Environmental Engineering and Management Journal March 2015, Vol.14, No. 3, 665-672
http://omicron.ch.tuiasi.ro/EEMJ/

"Gheorghe Asachi" Technical University of Iasi, Romania

EFFECT OF HYDROGEN ADDITION ON EXHAUST EMISSIONS AND PERFORMANCE OF A SPARK IGNITION ENGINE

Yasin Karagöz*, Emre Orak, Levent Yüksek, Tarkan Sandalcı

Yıldız Technical University, Mechanical Engineering Faculty, Laboratory of Internal Combustion Engines, Automotive Division, 34349 Istanbul, Turkey

Abstract

The use of hydrogen in spark ignition engines as a supplementary fuel can enhance combustion and reduce toxic emissions. Difficulties in hydrogen storage and production limit its use in internal combustion engines. This paper investigates the performance of a spark ignition engine with the addition of a mixture of hydrogen (H_2) and oxygen (O_2) into the intake manifold. Hydrogen is produced by an alkaline electrolyser and consumed simultaneously to eliminate the need for a storage device. Flow rates of 0 and 10 L/min H_2-O_2 mixture were introduced into the manifold. No flow, or 0 L/min, refers to the case without hydrogen, and 10 L/min represents the case with hydrogen. Brake torque, fuel consumption, nitrogen oxides, carbon monoxide, and total unburned hydrocarbons were measured. The results show that brake power, brake torque, and nitrogen oxide emissions increased with the addition of H_2-O_2, while total unburned hydrocarbons, carbon monoxide emissions, and brake-specific energy consumption decreased.

Key words: electrolysis, hydrogen fuel, spark ignition engine

Received: August, 2013; Revised final: June, 2014; Accepted: July, 2014

1. Introduction

Increasing energy demand and environmental concern have stimulated researchers' interest in non-polluting alternatives to petroleum-derived fuels. Today, a significant part of the energy demand is met by fossil fuels. In spite of the measures taken by the *Kyoto Protocol to the United Nations Framework Convention on Climate Change* during the period of 1990-2004, CO_2 emissions increased by 27% and the energy consumption of the transportation sector increased by 37%, which was not forecast (Sopena et al., 2010). Petroleum-based fuels can be replaced in part by an alternative energy source such as hydrogen (Al-Baghdadi, 2004; Lako et al., 2008; Sastri, 1987). Automotive manufacturers have developed different technologies, such as fuel cell, hydrogen fuelled internal combustion engine (ICE), hybrid, and electric vehicle configurations (Offer et al., 2010; Pasculete et al., 2007). Some manufacturers have been making progress on polymer electrolyte membrane fuel cells (PEMFC), but investment costs are high and a PEMFC requires high purity hydrogen. Thus, investment and operation costs of fuel cell systems are even more expensive than other hydrogen fuelled engines (Sopena et al., 2010). One way to increase performance of a spark ignition (SI) engine is to use supplementary fuels, which improve thermal efficiency and reduce emissions (Bari and Esmaeil, 2010).

Hydrogen has unique combustion properties, and using hydrogen as a supplementary fuel in internal combustion engines improves thermal efficiency and tail-pipe emissions. The diffusion coefficient of hydrogen is higher than gasoline, which improves the homogeneity of the combustible mixture (Ji and Wang, 2009a). The flame speed of hydrogen is five times higher than that of gasoline, which improves thermal efficiency because the combustion of hydrogen is much closer to ideal

* Author to whom all correspondence should be addressed: e-mail: ykaragoz@yildiz.edu.tr; Phone: +902123832901; Fax: +90 212 2616659

constant volume combustion in ICEs (Ji and Wang, 2009b; Ma et al., 2008).

Alternative fuels can be used as bulk or supplements; the most common instance for this type of application is biodiesel (Dai et al., 2014; Lapuerta et al., 2008; Nita and Mandopol, 2009; Opera et al., 2009). Using supplementary fuels is a promising method to reduce the cost of fossil fuels. Hydrogen is the most promising additive that can significantly reduce fuel consumption and harmful emissions in ICEs (Bari and Esmaeil, 2010; Pasculete et al., 2007). Bari and Esmaeil (2010) used an H_2-O_2 mixture as an additional fuel in a diesel engine at 1500 rpm under different loads. The authors reported that the brake thermal efficiency and nitrogen oxide (NO_x) emissions increased, while total hydrocarbons (THC), carbon dioxide (CO_2), and carbon monoxide (CO) emissions decreased with H_2-O_2 addition. Ji and Wang (2009a) investigated hydrogen as a supplementary fuel in 3% and 6% volume fractions of total fuel intake at a constant engine speed of 1400 rpm. An increase in brake thermal efficiency of the engine was reported with hydrogen addition. Furthermore, the authors indicated that THC and CO emissions were reduced with hydrogen addition. Kumar et al. (2003) investigated hydrogen addition in an SI engine. The authors reported an increase in brake thermal efficiency and a reduction in tail-pipe emissions. Tomita et al. (2001) published similar results. In the study of Saravanan et al. (2008) hydrogen was introduced into cylinders as a supplementary fuel at rates of 10 L/min and 20 L/min, and performance parameters with and without exhaust gas recirculation (EGR) were investigated (Saravanan et al., 2008). The authors obtained an increase in brake thermal efficiency. Stebar and Parks (1974) carried out a study on a single-cylinder SI engine fuelled with a hydrogen-gasoline mixture. According to the authors, the lean burn limit of the engine was extended by hydrogen enrichment, and NO_x emissions decreased. However, THC emissions increased with the increase in excess air in the air-fuel mixture. Apostolescu and Chiriac (1996) studied the effect of hydrogen addition to a single cylinder SI engine. Shortened combustion durations, reduced cycle-to-cycle variations, and extended lean limits of operation were reported by the authors. Ma and Wang (2008) investigated the performance of hydrogen-enriched methane. According to their results, thermal efficiency was improved with hydrogen addition and toxic emissions were decreased. Additionally, cyclic variations were improved and the lean burn limit of the natural gas engine was extended with hydrogen addition. Ji and Wang (2009b) investigated the effect of hydrogen addition on SI engine performance at idle and stoichiometric conditions. The authors found that the engine thermal efficiency and emissions were improved after hydrogen enrichment. Ceviz et al. (2012) investigated hydrogen addition of 0%, 2.14%, 5.28%, and 7.74% by volume to a spark ignition engine at 2000 rpm constant engine speed.

According to their results, brake-specific fuel consumption, THC, and CO emissions decreased, whereas NO_x emissions increased with hydrogen addition. Wang et al. (2012) experimentally investigated the effect of hydrogen-oxygen blends as supplementary fuel on engine performance and emissions of a gasoline engine. The blends were called hydroxygen in this study (Wang et al., 2012). A hybrid electronic control unit (ECU) was developed to control spark timing and the overall volume fraction of hydroxygen. The hydroxygen was varied from 0% to 100% by varying the injection duration of the injectors. According to their results, flame development and propagation duration periods were shortened and emissions were reduced. Ji et al. (2012) carried out a study of a hybrid hydrogen-gasoline engine with a hydrogen injection system and a hybrid ECU that they developed. The engine was operated with hydrogen at cold start and was operated with hydrogen-gasoline blends at idle and part loads. According to their results, thermal efficiency was improved and emissions were reduced with hydrogen addition. Ji et al. (2013) studied the emissions of a passenger car powered by a hydrogen-gasoline engine under the New European Driving Cycle. The hydrogen was produced by a water electrolyser, and they found that CO and THC emissions were reduced by 62.1% and 64.1%, respectively. Several studies offer similar results for hydrogen enrichment (D'Andrea et al., 2004; Li et al., 1998; Varde, 1981; Wang et al., 2011).

Most of the studies that investigated hydrogen implementation indicated a fuel storage problem. Hydrogen has a very low density. It can be stored in pressurized tanks or it can be combined chemically with a metal alloy (Bari and Esmaeil, 2010). However, a tank is required to store hydrogen on-board a vehicle, which increases overall system weight (Fontana et al., 2002). Alternatively, when hydrogen is stored as a liquid, on-board cryogenic container costs are high and a significant amount of energy is needed to convert gaseous hydrogen into liquid phase (White et al., 2006). To solve the storage difficulties, the hydrogen can be produced on-board through the electrolysis of water. On-board production eliminates the need for a high pressure tank and provides for safer operation. A simultaneous producing-consuming operation makes the application safer.

In this study, the effect of hydrogen addition on SI engine performance and emissions was investigated. Hydrogen fuel was produced by electrolysis of water in an alkaline solution. The flow rate of supplementary fuel was set to a constant 10 L/min.

2. Experimental setup

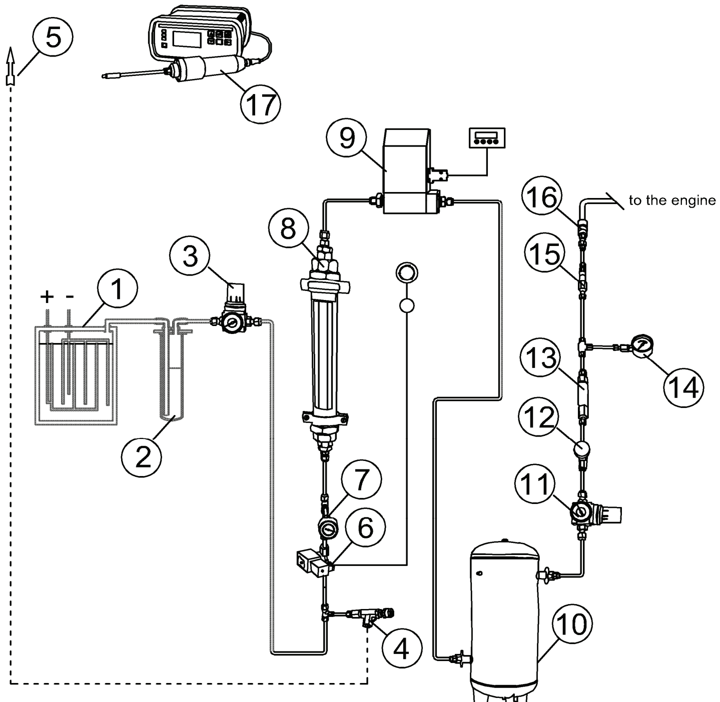
2.1. Test engine and modifications

Tests were carried out on a multi-cylinder spark ignition engine with an electronically controlled port fuel injection system. The main engine specifications are listed in Table 1. The test bench was modified for hydrogen injection. The H_2-O_2 mixture and gasoline were separately introduced into the intake manifold for each cylinder.

A schematic diagram of the hydrogen line is shown in Fig. 1. The H_2-O_2 mixture was delivered into the engine with an additional fuel supplement system. A pressure regulator was used to reduce the pressure of the H_2-O_2 gas mixture produced by the electrolyser. The H_2-O_2 gas mixture passed through a bubbler before being fed to the engine to prevent backfires. A relief valve was used to prevent overpressure, and a second pressure regulator was installed to regulate line pressure. A thermal mass-flow meter was used to measure flow rate. A rotameter was also used to check the hydrogen fuel flow rate against the thermal mass-flow meter. A buffer tank was installed between the flow meters and engine to reduce H_2-O_2 mixture flow fluctuations. A check valve and a flame arrestor were used before the engine intake manifold to prevent backfiring. The gas pressure regulator and hydrogen line were made of 316 stainless steel to fulfil ECE R110, EIHP Draft, and ECE R67 standards (ECE R67, 2013; ECE R110, 2013; EIHP regulations, 2000).

Table 1. Specifications of the engine

Definition	***Value/Specification***
Manufacturer & Type	Peugeot-1B53318F
Displacement volume (cm^3)	1124
Number of cylinders	4
Bore/stroke (mm)	72/69
Compression ratio	10.2:1
Number of valves per cylinder	4
Rated power	44 kW@5500 rpm
Aspiration	Naturally aspirated
Ignition system	Electronic
Fuel system	Multi-point fuel injection
Cylinder arrangement	In-line



1. Electrolyser
2. Bubbler
3. Pressure regulator
4. Relief valve
5. Discharge line
6. Shut-off valve
7. Needle valve
8. Hydrogen rotameter
9. Hydrogen mass-flow meter
10. Buffer tank
11. Pressure regulator
12. Ball valve
13. Check valve
14. Pressure gauge
15. Flame arrester
16. Quick connect
17. Hydrogen leak detector

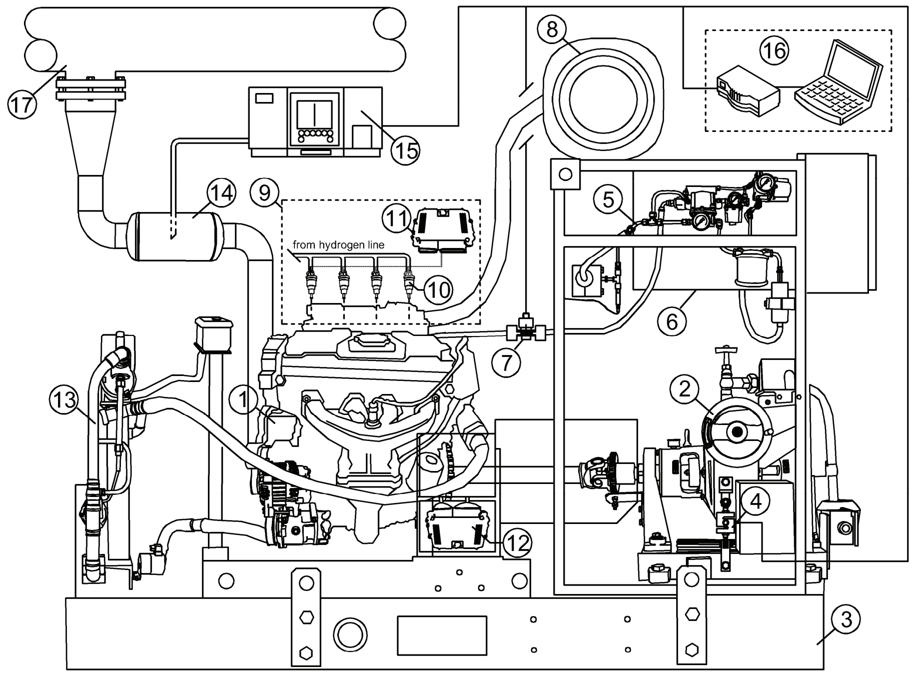
Fig. 1. Schematic diagram of hydrogen fuel system

No modification was made to the original ECU of the test engine. A self-developed ECU was used to trigger the hydrogen injectors. The flow rates of injectors were determined according to the signal length with a series of preliminary tests. A power supply with constant current capability was used to control the current and the voltage of the electrolyser. The safety system of the test cell was upgraded to prevent possible hazards. An air venting system was used to prevent hydrogen accumulation, and a hydrogen leak detector was installed to detect hydrogen leaks.

2.2. Test bench

The test bench scheme is shown in Fig. 2. A hydrokinetic dynamometer was used to load the test engine, where the load was varied by controlling the servo motor position. A turbine-type flow meter was used to measure the gasoline flow rate. The exhaust emissions were measured with an AVL Dicom 4000 exhaust gas analyser.

During experiments, the brake torque, brake power, brake-specific energy consumption (BSEC), NO_x, THC, and CO measurements were acquired with a data acquisition system (DAS) at a sampling rate of 1 Hz. The accuracies of the measurements and the uncertainties in the calculated results are listed in Table 2. All of the tests were performed at steady-state and part-load conditions with constant throttle position. Additionally, tests were conducted with a stoichiometric air-fuel ratio (AFR) value, which is typical for a catalyst-equipped SI engine.



1. Test engine
2. Hydrokinetic dynamometer
3. Chasis
4. Load cell
5. Fuel line
6. Fuel tank
7. Fuel flow meter
8. Air tank
9. Hydrogen line
10. Hydrogen injectors
11. Self-developed ECU
12. OEM ECU
13. Cooling system
14. Exhaust gas tank
15. Gas emission analyzer
16. DAS
17. Exhaust line

Fig. 2. Schematic diagram of test bench

Table 2. Accuracies of the measurements and uncertainties of calculated results

Measured parameter	***Measurement device***	***Accuracy***
Engine torque	Load cell	±0.05 Nm
Engine speed	Incremental encoder	±5 rpm
Fuel flow rate	Sika VZ 0.2	±1%
Hydrogen mass-flow rate	New-flow TLF	±1%
CO	AVL Dicom 4000	±0.01 vol.%
THC	AVL Dicom 4000	±1 ppm
NO_x	AVL Dicom 4000	±1 ppm
Calculated results		**Uncertainty (entire speed range)**
Brake power		±0.09÷0.12%
BSEC		±0.43÷0.56%

The flow rates of 0 L/min and 10 L/min H_2-O_2 mixture were introduced into the intake manifold as additional fuel at 1500, 2000, 2500, 3000, and 3500 rpm engine speeds. The H_2-O_2 flow rate was set at 10 L/min constantly to demonstrate that using a small amount of hydrogen can enhance gasoline combustion.

Using higher levels of hydrogen requires high levels of electrical energy, making it very difficult to implement this system on the electrical architecture of current vehicles. During the study, the introduced hydrogen to oxygen molar ratio was 2:1. The energy content of additional H_2-O_2 at 1500, 2000, 2500, 3000, and 3500 rpm was equal to 3.3%, 2.7%, 2.2%, 1.9% and 1.7% of the total energy of the charge, respectively.

3. Results and discussion

Brake power and brake torque variation are shown in Fig. 3. According to the results, engine performance improved with hydrogen addition for the entire engine speed range measured. The maximum brake power of the engine increased by 1% at 3500 rpm engine speed with 10 L/min H_2-O_2 enrichment.

BSEC is defined as the amount of energy consumed per kilowatt of power produced by the engine. For comparing the fuel economy of test fuels, BSEC is better than brake-specific fuel consumption because the heating value and density of the fuels exhibit different trends. The variation of BSEC is shown in Fig. 4. The figure reveals that adding a small amount of H_2-O_2 decreases BSEC regardless of the engine speed. The higher flame speed of the mixture has a positive effect on improving BSEC because the flame speed of hydrogen is five times as large as that of gasoline (Ji and Wang, 2009b; Ji and Wang, 2010a). Additionally, hydrogen has a wider flammability range than gasoline (Ji and Wang, 2009a). Consequently, the shorter burning duration and wider flammability range of the hydrogen gasoline mixture lead to higher combustion efficiency (Ma et al., 2008). For this reason, it can be concluded that a higher degree of constant volume combustion is completed, which means that an SI engine operates much closer to its theoretical cycle (Ji and Wang, 2009b). According to the test results, BSEC reduction reached its maximum value of 8.64% at 1500 rpm, while the minimum of 1.17% was obtained at 2500 rpm.

The results clearly indicate that the thermodynamic improvement of the test engine minimizes BSEC in the high efficiency region and vice-versa. Improvement in BSEC mainly originated in lower amount of gasoline injection which was a result of engine control unit algorithm. Neither an interruption nor a signal modification was implemented on the ECU. However, as shown in Fig. 5, the gasoline injection quantity decreased significantly. The main reason for this situation is the decrease in the inducted air due to the gas phase injection of the H_2-O_2 mixture. Hydrogen possesses many unique combustion properties that improve the more complete combustion in ICEs (Ji and Wang, 2009a). THC, CO, and NO_x are the main toxic pollutants that are emitted from ICEs, and these toxic pollutants can be reduced by inducting hydrogen into gasoline (Ji and Wang, 2009b). The variation of THC is depicted in Fig. 6.

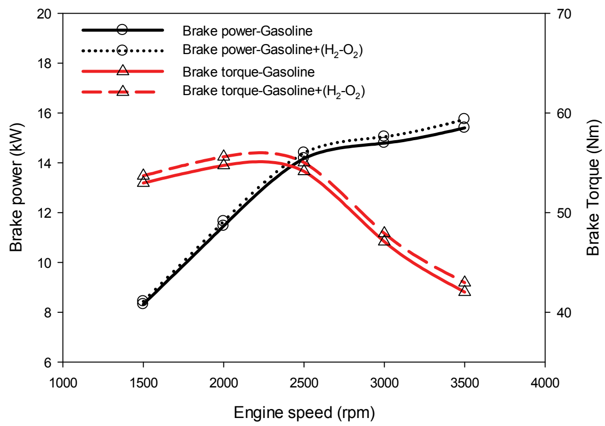


Fig. 3. Variations in brake power and brake torque at part-load operation versus engine speed

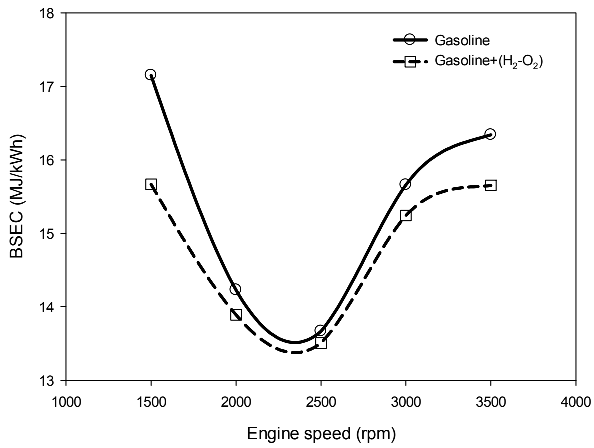


Fig. 4. Variation of BSEC versus engine speed

According to the Fig. 6, THC emissions were decreased regardless of the engine speed by inducting H_2-O_2 mixture. Similar results are explained in the literature as the formation of OH radicals accelerated by hydrogen addition (Ji and Wang, 2009b). Due to the accelerated formation of OH and the improved chain reaction, a gasoline-hydrogen mixture can be more completely burnt and will emit less THC (Ji and Wang, 2009a). Additionally, the decrease in THC emissions can be related to H_2-O_2 induction because of the absence of carbon in hydrogen fuel (Bari and Esmaeil, 2010).

Lastly, the shorter quenching distance of hydrogen causes a reduction in THC emissions (Ji and Wang, 2010b). The quenching distance of hydrogen is one-third that of gasoline (Ji and Wang, 2010b). Therefore, the flame of a gasoline hydrogen mixture can be propagated much closer to cylinder walls and crevices than can gasoline fuel (Ji and Wang, 2009a). A maximum reduction in THC of 13.3% was obtained at 2000 rpm.

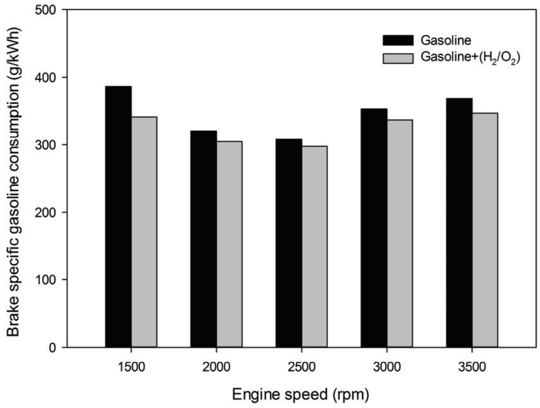


Fig. 5. Brake-specific gasoline consumption of the test engine

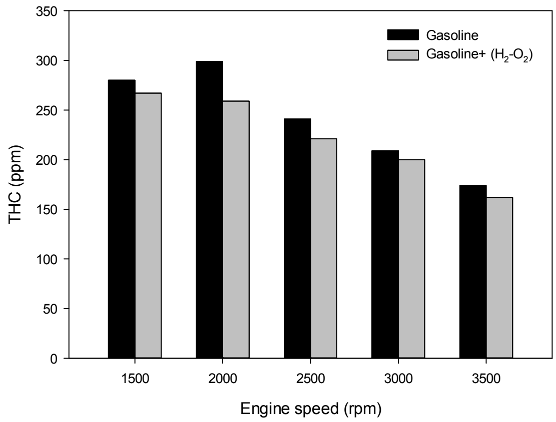


Fig. 6. Variation of THC emissions versus engine speed

The variation of NO_x emissions at part-load conditions with 10 L/min H_2-O_2 addition is shown in Fig. 7. According to test results, NO_x emissions were increased with hydrogen addition regardless of the engine speed. A maximum increase of 17.6% was obtained at 3000 rpm, while the minimum gain measured was 3.7% at 2000 rpm. When the increase of NO_x emissions and improvement of engine performance are considered together, it is concluded that peak cylinder pressure and bulk cylinder temperature were increased with hydrogen addition (Bari and Esmaeil, 2010).

Both high temperature and more available oxygen in the charge may cause NO_x emissions to rise (Heywood, 1988). It is expected that the maximum NO_x emission will occur at maximum torque range in ICEs, but higher NO_x measurements in test results can be attributed to additional oxygen introduced into the cylinder. Almost equal NO_x at low engine speeds indicates the improvement of combustion. Due to a constant flow rate of the H_2-O_2 mixture, the inducted oxygen amount per cycle decreased at higher engine speeds. Significant reduction of NO_x emissions at higher engine speeds indicates the importance of the oxygen ratio. Additionally, the higher flame temperature and speed of hydrogen combustion cause higher local in-cylinder temperatures and a larger amount of NOx emissions (Ji et al., 2012).

As shown in Fig. 8, CO emissions were lower than those from pure gasoline. The minimum CO reduction was observed at 2500 rpm, while the positive effect of H_2-O_2 addition on CO emission reached up to 10.7% at 3000 rpm. Considering the increase in CO emissions of gasoline fuel at higher engine speeds, one can easily conclude the reduction of combustion efficiency. Additionally, Fig. 7 clearly indicates the importance of H_2-O_2 mixture addition in the high rpm region. With respect to tail-pipe emissions, H_2-O_2 mixture addition improved combustion efficiency while NO_x emissions increased.

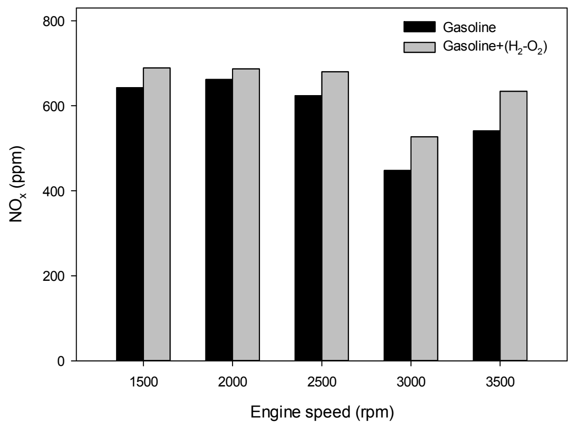


Fig. 7. Variation of NO_x versus engine speed

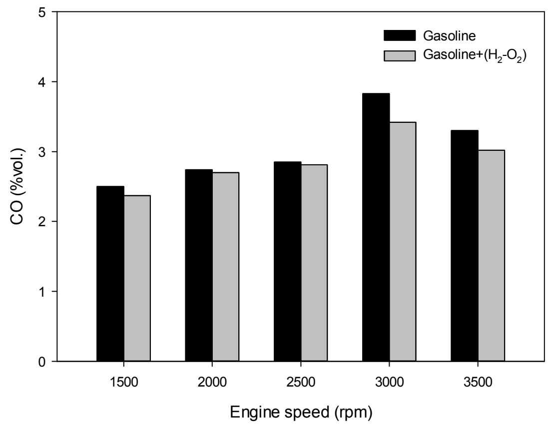


Fig. 8. Variation of CO versus engine speed

4. Conclusions

An experimental study was conducted to investigate the effects of hydrogen addition on emissions and performance of a gasoline engine. During the experiments, an SI engine was operated at part-load, and the throttle was kept at a constant position; 0 L/min and 10 L/min of an H_2-O_2 mixture as supplementary fuel was introduced into the intake manifold, where 0 L/min is referring to the case without hydrogen and 10 L/min refers to the case with hydrogen.

The required amount of H_2-O_2 mixture was produced by an alkaline water electrolyser and simultaneously consumed by the engine. The high diffusion coefficient of hydrogen improves the homogeneity of the combustible mixture. The flame speed of hydrogen is higher than gasoline, so using a small amount of H_2-O_2 mixture as additional fuel improves combustion efficiency. Additionally, engine performance and emissions were evaluated. It was proved that by using a small amount of hydrogen, stringent emission regulations will be met, and the hydrogen will have a positive effect on the environment. The effect is positive because emissions of greenhouse gases from combustion of fossil fuels cause global warming and are responsible for adverse environmental effects such as photochemical smog, acid rain, and the death of forests.

The emissions of THC and CO are reduced by hydrogen addition, but NO_x emissions are increased due to higher in-cylinder temperatures.

Further studies are required to reveal the effect of different amounts of the H_2-O_2 mixture on engine parameters. In particular, higher engine-out NOx emissions will have to be considered, so a possible optimisation and/or trade-off solution may be required. Lowering nitrogen oxides without a penalty from the findings mentioned above can be maintained by varying the engine control parameters such as the ignition timing and EGR ratio. Finally, hydrogen has the potential to reduce tail-pipe emissions, and the instantaneous production and consumption method is a safe means of integration into gasoline engine-powered vehicles.

Nomenclature

BSEC	Brake-specific energy consumption, MJ/kWh
CO	Carbon monoxide
CO2	Carbon dioxide
DAS	Data acquisition system
ECE	Economic Commission for Europe
ECU	Electronic control unit
EIHP	European Integrated Hydrogen Project
EGR	Exhaust gas recirculation
H2	Hydrogen
ICE	Internal combustion engine
NOx	Nitrogen oxide
OH	Hydroxyl radical
O2	Oxygen
PEMFC	Polymer electrolyte membrane fuel cell
rpm	Revolutions per minute (engine speed)
SI	Spark ignition
THC	Total hydrocarbons

References

Al-Baghdadi M.A.R.S., (2004), Effect of compression ratio, equivalence ratio and engine speed on the performance and emission characteristics of a spark ignition engine using hydrogen as a fuel, *Renewable Energy*, **29**, 2245-2260.

Apostolescu N., Chiriac R., (1996), A study of combustion of hydrogen-enriched gasoline in a spark ignition engine, SAE International, 960603, On line at: http://papers.sae.org/960603/.

Bari S., Esmaeil M.M., (2010), Effect of H_2/O_2 addition in increasing the thermal efficiency of adiesel engine, *Fuel*, **89**, 378-283.

Ceviz M.A., Sen A.K., Küleri A.K., Öner İ.V., (2012), Engine performance, exhaust emissions, and cyclic variations in a lean-burn SI engine fueled by gasolineehydrogen blends, *Applied Thermal Engineering*, **36**, 314-324.

Dai H., Peng J., Qiu T., Li X., Lei Y., (2014), Investigation on impact of biodiesel on injection process of unit pump fuel system, *Environmental Engineering and Management Journal*, **13**, 1843 - 3707.

D'Andrea T., Henshaw P., Ting D.S.K., (2004), The addition of hydrogen to a gasoline-fuelled SI engine. *International Journal of Hydrogen Energy*, **29**, 1541-1542.

ECE R110, (2013), Proposal for Supplement 1 to the 01 series of amendments to Regulation No. 110 (CNG vehicles), Economic Commission for Europe-Inland Transport Committee (World Forum for Harmonization of Vehicle Regulations), Geneva, On line at: http://www.unece.org/fileadmin/DAM/trans/doc/2013/wp29/ECE-TRANS-WP29-2013-101e.pdf.

ECE R67, (2013), Proposal for Supplement 1 to the 01 series of amendments to Regulation No. 110 (CNG vehicles), Economic Commission for Europe-Inland Transport Committee (World Forum for Harmonization of Vehicle Regulations), Geneva, On line at: http://www.unece.org/fileadmin/DAM/trans/doc/2013/wp29/ECE-TRANS-WP29-2013-097e.pdf.

EIHP regulations, (2000), European Integrated Hydrogen Project, Geneva, On line at: http://www.eihp.org/.

Fontana G., Galloni E., Jannelli E., Minutillo M., (2002), *Performance and Fuel Consumption Estimation of a Hydrogen Enriched Gasoline Engine at Part-Load Operation*, SAE International 2002-01-2196, On line at: http://papers.sae.org/2002-01-2196/.

Heywood J.B., (1988), *Internal Combustion Engine Fundamentals*, McGraw-Hill, New York.

Ji C.W., Wang S.F., (2009a), Effect of hydrogen addition on combustion and emissions performance of a spark ignition gasoline engine at lean conditions, *International Journal of Hydrogen Energy*, **34**, 7823-7834.

Ji C.W., Wang S.F., (2009b), Effect of hydrogen addition on the idle performance of a spark ignited gasoline engine at stoichiometric condition, *International Journal of Hydrogen Energy*, **34**, 3546-3556.

Ji C.W., Wang S.F., (2010a), Combustion and emissions performance of a hybrid hydrogen-gasoline engine at idle and lean conditions, *International Journal of Hydrogen Energy*, **35**, 346-55.

Ji C.W., Wang S.F., (2010b), Experimental study on combustion and emissions performance of a hybrid hydrogen-gasoline engine at lean burn limits, *International Journal of Hydrogen Energy*, **35**, 1453-1462.

Ji C., Wang S., Zhang B., (2012), Performance of a hybrid hydrogen–gasoline engine under various operating conditions, *Applied Energy*, **97**, 584-589.

Ji C., Wang S., Zhang B., Liu X., (2013), Emissions performance of a hybrid hydrogen–gasoline engine-powered passenger car under the New European Driving Cycle, *Fuel*, **106**, 873-875.

Kumar M.S., Ramesh A., Nagalingam B., (2003), Use of hydrogen to enhance the performance of a vegetable oil fuelled compression ignition engine, *International Journal of Hydrogen Energy*, **28**, 1143-1154.

Lakó J., Hancsók J., Yuzhakova T., Marton G., Utasi A., Rédey Á., (2008), Biomass – a source of chemicals and energy for sustainable development, *Environmental Engineering and Management Journal*, **7**, 499-509.

Lapuerta M., Armas O., Rodriguez-Fernandez J., (2008), Effect of biodiesel fuels on diesel engine emissions, *Progress in Energy and Combustion*, **34**, 198-223.

Li J.D., Guo L.S., Du T.S., (1998), Formation and restraint of toxic emissions in hydrogen-gasoline mixture fueled engines, *International Journal of Hydrogen Energy*, **23**, 971-975.

Ma F.H., Wang Y., (2008), Study on the extension of lean operation limit through hydrogen enrichment in a natural gas spark-ignition engine, *International Journal of Hydrogen Energy*, **33**, 1416-1424.

Ma F.H., Wang Y., Liu H.Q., Li Y., Wang J.J., Ding S.F., (2008), Effects of hydrogen addition on cycle-by-cycle variations in a lean burn natural gas spark-ignition engine, *International Journal of Hydrogen Energy*, **33**, 823-831.

Nita I., Mandalopol D., (2009), Study of the viscosity of some biodiesel – diesel oil blends, *Environmental Engineering and Management Journal*, **8**, 639-643.

Offer G.J., Howey D., Contestabile M., Clague R., Brandon N.P., (2010), Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system, *Energ Policy*, **38**, 24-29.

Oprea I., Pîşă I., Mihăescu L., Prisecaru T., Lăzăroiu G., Negreanu G., (2009), Research on the combustıon of crude vegetable oils for energetic purposes, *Environmental Engineering and Management Journal*, **8**, 475-482.

Păsculete E., Condrea F., Rădulescu C., (2007), Hydrogen and sustainable energy. Research for hydrogen productıon, *Environmental Engineering and Management Journal*, **6**, 45-49.

Saravanan N., Nagarajan G., Kalaiselvan K.M., Dhanasekaran C., (2008), An experimental investigation on hydrogen as a dual fuel for diesel engine system with exhaust gas recirculation technique, *Renewable Energy*, **33**, 422-427.

Sastri M.V.C., (1987), Hydrogen Energy Research-and-Development in India - an Overview, *International Journal of Hydrogen Energy*, **12**, 137-145.

Sopena C., Dieguez P.M., Sainz D., Urroz J.C., Guelbenzu E., Gandia L.M., (2010), Conversion of a commercial spark ignition engine to run on hydrogen: Performance comparison using hydrogen and gasoline, *International Journal of Hydrogen Energy*, **35**, 1420-1429.

Stebar R.F., Parks F.B., (1974), *Emission Control with Lean Operation Using Hydrogen-Supplemented Fuel*, SAE International, 740187.

Tomita E., Kawahara N., Piao Z., Fujita S., Hamamoto Y., (2001), *Hydrogen Combustion and Exhaust Emissions Ignited with Diesel Oil in a Dual Fuel Engine*, SAE International, 2001-01-3503, On line at: http://papers.sae.org/2001-01-3503/.

Varde K.S., (1981), *Combustion Characteristics of Small Spark Ignition Engines Using Hydrogen Supplemented Fuel Mixtures*, SAE International, 810921, On line at: http://papers.sae.org/810921/.

Wang S., Ji C., Zhang B., (2011), Starting a spark-ignited engine with the gasoline-hydrogen mixture, *International Journal of Hydrogen Energy*, **36**, 4461-4468.

Wang S., Ji C., Zhang B., Liu X., (2012), Performance of a hydroxygen-blended gasoline engine at different hydrogen volume fractions in the hydroxygen, *International Journal of Hydrogen Energy*, **37**, 3209-3218.

White C.M., Steeper R.R., Lutz A.E., (2006), The hydrogen-fuelled internal combustion engine: a technical review, *International Journal of Hydrogen Energy*, **31**, 1292-1305.