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THE USAGE OF HYDROGEN FOR IMPROVING EMISSIONS AND FUEL CONSUMPTION IN A SMALL GASOLINE ENGINE

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Abstract: As small gasoline engines run on slightly rich mixture, and do not have catalytic converter, their specific fuel consumption and emission values are very high. When the gasoline engines are operated with pure hydrogen, NO_x emissions increase and the backfire occurs. In this study, a small engine was run with hydrogen at a suitable lean mixture without occurring backfire, and improvements on fuel consumption and emissions were aimed. Performance, emissions and cylinder pressures of the engine were measured for hydrogen and gasoline. The specific fuel consumption and NO_x emissions were reduced by about 57% and 66%, respectively at hydrogen operation. Moreover, the values near zero for CO, CO_2 and HC emissions were obtained. The test results showed that the small gasoline engine can operate with pure hydrogen at a suitable lean mixture without any backfire, and provide important improvements in emissions and fuel consumption without using any exhaust control system, electronic ignition system and fuel injection system which increase cost of engine.
Keywords: Small engine, Hydrogen, Emissions, Fuel consumption, Backfire.

DÜŞÜK GÜÇLÜ BENZİNLİ MOTORDA EMİSYONLARI VE YAKIT TÜKETİMİNİ İYİLEŞTİRMEK İÇİN HİDROJEN KULLANIMI

Özet: Düşük güçlü benzinli motorlar hafif zengin karışımla çalıştıkları ve katalitik dönüştürücüye sahip olmadıkları için yakıt tüketimleri ve emisyon değerleri oldukça yüksektir. Benzinli motorlar saf hidrojenle çalıştırıldığında NO_x emisyonları artmakta ve geri tepme olmaktadır. Bu çalışmada, düşük güçlü bir motor hidrojen yakıtı ile uygun bir fakir karışımla geri tepme olmadan çalıştırılmış ve yakıt tüketimi ve emisyonların iyileştirilmesi amaçlanmıştır. Performans, emisyon ve silindir basınç değerleri her iki yakıt için ölçülmüştür. Hidrojenli çalışmada özgül yakıt tüketimi ve NO_x emisyonu sırayla yaklaşık %57 ve %66 oranında azalmıştır. Ayrıca, CO, CO_2 ve HC emisyonlarında sıfıra yakın değerler elde edilmiştir. Deney sonuçları; benzinli motorun saf hidrojenle geri tepme olmadan çalışabildiğini ve motor fiyatını artıran egzoz kontrol sistemi, elektronik ateşleme sistemi ve yakıt enjeksiyon sistemi kullanılmadan yakıt tüketimi ve emisyonlarda önemli iyileşmeler sağlandığını göstermiştir.
Anahtar Kelimeler: Düşük güçlü motor, Hidrojen, Emisyon, Yakıt tüketimi, Geri tepme.

INTRODUCTION

With increasing concern about energy shortage and environmental protection, research on improving engine fuel economy and on reducing exhaust emissions have become the major research areas in combustion and engine development. Due to limited reserves of crude oil, development of alternative fuel engines has attracted more and more attention in the engine community (Huang, 2007). Hydrogen as a renewable fuel resource can be produced through the expenditure of energy to replace depleting sources of conventional fossil fuels. It is the only fuel that can be produced entirely from the plentiful renewable resource of the water. These features make hydrogen an excellent fuel to potentially meet the ever increasingly stringent environmental controls of exhaust emissions from combustion devices, including the reduction of green house gas emissions (Karim, 2003). When hydrogen is burned, hydrogen combustion does not produce toxic products such as hydrocarbons, carbon monoxide, oxides of sulfur, organic acids or carbon dioxide, instead its main product is water (Akansu *et al*, 2004). Its combustion in oxygen produces only water but in air it also produces some oxides of nitrogen.

Hydrogen is a remarkably light gaseous fuel. Its heating value on mass basis is exceedingly high but on volume basis it is the lowest among common fuels. Its energy release by combustion per unit mass of stoichiometric mixture remains high. The combustion properties of hydrogen have much influence on its performance as an engine fuel. It has a very wide flammable mixture range in air that permits extremely lean or rich mixtures to support combustion. It requires also a remarkably low minimum amount of energy to effect ignition with extremely fast resulting flames (Li and Karim, 2004).

Several studies have been conducted on the usage of hydrogen as fuel in the SI (Spark Ignition) engines. Kahraman *et al.* (2007) compared the performance and emissions of a four cylinder SI engine running on both gasoline and hydrogen. Variation of moment, power, thermal efficiency, mean effective pressure, exhaust gas temperature and exhaust emissions (NO_x, CO, CO_2, HC and O_2) for both hydrogen and gasoline were investigated by testing the engine at partial load. The values near zero for CO, CO_2 and HC emissions were measured at hydrogen operation. However, severe backfire occurred below 2600 rpm engine speed with hydrogen fuel. Mohammadi *et al.* (2007) used internal mixing method to avoid backfire and detonation which are a difficult challenge when hydrogen is introduced to the engine through the intake manifold. Gaseous hydrogen was injected directly into the cylinder of a test engine via a high pressure gas injector. The results showed that direct injection of hydrogen prevented backfire, and high thermal efficiency and power output could be achieved by injecting the hydrogen at the later stages of compression stroke.

Sierens and Verhelst (2001) converted a GM V-8 SI engine to have it run on hydrogen fuel. Hydrogen was delivered to the engine by both a carburetor and an in-line multi point injection system. With delivering the gaseous fuel via injection system, more power and moment were obtained for all engine speeds compared to the carburetor system. In the tests performed with carburetor system, values of engine performance could not be recorded at low engine speeds. Al-Baghdadi (2004) investigated the effect of compression ratio, equivalence ratio and engine speed on the performance and emission characteristics of a spark ignition engine using hydrogen as fuel. It was reported that the compression ratio and equivalence ratio had a significant effect on both performance and emission characteristics of the engine. According to the results of this study, NO_x emissions decreased as the mixture became leaner. Zhenzhong *et al.* (2002) investigated the optimum control of injection system in an in-cylinder injection type hydrogen fuelled engine with electronic control unit. Their results showed that the use of electronic control system had advantages for achieving the purpose and improving the performance of hydrogen fuelled engine.

Das *et al.* (2000) experimentally investigated the performance characteristics of a spark ignition engine running on hydrogen and compressed natural gas as alternative fuels. According to the result of this study, it was found that the brake-specific fuel consumption was reduced and the brake thermal efficiency was improved with hydrogen operation compared to natural gas. Jing-Ding *et al.* (1986) investigated the improvement of the combustion in a hydrogen fuelled engine. It was reported that the combustion process improved thanks to rapid burning of hydrogen, and thus an increase in fuel economy and a decrease in emissions were obtained. Mathur and Khajuria (1984) investigated the performance and emission characteristics of hydrogen fuelled spark ignition engine. Their results showed that hydrogen operation of spark-ignited engines was found to be very profitable at low equivalence ratios in terms of both thermal efficiency and nitrogen oxides emissions.

El-Emam and Desoky (1985) investigated the combustion of alternative fuels in spark-ignition engines. They performed the tests using gasoline, alcohol, hydrogen and ammonia fuels. It was determined that both the energy content and carbon to hydrogen ratio was influential on determining the engine performance and exhaust content of potential air pollutants emitted to the atmosphere. According to the results, neither hydrogen nor ammonia produced carbon monoxide or unburned hydrocarbons.

Studies were also carried out regarding the improvement of the efficiency and emission characteristics of small gasoline engines (25 HP or less) with low efficiency. Subramanian *et al.* (2007) investigated the effects of equivalence ratio on NO_x emission of a hydrogen engine. In this study, a single cylinder small SI engine was tested at various equivalence ratios at full load. It was determined that the NO_x emission was near zero up to equivalence ratio of 0.55, and it increased after 0.55. Bartolini *et al.* (2003) carried out work on a prototype two-stroke gasoline direct-injected engine. The experimental data obtained showed how the system significantly reduced hydrocarbon emissions and specific fuel consumption. Zhiyuan *et al.* (2003) investigated the application of ceramic-metal functionally gradient material (FGM) plated to small high speed gasoline engines. The results showed that when the engine was plated, the output could be increased by 5.6%~12%, the brake specific fuel consumption decreased by 8%~10%, and the CO and HC emissions decreased by about 30% and 25%, respectively.

Murillo *et al.* (2003) studied the viability of LPG use in low-power outboard engines for reduction of consumption and pollutant emissions. The results obtained showed an important decrease in specific fuel consumption (nearly 20%) and reductions in pollutants (CO, HC and NOx) but with a small power loss (about 5%). Poola (1994) investigated the effect of biomass-derived high-octane fuel additives on performance of a two-stroke spark-ignition engine. Yi *et al.* (2000) investigated the effects of carburetion method on performance in a hydrogen fuelled single cylinder test engine. In this study, a fuel induction system was designed which can feed the fuel either into intake port or into the cylinder. It was reported that hydrogen fuelled engines could be operated more stably with the in-cylinder injection at high load and more efficiently with the intake port injection at low load. Desoky *et al.* (1983) carried out a comparative performance study of small spark ignition engines burning alcohols, gasoline and alcohol-gasoline blends. Varde (1981) investigated the performance of small spark ignition engine using hydrogen supplemented fuel mixtures.

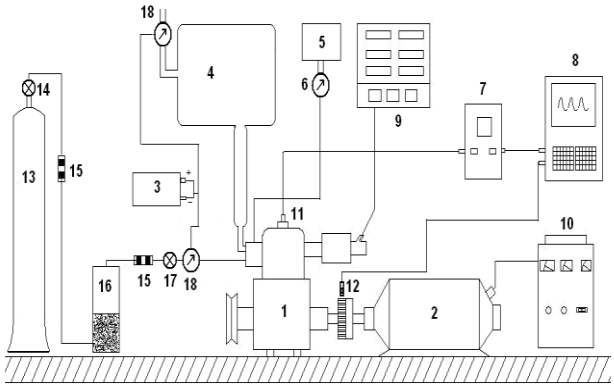
Small spark-ignition engines are typically gasoline-fuelled engines. To attain low cost, these engines are air-cooled, use simple carburetors to regulate the fuel supply and employ magneto ignition systems (Lee et al., 2003). As these engines run at low compression ratio and slightly rich mixture, they have very low efficiency and high emission values. Moreover, these engines cause significant air pollution because they do not have a catalytic converter (Celik, 2007). EPA (Environmental Protection Agency) proposes more stringent emission rules for small non-road and marine spark-ignition engines. Comparing to gasoline, hydrogen has higher lower heating value and gives lower emission values. Fuel consumptions and emission values of small engines can be improved by using hydrogen as alternative fuel.

From the above literature review, it is understood that the hydrogen can be used in SI engines seamlessly if it is injected directly into the cylinder. However, the engine shows malfunction due to backfire at low engine speeds when the hydrogen is given to the engine with external mixing method. The values near zero for CO, CO_2 and HC emissions are obtained at hydrogen operation. NO_x emissions decrease if the engine runs with hydrogen at lean mixture. Backfire problem can be solved in a number of ways, among which are direct in-cylinder fuel injection or running on lean mixtures. In this study, hydrogen was fed to just behind the intake valve at a suitable lean mixture
by using the wide flammability range of hydrogen. Thus, it was provided that the preventing backfire which occurs in the engines with carburetor and reducing NO_x emission which is high at hydrogen operation. This does not necessitate major modifications such as fuel injection system, electronic ignition system and exhaust control system which increase cost of engine.

To the best of the authors' knowledge, little experimental work on the usage of hydrogen as fuel in the small engines is available. There are two aims of this study. One of them is to determine the suitable excess air ratio in terms of stable engine operation (without any backfire and knock) for small engines burning hydrogen. The other is to investigate experimentally the improvement of the fuel consumption and emissions by testing the engine with hydrogen fuel at suitable excess air ratio.

EXPERIMENTAL STUDY

The experimental setup, shown in Fig.1, consists of test engine, dynamometer (D.C. dynamometer), fuel and air flow meters, cylinder pressure measuring system, hydrogen fuel feeding system (hydrogen cylinder, pressure regulator, water trap, fuel control vane), exhaust gas analyzer and various measuring equipments. A single cylinder four stroke small SI engine was used as the test engine.



1-Test engine 2- Dynamometer 3- Power supply 4- Air surge tank 5- Gasoline Fuel tank 6- Gasoline fuel-meter 7- Charge amplifier 8- Oscilloscope 9- Exhaust gas analyzer 10- Dynamometer control panel 11-Pressure transducer 12- Inductive pick-up 13-Hydrogen cylinder 14- Hydrogen regulator 15- Flame arrestor 16- Water trap 17- Flow control vane 18- Gas flow-meter

Figure 1. Test setup.

Table 1 shows the specifications of this engine. The emissions were measured with MRU DELTA 1600L exhaust gas analyzer.

Table 1. Specifications of the test engine.

Items	Engine
Mark	Datsu LT 200
Engine type	Four stroke, single cylinder
Bore (mm)	68
Stroke (mm)	54
Compression ratio	8.5/1
Fuel system	Carburetor
Cooling system	Air cooled
Engine working temp. for gasoline (^oC)	120
Engine working temp. for hydrogen (^oC)	90

The specifications of the exhaust gas analyzer are given in the Table 2.

Table 2. Specifications of the exhaust gas analyzer.

	Measurements range	Accuracy
CO (% vol.)	0 – 15	0.01
CO_2 (% vol.)	0 – 20	0.01
HC (ppm)	0 – 20000	1
NO_x (ppm)	0 – 4000	1
O_2 (% vol.)	0 – 25	0.1

Hydrogen and air flow rates were measured with electronic flow meters (IFM flow meter fed by 19-30V DC). Flow rate of hydrogen was adjusted by a control vane on the gas line. Properties of hydrogen and gasoline fuels used in the experiments are shown in Table 3.

Table 3. Properties of gasoline and hydrogen (Kosar, 2007).

Fuel property	Gasoline	Hydrogen
Molecular weight (kg/kmol)	114.18	2.02
Molar C/H ratio	0.445	0
Density (g/ cm^3), liquid	0.73	0.07
Lower heating value (MJ/kg)	44	119.93
Stoichiometric air/fuel ratio	14.6	34.32
Auto-ignition temperature (K)	501-744	858
Heat of vaporization (kJ/kg)	305	447
Research octane number	91-100	130
Laminar flame speed (m/s)	0.37	1.90
Diffusion coefficient (cm^2/s)	0.05	0.61

To avoid a possible accident, necessary precautions were taken. To prevent backfire, a suitable lean mixture was sent to the back of inlet valve through a copper pipe attached to the intake manifold (Fig.2). As the hydrogen gas is fed directly into the intake port, it does not have the time to propagate back through the intake manifold and thus the backfire does not occur. On the other hand, if the mixture is formed in a carburetor, the manifold volume between the carburetor and intake port is filled up with hydrogen-air mixture which produces a potential for a serious backfire (Kosar, 2007). Air cooled engines work at higher operation temperatures compared to water cooled engines, so the engine temperature was decreased from 120^{o}C to 90^o using an external electric fan in order to help prevent the backfire and detonation.

Figure 2. Induction of hydrogen to the engine.

In order to reduce pumping losses and increase the amount of charge into the cylinder, the carburetor was removed from the engine at hydrogen operation. At all the tests, as the test engine has the magneto ignition system the ignition timing could not be changed.

A system consisting of a piezoelectric pressure transducer, inductive pick-up, charge amplifier and oscilloscope is used to measure the in-cylinder pressure of the test engine. In this study, in-cylinder pressure data was collected using a Kistler model 601A piezoelectric transducer mounted to the spark plug, Kistler model 5011 charge amplifier and a Hitachi digital oscilloscope (VC-5430) were used. The data regarding the crank angles and position of the top dead centre was transmitted to oscilloscope using an inductive pick-up.

The tests were performed at two stages. At first stage, the engine was tested with gasoline at full load in the ranges of 1400– 3800 rpm at intervals of 400 rpm, full throttle opening and excess air ratio of 1.0. At second stage, the engine was tested with hydrogen fuel by removing carburetor at 2200 rpm and various excess air ratios (λ). According to results of these tests, it was found that the most suitable air excess ratio was 1.5 in terms of stable engine operation (without backfire and knock). Then, the tests were performed with hydrogen at the ranges of 1400– 3800 rpm at intervals of 400 rpm and excess air ratio of 1.5.

The engine tune up was checked prior to the test and the measurements were conducted after reaching the working temperature of the engine. Engine power, air and fuel consumption, engine working temperature, HC, CO, CO_2 and NO_x emissions, and the cylinder pressures for both fuels were recorded. The tests were repeated three times and the mean of the test data were calculated.

RESULTS AND DISCUSSIONS

The tests were performed in two stages. Initially, the engine was tested at full throttle opening and various speeds with gasoline fuel. Then, the carburetor was removed from the engine and the engine was tested at various speeds with hydrogen fuel. The results are given below.

The Effects of Gasoline and Hydrogen Fuels on Engine Performance

The effect of the gasoline and hydrogen fuels on engine power is shown in Fig.3. It can be seen from this figure that the power output of hydrogen engine is an average of 24% less than that of gasoline. This decrease in power can be explained by the leaner mixture (λ=1.0 for gasoline operation; λ=1.5 for hydrogen operation) and little amount of charge into the cylinder. At the hydrogen operation, air-fuel mixture does not enter the cylinder as much as at gasoline operation as specific volume of hydrogen gas is higher compared to liquid gasoline. Gasoline engine must have a 40-60% more volume to produce the same amount of power when it is operated with hydrogen (Li and Karim, 2004). Although the power loss of hydrogen fuel had been expected greater than 24%, increased amount of the charge which was accomplished by removing carburetor and decreasing engine operating temperature prevented further decrease in power. It is seen from Fig. 3 that power curve begins to decrease after 3400 rpm for gasoline whereas it continues to increase with hydrogen fuel. This can be attributed to the higher burning speed of hydrogen which produces a better combustion at high engine speeds.

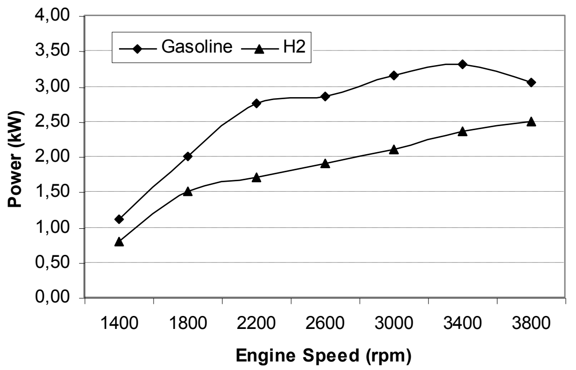


Figure 3. The effect of gasoline and hydrogen fuels on engine power.

Fig. 4 shows the superimposed pressure-time curves of two different fuels at the same engine speed (2200 rpm). The maximum cylinder pressure (about 25 bar) was obtained with gasoline fuel where the maximum pressure was about 23 bar for hydrogen. The slope of the pressure curve of hydrogen is higher than that of the gasoline due to fast burning characteristic of hydrogen fuel. It can be seen from Figs. 3 and 4 that there is an agreement between power increase and cylinder pressure increase.

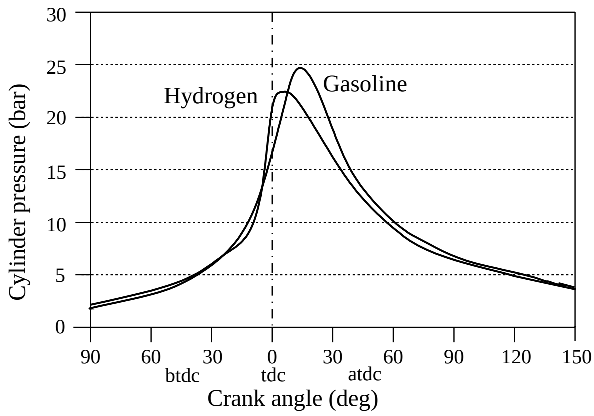


Figure 4. The pressure-time curves of gasoline and hydrogen fuels (2200 rpm).

Fig.5 shows the specific fuel consumption values (SFC) for the both fuels. SFC obtained with hydrogen was about 57% less than that with gasoline. The minimum SFC values for gasoline and hydrogen were obtained at 2200 rpm and 1800 rpm, respectively. Since hydrogen has a much higher lower heating value than gasoline (as seen in Table 3), the SFC for hydrogen becomes considerably less than that for gasoline. Another reason which reduces SFC is the high burning rate of hydrogen which reduces heat losses (Nagalingam et al., 1983). SFC obtained with hydrogen at high engine speeds (3000, 3400 and 3800 rpm) is significantly lower than that with gasoline thanks to more efficient combustion at these speeds (Fig. 5).

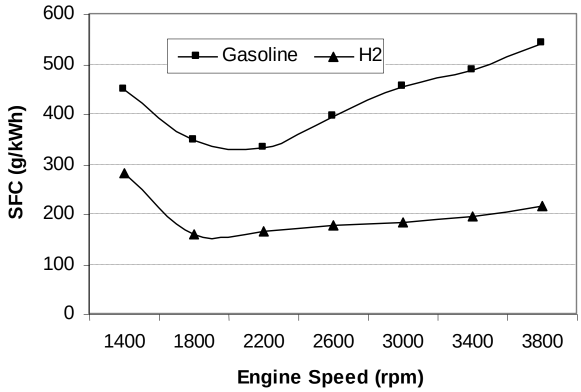


Figure 5. The effect of gasoline and hydrogen fuels on specific fuel consumption (SFC).

The Effects of Gasoline and Hydrogen Fuels on Exhaust Emission

Fig.6 shows the NO_x emission values for the both fuels. NO and NO_2 emissions occur by combination of nitrogen and oxygen at high temperatures in the combustion chamber. One of the main problems with hydrogen fuelled internal combustion engines is the high NO level due to rapid combustion (Subramanian et al., 2007). In this study, NO_x emission of hydrogen fuel was found to be about 66% less than that of gasoline fuel thanks to leaning the mixture. Maximum NO_x values for gasoline and hydrogen are observed at 2200 rpm and 1800 rpm, respectively.

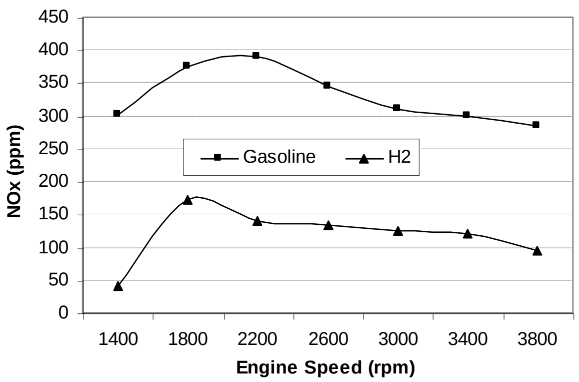


Figure 6. The effect of gasoline and hydrogen fuels on NO_x emissions.

Figures 7 and 8 show CO and CO_2 emission values for the both fuels. Both of the emission values are close to zero at hydrogen operation. CO_2 is non-toxic but contributes to the greenhouse effect. CO and CO_2 emissions are not expected from the combustion of pure hydrogen. As engine lubrication oil film sticks onto the cylinder wall and burn with the air-hydrogen mixture, it can account for these traces of carbon emissions (Li and Karim, 2005).

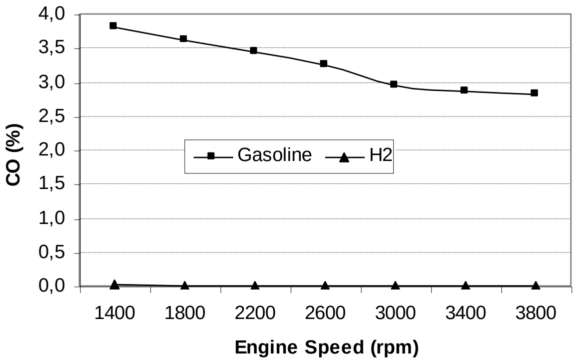


Figure 7. The effect of gasoline and hydrogen fuels on CO emissions.

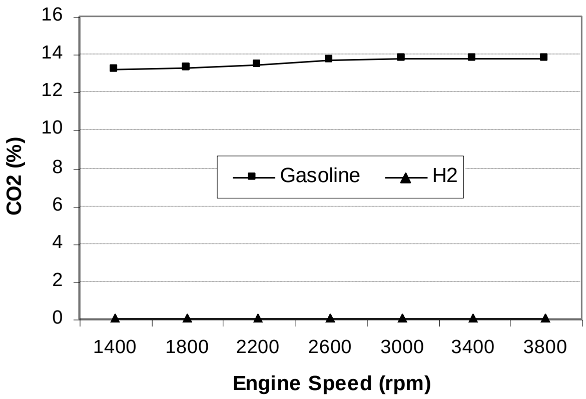


Figure 8. The effect of gasoline and hydrogen fuels on CO_2 emissions.

Fig. 9 shows the variations of HC emissions for the both fuels. HC emissions are also close to zero at hydrogen operation. This little amount of HC emission comes from the unburned portion of the evaporated lubrication oil which passed into the combustion side of the piston rings (Li and Karim, 2005).

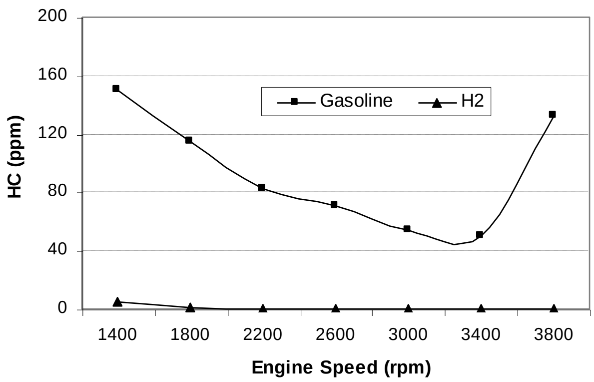


Figure 9. The effect of gasoline and hydrogen fuels on HC emissions.

CONCLUSIONS

This study mainly focused on the investigation of usability of hydrogen as fuel in a small engine with carburetor without major modifications. A small engine with carburetor was adopted for hydrogen fuel. The engine was tested to determine the effect of the hydrogen usage on fuel consumption and emissions. The following conclusions are drawn from the present work:

1. The engine was tested with hydrogen fuel by removing carburetor at 2200 rpm, various excess air ratios. According to results of these tests, it was found that the most suitable air excess ratio was 1.5 in terms of stable engine operation (without backfire and knock).
2. Backfire problem which has frequently been a challenge for hydrogen operation of SI engine with carburetor was eliminated by employing a suitable lean mixture and by feeding the gaseous hydrogen just behind the intake valve. No backfire was encountered at full load for all the engine speeds.
3. One of the main problems with hydrogen fuelled internal combustion engines is the high NO level due to rapid combustion. Thanks to leaning the mixture at the hydrogen operation, NO_x emission was reduced by about 66%.
4. The specific fuel consumption was reduced by about 57% when running with hydrogen since lower heating value of hydrogen is very high relative to that of gasoline.
5. The engine power decreased by about 24% when running with hydrogen fuel relative to that with gasoline fuel. If ever the ignition timing can change depending on engine speed, the more power can be obtained for both fuels.
6. Traces of HC emissions were seen at hydrogen operation due to vaporization of the lubricating oil.
7. As the lubrication oil passed into the combustion chamber, some very little CO and CO_2 emissions were observed when running with hydrogen fuel.
8. The test results showed that the significant improvements in fuel consumption and CO, CO_2, HC and NO_x emissions can be obtained when hydrogen as fuel is used in the small engines with carburetor. This does not necessitate major modifications such as fuel injection system, electronic ignition system and exhaust control system which increase cost of engine.

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