition of hydrogen improves the brake thermal efficiency with the increase of hydrogen percentage up to percentage 31% for all tested loads. After that the thermal efficiency starts to decrease with the increase in hydrogen percentage more than 31% due to reduction in amount of air inside the cylinder. The same trends were noticed for HC and CO emission values which also decrease with the increase in hydrogen percentage up to the same hydrogen fraction 31%. After that the amount of HC and CO emissions starts to increase due to the high burning rate of hydrogen compared with gasoline and reduction in amount of air but not reach to their concentrations when using gasoline fuel alone.

Comparing present results (with hydrogen percentages from 24% up to 49%) with experimental results of Ref. [10] (with hydrogen percentages from 5% up to 25%) was performed using percentage of enhancement for each hydrogen percentage compared with no hydrogen use. The comparison shows that there is a consistency in results trend for both experiments. Also the results of the two experiments together give a wide range of tested hydrogen percentages which help in exploring the engine performance when using hydrogen additions to gasoline fuel.

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