Arab J Sci Eng
DOI 10.1007/s13369-016-2228-x

RESEARCH ARTICLE - MECHANICAL ENGINEERING

Effect of Hydrogen–Oxygen Mixture Addition on Exhaust Emissions and Performance of a Spark Ignition Engine

Mohamed Brayek[1] · Mohamed Ali Jemni[1] · Gueorgui Kantchev[1] · Mohamed Salah Abid[1]

Received: 9 December 2015 / Accepted: 18 May 2016

Abstract In the last decade, there has been a major ascending interest in reducing the polluting concentration and fuel consumption of internal combustion engines. The solution proposed in this research project was to integrate a hydrogen and oxygen mixture H_2/O_2, obtained through an electrolysis process of water, as supplementary fuel, in a 93 cm^3 gasoline engine. Several experimental tests were carried out under different engine loads (0, 20, 50, 80 and 100 %) in order to investigate the effect of H_2/O_2 addition on the engine performance characteristics and the exhaust gas concentration. At engine loads more than 20 %, tests showed that adding H_2/O_2 reduced the brake-specific fuel consumption by an average of 7.8 %. They also showed that the alternative fuel was very efficient in reducing the concentration of pollutant emissions in the exhaust gases: hydrocarbon (HC) concentration diminished by an average of 18 %, carbon monoxide (CO) concentration decreased by an average of 31.8 %, and CO_2 concentration decreased up to 30 %. However, at low engine loads, NO_x concentration decreased by an average of 26 %, but it increased significantly with the increase in engine loads (exceeding 80 %).

Keywords BSFC · Engine load · Gasoline engine · Hydrogen · Oxygen · Pollutant concentrations

✉ Mohamed Brayek
medbrayek@gmail.com

1 Laboratory of the Electromechanical System (LASEM), National School of Engineers of Sfax (ENIS), BP 1173, Avenue of Soukra, 3038 Sfax, Tunisia

1 Introduction

The world energy market is attempting to explore alternative fuels for internal combustion (IC) engines. Research and development of non-polluting and clean alternative fuels is important for energy safety and environmental protection [1]. The use of hydrogen in IC engines was proposed in the 1970s [2]. Hydrogen can be considered as the most potential alternative to conventional fuels because it has benign effects on environment and it can be produced from renewable sources. The combustion of hydrogen engines is much closer to ideal constant volume combustion; therefore, it may improve thermal efficiency [3–6]. These advantages have attracted researchers to check the feasibility of hydrogen as a fuel for spark ignition (SI) engine applications. Hence, numerous hydrogen engines have been developed and much research focusing on the study of the effect of using hydrogen as fuel in internal combustion engines has been conducted. Results show the successful running of these engines using hydrogen under various operating conditions [3–8]. However, pure hydrogen-fuelled IC engines suffer from weak power output because of the lower volumetrically heating value of hydrogen [4,9,10]. Besides, hydrogen engine produces high level of nitrogen oxides because of the high flame temperature [9]. These drawbacks limit the commercialisation of pure hydrogen as a fuel for SI engines.

Instead of using pure hydrogen, the use of a mixture of hydrogen and other fuels is considered to be a more practical way for improving the SI engine performance [11–13]. Therefore, the mixture of hydrocarbon and hydrogen, for instance, would take the positive physicochemical properties of both fuels. As a result of this mixture, the combustion duration is reduced. The more the hydrogen blending fraction is higher, the closer the combustion is to ideal thermodynamic

Published online: 03 June 2016

cycle. Besides, this blending enhances the thermal efficiency [8,13,14]. Moreover, the addition of hydrogen to gasoline–air mixtures reduces carbon monoxide (CO) and hydrocarbon (HC) concentrations [5,15–17], and carbon dioxide CO_2 concentration [18–21]. Furthermore, despite the fact that the use of hydrogen generally increases oxides of nitrogen (NO_x) concentration because of increased cylinder gas temperature [16–20], under specific operating conditions, the use of hydrogen with gaseous fuel can reduce NO_x concentration. The addition of hydrogen to ethanol produced less NO_x in base case operation conditions [21,22]. At ultra-lean burn conditions, the addition of hydrogen led also to reduction in the NO_x concentration [23].

However, some studies show that the use of hydrogen in SI engines sometimes leads to knocking and backfiring problems [8,9,24].

Although hydrogen energy is considered as an ideal alternative for internal combustion engines, there are some problems limiting the commercialisation of hydrogen, such as the high costs of production, the lack of fuelling infrastructure and the refilling onboard storage problem [25]. To reduce these problems, it is proposed that hydrogen can be produced through the electrolysis of water.

Water electrolysis is the decomposition of water (H_2O) into oxygen (O_2) and hydrogen gas (H_2) using an electric current. Research on electrolysers is currently going on all around the world. Open literature [26–31] has discussed the electrolyser in detail and in all aspects. Niro and Masanori [31], for instance, studied the efficiency of alkaline water electrolysis to obtain optimum conditions.

Getting hydrogen through water electrolysis solves some of the above-mentioned problems. First, the cost of hydrogen is low. Second, the immediate use of hydrogen directly from the electrolyser eliminates all the hydrogen storage problems.

Most studies concerned with the optimisation of the electrolyser operating systems have not considered the output of these systems as a supplementary fuel. On the contrary, those who focused on the use of hydrogen as a supplementary fuel have been using bottled hydrogen. Very few have considered its use as a by-product of electrolyser systems [32,33].

This study focuses on the addition of hydrogen oxygen mixture, obtained by water electrolysis, to gasoline in SI engine. Multiple experimental tests were carried out under different engine loads (0, 20, 50, 80 and 100 %) so as to investigate the effect of H_2/O_2 addition on the brake-specific fuel consumption, the exhaust gas temperature and the pollutant concentrations in the exhaust gas (HC, CO, CO_2 and NO_x). H_2/O_2 was produced by water electrolyser and sent simultaneously to the operating SI engine.

2 Experimental Set-up and Procedure

2.1 Fuel Cell

A water electrolyser was designed and manufactured in order to generate hydrogen and oxygen. Yull Brown's patent (1977), a technique to decompose water (H_2O) into oxygen (O_2) and hydrogen gas (H_2) based on electrolysis process, was adopted.

The main units of an electrolyser are an anode, a cathode and an electrolyte that transmits the ions between an anode and a cathode (electrodes). The positive current charges the anodes which yield the electrolysis reaction of the electrolytic solution and eventually release oxygen and hydrogen. The electrical power that fed the electrodes was measured. The electrolyser used in this research is basically an electrolyte cell which decomposes distilled water (H_2O) into oxygen (O_2) and hydrogen (H_2).

The fundamental reactions at the electrodes of an electrolyser are:

$$\text{Cathode reaction: } 2H_2O\,(l) + 4e \rightarrow 2H_2\,(g) + 4OH^- \quad (1)$$

$$\text{Anode reaction: } 4OH^- \rightarrow O_2\,(g) + 2H_2O\,(l) + 4e^- \quad (2)$$

$$\text{Overall reaction: } 2H_2O\,(l) \rightarrow 2H_2\,(g) + O_2\,(g) \quad (3)$$

The cell electrodes were arranged inside a Plexiglas bottle supplied by the required fittings and piping. Heat was generated due to this electrolysis process. So, a potassium hydroxide was added to accelerate the decomposition of H_2O into H_2 and O_2. This cell had a volume capacity of 2.5 l. The output gas can easily be added into the combustion chambers. Figure 1 shows a photograph of the electrolyser used in this study.

2.2 Performed Engine Specifications and Modifications

The electrolyser system was connected to the engine without any modifications. H_2/O_2 gas was generated in a reactor container (Plexiglas). The general view of the experimental set-up is shown in Fig. 2. The engine-generator (SHX2000) used in this work and shown in Fig. 3 provides moderately 1.5 kW on single-phase generation. It includes a four-stroke single-cylinder air-cooled spark ignited engine (Honda GX100) of 98 cm^3. The motor specifications are shown in Table 1.

Two safety devices were designed and fabricated to prevent flames from reaching back to the electrolyser. The first safety device is the flame arrestor. It helps in quenching the flames propagating backwards by absorbing its energy. The second safety device is the flame trap (water trap). It quenches flames travelling backwards with great certainty.

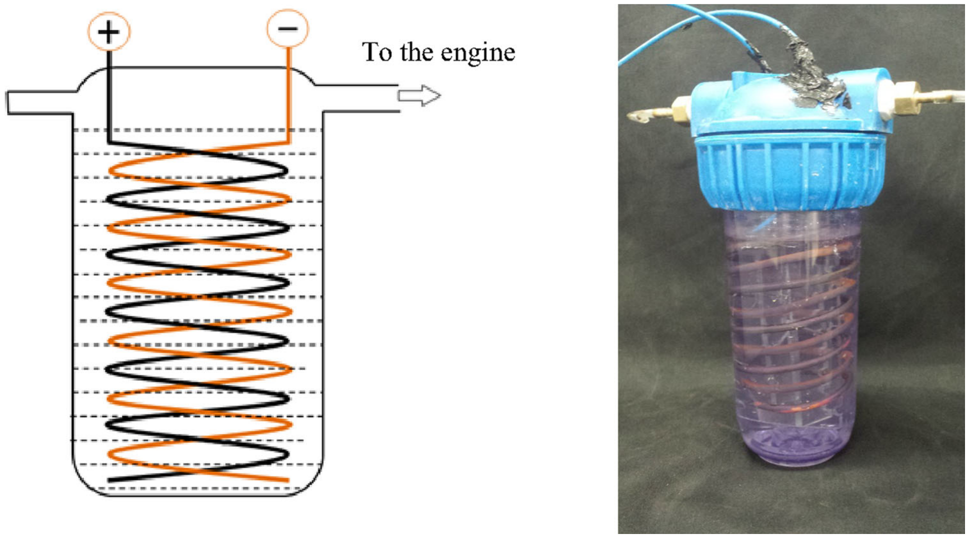

Fig. 1 Schematic diagram and photograph of H_2/O_2 fuel cell

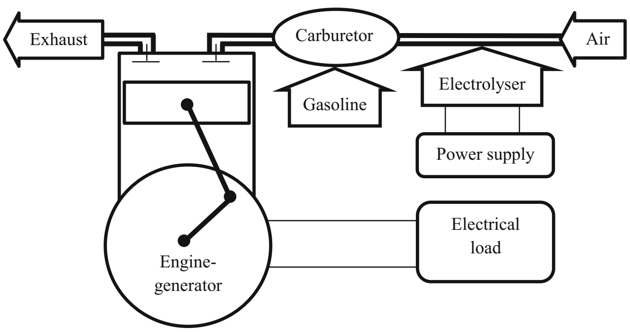

Fig. 2 Schematic experimental set-up

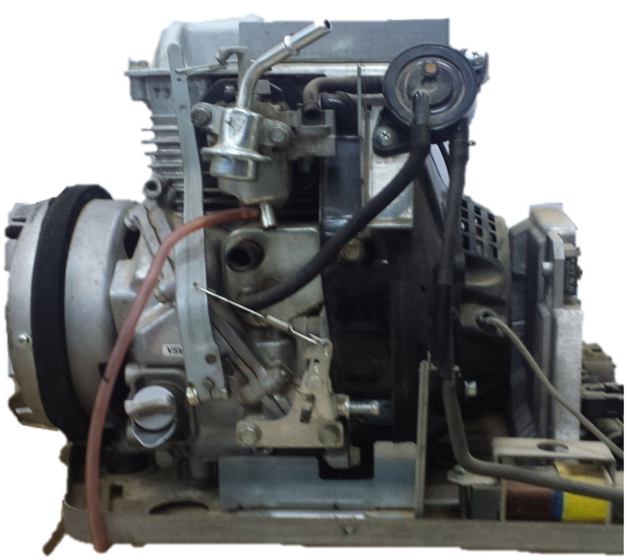

Fig. 3 The original engine-generator

Performance tests were carried out on the engine under variable load (0–100 %). Auxiliary equipment was used for data measurement: a voltmeter for cell voltage; an Extech 39272 Pocket Thermometer for ambient temperature; an InfraRed Thermometer EST-20 for exhaust gas temperature; a multimeter for output voltage and current measure; a graduated tube connected with carburettor for fuel consumption; a gas analyser KOEN KEG 500 for the measurement of NO_x, HC, CO and CO_2 concentration in the exhaust stream. A power supply was also used to provide the electrolyser with the necessary power (8 A and 12DC V).

Table 1 Engine specifications

Bore and stroke	56 × 40 mm
Displacement	98 cm^3
Compression ratio	8.5:1
Maximum torque	5.7 Nm at 3600 rpm
Dimension (L W H)	287 × 304 × 402 (mm)
Ignition system	Transistorised

2.3 Description of the Experimental Process and Measurements Techniques

The engine was motored initially without H_2/O_2 being inducted. All the tests were conducted at a steady-state condition. The exhaust temperature, the brake-specific fuel consumption, and the HC, CO, CO_2, and NO_x concentrations were measured. Experiments were done at 0, 20, 50, 80 and 100 % engine loads first with pure gasoline then with the addition of 5 l/min H_2/O_2 mixture to the fuel. The experimental set-up is shown in Fig. 2. In this study, H_2/O_2 gas mixture has a molar ratio of 2:1. All measurements were taken after the engine attained steady state as seen by the stability of the exhaust gas temperature. During these experiments, the pressure at the laboratory was 1 bar and the temperature was maintained at 25 °C. All parameters were measured and collected in each test. The mean values were calculated to minimise measurement errors.

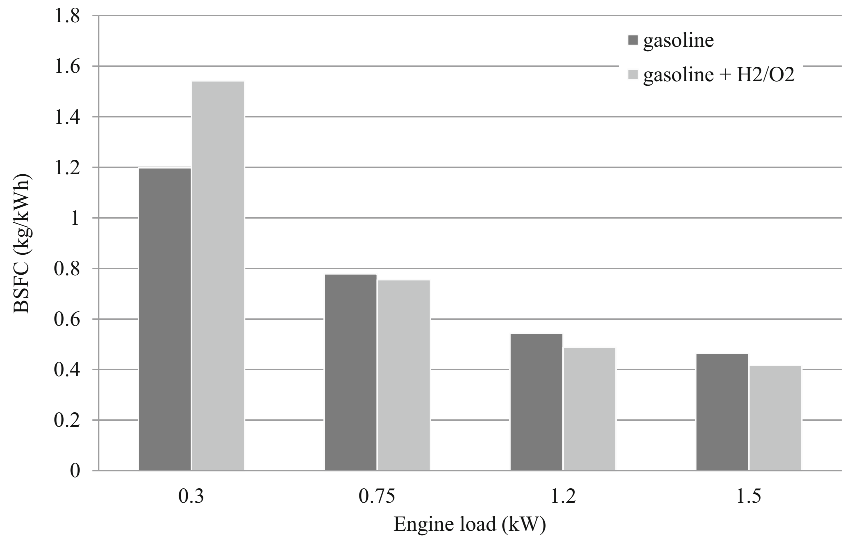

Fig. 4 Variation of the brake-specific fuel consumption (BSFC) versus engine load

3 Results and Discussion

3.1 Effect of H_2/O_2 Addition on BSFC at Different Engine Loads

The brake-specific fuel consumption (BSFC) is a measure of the mass of fuel consumed to produce unit power. The measured power to produce H_2/O_2 has been subtracted from the total output power of the engine-generator. In Fig. 4, the effect of enrichment of gasoline with H_2/O_2 on BSFC value at different working conditions is given. Firstly, it is noticeable that the present results confirm the fact that for low engine loads (20 %), BSFC is considerably higher for gasoline enriched with H_2/O_2 than for gasoline-only operation. This increase in BSFC might be due to the importance of the loss of power to produce H_2/O_2 as compared to the engine load. Then, with the increase in the engine load, the effect of this loss could be neglected. An important improvement in the BSFC is obtained on H_2/O_2 enriched conditions. At 0.75, 1.2 and 1.5 kW (50, 80 and 100 % engine loads), a decrease by 3, 10, and 10.4 % is, respectively, obtained using H_2/O_2 enriched gasoline.

This can be explained by the high flame velocities and high calorific content of the participating hydrogen with oxygen. In fact, the high diffusivity of hydrogen leads to a better mixing of fuel air and hence improved combustion.

3.2 Effect of H_2/O_2 Addition on Exhaust Temperature at Different Engine Loads

Figure 5 depicts the variation of exhaust gas temperature versus engine loads when using H_2/O_2 enriched gasoline instead of using gasoline only. As expected, the exhaust gas temperature increases with the increase in the engine loads. This is because more fuel is introduced into the cylinder at high loads.

As shown in Fig. 5, with the use of H_2/O_2, the exhaust gas temperature decreases because of the vaporisation of water that was produced by the combustion reaction and that cooled the charge and reduced the average temperature of the cylinder. This resulted in lower peak combustion temperatures. Furthermore, the exhaust gas temperature is mainly influenced by the post-combustion of the fuel–air mixtures. Since the combustion duration is shortened after the hydrogen blending, less fuel is burnt during the piston moving downwards. Thereby, the exhaust gas temperature is generally reduced after the addition of H_2/O_2. Increasing hydrogen fraction is beneficial for the quick and complete combustion of the fuel–air mixtures [34]. Meanwhile, under the same turbulence intensity, the addition of hydrogen avails the promoted wrinkling of turbulent flame surface. The obtained results are in agreement with previous research findings [32, 33].

3.3 Effect of H_2/O_2 Addition on HC Concentration at Different Engine Loads

Hydrocarbons are formed because of incomplete combustion of hydrocarbon fuels. In Fig. 6, the variation of the hydrocarbons (HC) concentration depending on fuel, gasoline and gasoline in dual fuel mode versus engine load is represented. The maximum HC concentration emitted by the engine dropped from 51 to 45 ppm at 0 % engine load with 5 l/min H_2/O_2 induction.

At 0.3 kW (20 % engine load), enriched gasoline fuel usage decreased HC concentration from 49 to 40 ppm. Similarly, at 0.75 kW (50 % engine load), HC concentration decreased from 39 to 35 ppm. At 1.2 kW (80 % engine load), it decreased from 34 to 27 ppm. At 1.5 kW (100 % engine load),

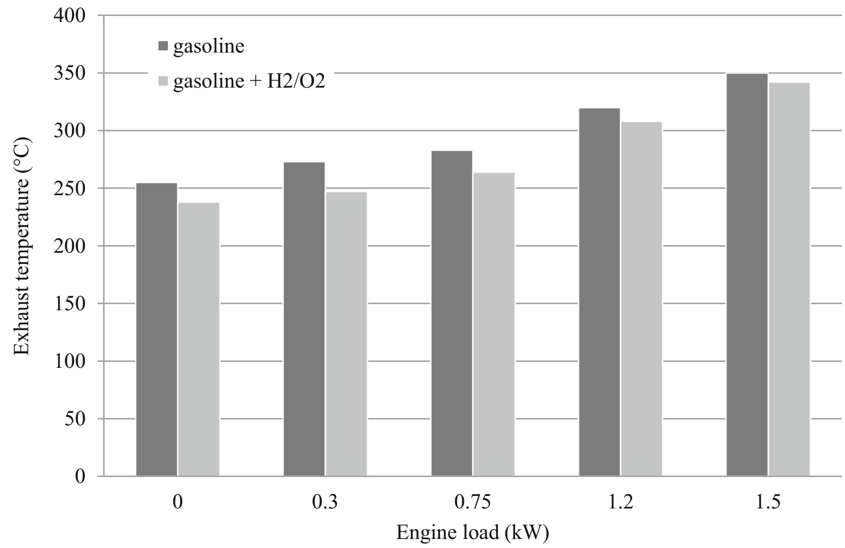

Fig. 5 Variation of exhaust gas temperature versus engine load

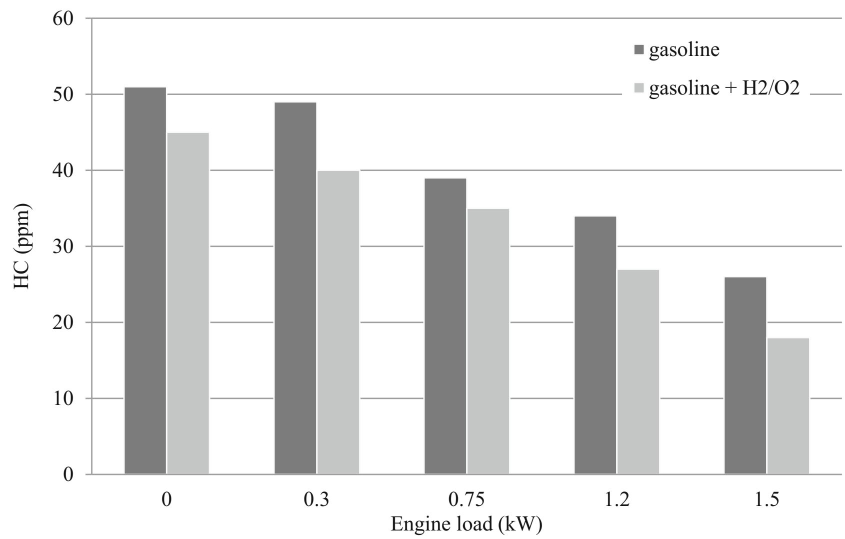

Fig. 6 Variation of HC concentration versus engine load

it decreased from 26 to 18 ppm. At 0, 20, 50, 80 and 100 % engine loads, a decrease by 11.7, 18.3, 10.2, 20.5 and 30.7 %, respectively, is obtained.

With the addition of H_2/O_2, the hydrocarbon values decreased due to the absence of carbon in H_2/O_2. This decrease may be explained also with reference to the accelerated chain reactions [34]. In fact, the quenching distance of hydrogen is shorter than that of gasoline and the crevice effect improves with hydrogen addition. These results are similar to those found by Refs. [18,19].

3.4 Effect of H_2/O_2 Addition on CO Concentration at Different Engine Loads

Carbon monoxide is a poisonous gas which is produced by the incomplete combustion of petroleum fuels. The relative amount of carbon monoxide formed depends on combustion efficiency.

Figure 7 depicts the variation of carbon monoxide concentration versus engine load. It is observed that there is a reduction in CO concentration for all tested loads.

The maximum CO reduction (43 %) was obtained at 1.2 kW engine load with 5 l/min H_2/O_2 addition. CO value decreased by 18.4, 24.1, 32.1, 16.4 and 42.3 %, respectively, at 0, 0.3, 0.75, 1.5 kW engine loads with H_2/O_2 addition. A reduction in CO concentration with the use of H_2/O_2 is observed. This could be explained by the increase in the in-cylinder temperature that intensifies the oxidation reactions of CO into CO_2 [34]. So, combustion efficiency increases with hydrogen fuel addition [35]. This trend is in agreement with the results found by Ref. [32].

3.5 Effect of H_2/O_2 Addition on CO_2 Concentration at Different Engine Loads

Carbon dioxide (CO_2) is the most prominent human made greenhouse gas. The disparity of CO_2 concentration for dif-

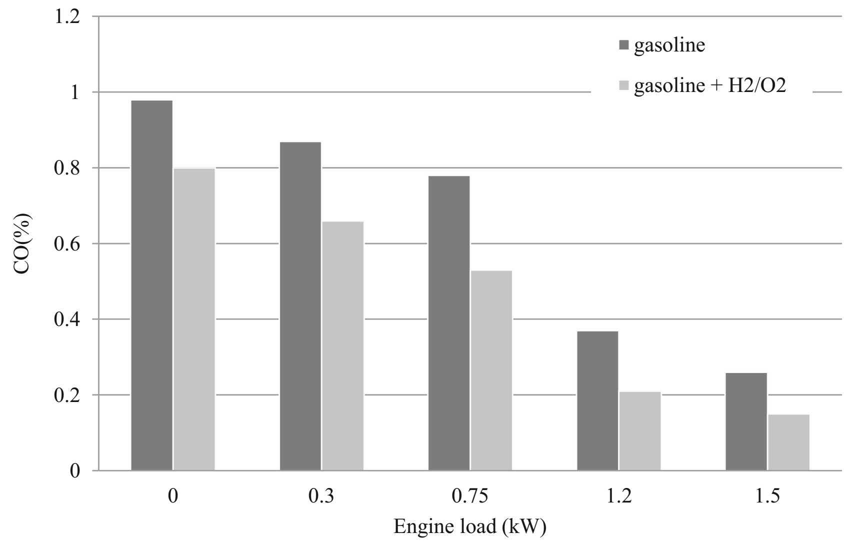

Fig. 7 Variation of CO concentration versus engine load

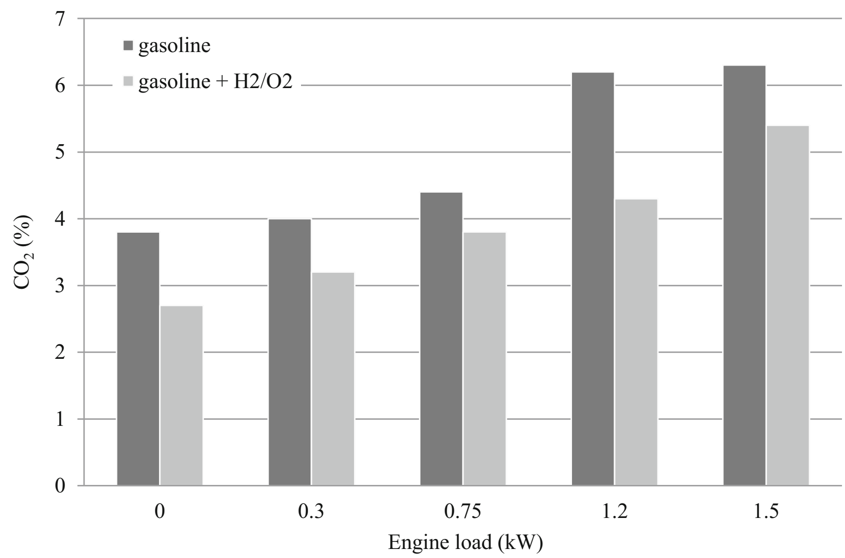

Fig. 8 Variation of CO_2 concentration versus engine load

ferent engine loads is presented in Fig. 8. Operating with enriched gasoline produces lower CO_2 concentration than gasoline at any operating condition. At 0, 0.3, 0.75, 1.2 and 1.5 kW, CO_2 concentration was, respectively, 3.8, 4, 4.4, 6.2 and 6.3 %, (neat gasoline fuel). With H_2/O_2 enhancement, a significant diminution is observed in the CO_2 concentration which decreased, respectively, to 2.7, 3.2, 3.8, 5.7 and 6.1 %.

The explanation comes from the fact that H_2/O_2 is a carbon free fuel. Many earlier findings show that the higher the H/C ratio of the blended fuel is, the superior premixed combustion is and the higher the diminution of CO_2 concentration becomes because of flame speed propagation Refs. [16–18].

3.6 Effect of H_2/O_2 Addition on NO_x Concentration at Different Engine Loads

Figure 9 shows the NO_x concentration with the H_2/O_2 addition at different engine loads.

During tests, it is found that NO_x formations change with engine loads. It can be noticed that there is a large decrease in NO_x concentration with the addition of H_2/O_2 for all low engine loads (0, 20 and 50 %). The NO_x concentration decreased to 71 ppm from 85 ppm with 5 l/min H_2/O_2 induction at 0.75 kW engine load. It can be observed from Fig. 9 that NO_x concentration drastically decreased upon H_2/O_2 enrichment at engine loads at 0 kW (by 36.2 %) and 0.3 kW (by 25.3 %).

At low load conditions, enriching gasoline with H_2/O_2 reduces NO_x concentration. The explanation comes from the fact that the evaporation of water, produced by the combustion reaction, has cooled the charge; then, there was not enough high heat release from combustion. Obtained results at low load conditions are consistent with those found by Ref. [32]

At high load conditions (80 % or more), it is observed that NO_x concentration increased with H_2/O_2 addition. At 80 %

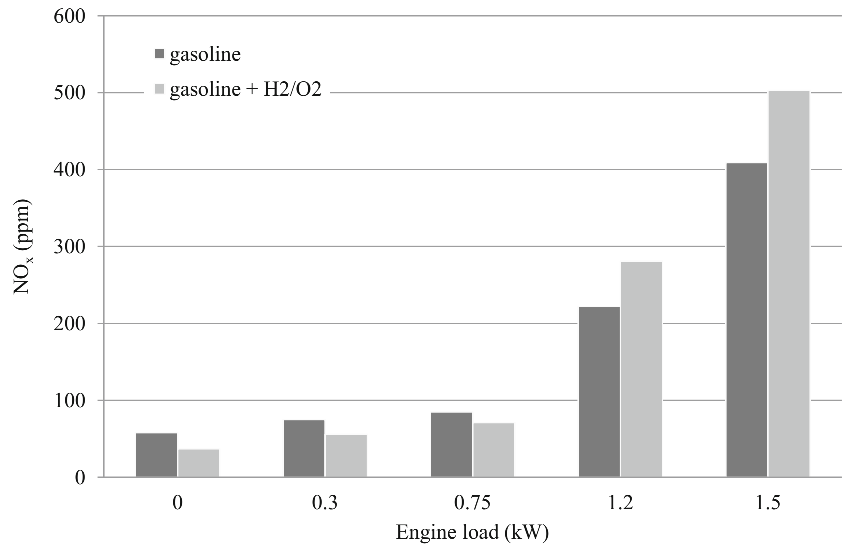

Fig. 9 Variation of NO_x concentration versus engine load

engine load, there was an increase from 222 to 281 ppm. At 100 % engine load condition, NO_x concentration increased by 23 %. The increase in the NO_x concentration as shown in Fig. 9 can be explained by the higher flame speed and the temperature of hydrogen which increased the in-cylinder temperature [34]. These results are in agreement with those by Refs. [13,18].

4 Conclusion

This paper aimed to investigate the effects of hydrogen addition at different engine loads (0, 0.3, 0.75, 1.2 and 1.5 kW) on a gasoline engine. Engine performance and concentration were experimentally investigated when 5 l/min of H_2/O_2 was introduced as supplementary fuel. Results were compared with pure gasoline condition. The test findings are presented below:

- H_2/O_2 enrichment results in reduction in BSFC. It was decreased by an average 7.8 % with H_2/O_2 addition at engine loads more than 0.3 kW.
- It was observed that the exhaust temperature had decreased after the H_2/O_2 addition. This could enhance the gasoline engine combustion and reduce the exhaust loss.
- A sharp drop of HC concentration was obtained with H_2/O_2 enrichment with all the engine loads. With 5 l/min H_2/O_2, the maximum HC concentration dropped from 49 to 40 ppm at 20 % engine load.
- At all engine loads, a significant reduction was observed in CO concentration when inducting 5 l/min H_2/O_2 mixture. CO concentration was reduced by an average of 31.8 %.
- A great diminution of CO_2 concentration was observed with H_2/O_2 addition. The maximum variation of the CO_2 concentration was observed at 80 % of engine load. It was reduced by 30.6 %.
- After the H_2/O_2 addition, NO_x concentration decreased at low engine loads. In the other hand, it increased significantly with the increase in the engine load (more than 80 %).

References

1. European Environment Agency (EEA). Trends and projections in Europe 2013: tracking progress towards Europe's climate and energy targets until 2020. Report No 10/2013 (2013)
2. Paul, B.D.: Vaporization of exhaust products in hydrogen–oxygen engine. United States patents 1974–10–29; US3844262 (A)
3. Shudo, T.: Thermal efficiency improvement in a hydrogen combustion engines. In: Proceedings of the 15th World Hydrogen Energy Conference, Yokohama (2004)
4. Sáinz, D.; Diéguez, P.M.; Sopena, C.; Urroz, J.C.; Gandía, L.M.: Conversion of a commercial gasoline vehicle to run bi-fuel (hydrogen-gasoline). Int. J. Hydrog. Energy **37**, 1781–1789 (2012)
5. Sáinz, D. et al.: Conversion of a gasoline engine-generator set to a bi-fuel (hydrogen/gasoline) electronic fuel-injected power unit. Int. J. Hydrog. Energy **36**, 13781–13792 (2011)
6. Antunes, J.M.G.; Mikalsen, R.; Roskilly, A.P.: An experimental study of a direct injection compression ignition hydrogen engine. Int. J. Hydrog. Energy. **34**, 6516–6522 (2009)
7. Salimi, F.; Shamekhi, A.H.; Pourkhesalian, A.M.: Role of mixture richness, spark and valve timing in hydrogen-fuelled engine performance and emission. Int. J. Hydrog. Energy **34**, 3922–3929 (2009)
8. Verhelst, S.; Sierens, R.: Hydrogen engine-specific properties. Int. J. Hydrog. Energy **26**, 987–990 (2001)
9. Verhelst, S.; Wallner, T.: Hydrogen-fueled internal combustion engines. Prog. Energy Combust. Sci. **35**, 490–527 (2009)
10. Boretti, A.A.: Vehicle driving cycle performance of the spark-less di-ji hydrogen engine. Int. J. Hydrog. Energy **35**, 4702–4714 (2010)

11. Porpatham, E.; Ramesh, A.; Nagalingam, B.: Effect of hydrogen addition on the performance of a biogas fuelled spark ignition engine. Int. J. Hydrog. Energy **32**, 2057–2065 (2007)
12. Andrea, T.D.; Henshaw, P.F.; Ting, D.S.K.: The addition of hydrogen to a gasoline-fuelled SI engine. Int. J. Hydrog. Energy **29**, 1541–1552 (2004)
13. Bari, S.; Esmail, M.M.: Effect of H_2/O_2 addition in increasing the thermal efficiency of a diesel engine. Fuel **89**, 378–383 (2010)
14. Verhelst, S.; Demuynck, J.; Sierens, R.; Huyskens, P.: Impact of variable valve timing on power, emissions and backfire of a bi-fuel hydrogen/gasoline engine. Int. J. Hydrog. Energy **35**, 4399–4408 (2010)
15. Marbán, G.; Solís, T.V.: Towards the hydrogen economy. Int. J. Hydrog. Energy **32**, 1625–1637 (2007)
16. Yousufuddin, S.; Masood, M.: Effect of ignition timing and compression ratio on the performance of hydrogen-ethanol fuelled engine. Int. J. Hydrog. Energy **34**, 6945–6950 (2009)
17. Ji, C.; Wang, S.: Effect of hydrogen addition on combustion and concentration performance of a spark ignition gasoline engine at lean conditions. Int. J. Hydrog. Energy **34**, 7823–7834 (2009)
18. Wang, S.; Ji, C.; Zhang, J.; Zhang, B.: Improving the performance of a gasoline engine with the addition of hydrogen-oxygen mixtures. Int. J. Hydrog. Energy **36**, 11164–11173 (2011)
19. Ji, C.; Wang, S.: Strategies for improving the idle performance of a spark-ignited gasoline engine. Int. J. Hydrog. Energy **37**, 3938–3944 (2012)
20. Ji, C.; Wang, S.: Combustion and concentration performance of a hybrid hydrogen-gasoline engine at idle and lean conditions. Int. J. Hydrog. Energy **35**, 346–355 (2010)
21. Wang, S.; Ji, C.; Zhang, B.: Effect of hydrogen addition on combustion and concentration performance of a spark-ignited ethanol engine at idle and stoichiometric conditions. Int. J. Hydrog. Energy **35**, 9205–9213 (2010)
22. Li, G.; Zhang, Z.; You, F.; Pan, Z.; Zhang, X.; Dong, J. et al.: A novel strategy for hydrous ethanol utilization: demonstration of a spark-ignition engine fueled with hydrogen-rich fuel from an onboard ethanol/steam reformer. Int. J. Hydrog. Energy **38**, 5936–5948 (2013)
23. Greenwood, J.B.; Erickson, P.A.; Hwang, J.; Jordan, E.A.: Experimental results of hydrogen enrichment of ethanol in an ultra-lean internal combustion engine. Int. J. Hydrog. Energy **39**, 12980–12990 (2014)
24. Li, H.; Karim, G.A.: Knock in spark ignition engines. Int. J. Hydrog. Energy **29**, 859–864 (2004)
25. Dunn, S.: Hydrogen futures: toward a sustainable energy system. Int. J. Hydrog. Energy **27**, 235–264 (2002)
26. Bacon, F.T.: The high pressure hydrogen oxygen cell. J. Ind. Eng. Chem. **52**(4), 301–303 (1960)
27. Akikusa, J.; Adachi, K.; Hoshino, K.; Ishihara, T.; Takita, Y.: Development of a low temperature operation solid oxide fuel cell. J. Electrochem. Soc. **148**, A1275–A1278 (2001)
28. Appleby, A.J.: Fuel cell electrolytes: evolution, properties, and future prospects. J. Power Sources **49**, 15–34 (1994)
29. Bacon, F.T.: Fuel cells, past, present and future. Electrochim. Acta **14**, 569–585 (1969)
30. Badwal, S.P.S.; Foger, K.; Zheng, X.G.; Jaffrey, D.: Fuel cell interconnect device. United States patent. WO 96/28855 A1. 1996 SEP 19
31. Niro, N.; Masanori, T.; Motohide, N.: Effects of generated bubbles between electrodes on efficiency of alkaline water electroltsis. JSME Int. J. **46**(4), 549–556 (2003)
32. Sa'ed, A.M.: Effect of HHO gas on combustion concentration in gasoline engines. Fuel **90**, 3066–3070 (2011)
33. Al-Rousan, A.A.: Reduction of fuel consumption in gasoline engines by introducing HHO gas into intake manifold. Int. J. Hydrog. Energy **35**, 12930–12935 (2010)
34. Heywood, J.B.: Internal Combustion Engine Fundamental. McGraw-Hill, Inc., New York (1988)
35. Yüksel, F.; Ceviz, M.A.: Thermal balance of a four stroke SI engine operating on hydrogen as a supplementary fuel. Energy **28**, 1069–1080 (2003)