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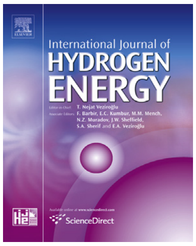

Effect of hydrogen and oxygen addition as a mixture on emissions and performance characteristics of a gasoline engine

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ABSTRACT

Use of hydrogen in spark ignition engines as supplementary fuel can be preferred due to improved combustion characteristics and emission advantages. However, hydrogen storage and production difficulties under the hood limit the use of it in internal combustion engines (ICEs). In this study, a different approach was used to overcome these difficulties. Hydrogen and oxygen gas mixture was produced by electrolyser and consumed simultaneously to eliminate the necessity of a storage device. Firstly, a practical alkaline water electrolyser was designed and manufactured to produce hydrogen from water to be subsequently used in ICE as a supplementary fuel. In order to optimize electrolyser, the parameters of gap between plates, concentration of solution and voltage were kept under control. Then, H_2/O_2 gas mixture used as secondary fuel in SI engine was generated by electrolyser on optimized operating conditions. 0 and 20 l/min H_2/O_2 mixture as supplementary fuel was introduced into intake manifold of engine using gas injectors where 0 l/min refers to without hydrogen case and 20 l/min with hydrogen case. According to the results, the brake power and brake thermal efficiency were increased by means of hydrogen addition. Besides, total hydrocarbon and carbon monoxide emissions decreased, whereas the dramatic increase of nitrogen oxides emissions couldn't be prevented during the experimental work.

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Introduction

Although the current energy and environment policies has forced researchers to be interested in non-polluting and clean alternative fuels for transport sectors, most of the energy demand is still supplied by fossil fuels. Even though the measures taken by Kyoto Protocol to the United Nations Framework Convention on Climate Change, during the period of 1990–2004, CO_2 emission increased by 27%, and the energy consumption in transport sector increased by 37% [1,2]. In relation with previous studies, hydrogen has been proved to be a green alternative energy and would be used on vehicles [3]. Fossil fuel can be substituted in part, by an alternative energy source, such as hydrogen [4]. Automotive manufacturers have profited from different technologies such as fuel cell, hydrogen fuelled ICE and hybrid configurations to evolve different type of vehicles. Some manufacturers study on polymer electrolyte membrane fuel cell (PEMFC). Since investment costs of PEMFCs are high and produced devices work only with high purity hydrogen (above 99.99%), fuel cell system becomes even more expensive [1].

Hydrogen's unique combustion properties may improve thermal efficiency and emission levels in ICEs, and may be useful for fuel saving. The diffusion coefficient of hydrogen (0.61 cm^2/s) is larger than gasoline (0.16 cm^2/s), for that reason, it improves the homogeneity of combustible mixture [5]. The aidabatic flame speed of hydrogen (237 cm/s) is five times as large as that of gasoline (42 cm/s) and therefore it may improve thermal efficiency, because the combustion of hydrogen engines is much closer to ideal constant volume combustion [5,6]. One of the possible ways to increase performance of an engine is to use additive as a supplementary fuel, leading to improve thermal efficiency and reduce emissions [7]. Some researchers have investigated different additives such as Jathropha Oil, 2-methoxyethyl acetate etc in diesel and gasoline engines [8]. However, hydrogen is the most promising additive with its unique combustion properties among many additives and it can reduce fuel consumption and harmful emissions emitted by ICEs [7] significantly. Karagoz et al. [9] used H_2/O_2 mixture as a supplementary fuel in an SI engine at idle condition, and it was found that brake thermal efficiency of engine increased, HC and CO_2 emissions decreased via hydrogen addition. H_2/O_2 mixture was used as supplementary fuel in a diesel engine at 1500 rpm constant engine speed and at different loads by Bari et al. [7]. Brake thermal efficiency of engine increased with H_2/O_2 addition. HC, CO_2 and CO emissions decreased, while the NO_x emissions increased. 3% and 6% hydrogen volume fraction of total intake was used as secondary fuel at 1400 rpm constant engine speed by Ji et al. [5]. Brake thermal efficiency of engine increased with hydrogen addition. Conversely, HC and CO emissions reduced with hydrogen addition. Hydrogen was introduced into biodiesel and diesel by Senthil et al. [10] during their experiment. Brake thermal efficiency of the engine with hydrogen enriched fuels was observed to be higher than the engines with conventional fossil fuels. Emissions also decreased. Tomita et al. [11] introduced hydrogen as secondary fuel into diesel fuel and observed a reduction in exhaust emission. 10 l/min and 20 l/min hydrogen were introduced into cylinders in experiment of Saravan et al. [12,13] and then performance parameters with/without EGR were prospected, and an increase in brake thermal efficiency was observed. Andrea et al. [14] studied on the effect of various engine speeds and equivalance ratios on combustion of a hydrogen blended gasoline engine. Combustion duration reduced with increase on hydrogen blending fraction. Mechanism of the toxic emission formation process for an engine fuelled with hydrogen-gasoline mixture was studied by Li et al. [15]. NO_x, HC and CO emissions released from the hydrogen-enriched gasoline engine were lower than the original one. Effect of hydrogen addition on a gasoline-fueled engine performance was studied by Ji and Wang [16] at idle and stoichiometric conditions. It was seen that the engine thermal efficiency and emissions accelerated after hydrogen enrichment. Wang et al. [17] experimented on effect of 3% hydroxygen (H_2+O_2) addition on engine performance in 1.6 L gasoline engine at 61.5 kPa manifold absolute pressures. Thermal efficiency increased with hydrogen proportion raise in hydroxygen gas mixture, moreover HC, CO, NO_x emissions recuperated. Ceviz et al. [18] studied on hydrogen addition of 0%, 2.14%, 5.28%, and 7.74% by volume to a spark ignition engine at 2000 rpm constant engine speed. Ji et al. [19] studied on emissions of a passenger car powered by a hydrogen-gasoline engine under the New European Driving Cycle. Ji et al. [20] observed via CFD calculation effect of 3% and 6% hydrogen addition by volume into gasoline. According to obtained results, peak flame propagation increased by 37.18% and 60.47% with 3% and 6% H_2 addition. Greenwood et al. [21] studied with H_2 and ethanol fuel mixture in a 0.745 L, two cylinder spark ignited engine. At ultra lean operating conditions, NO_x emissions decreased by 95% compared to stoichiometric gasoline operating conditions at stable engine speed with 0%, 15% and 30% H_2 addition by volume. Lee et al. [22] studied on a naturally aspirated gasoline engine with H_2 and low calorific gas blends at EGR and lean burn mode. Low calorific gas blends are composed of 40% natural gas, 60% nitrogen gas mixture and it corresponds to 0%–20% of H_2 gas mixture by volume. Although a decrease exists on brake thermal efficiency and an increase on THC emission at all H_2 added gas mixtures with EGR working condition, there is a decrease on NO_x emissions compared to lean burn working condition.

Most of the investigations focused on usage of pure hydrogen as secondary fuel but this may cause storage problems. Hydrogen has very low density, so it can be stored by compression in tanks (typically 70 MPa) or can be combined chemically with a metal alloy [7]. However, a tank with sufficient amount of hydrogen which increases overall system weight is needed for storage of hydrogen on-board [23]. Alternatively, liquid hydrogen storage method is used, but on-board cryogenic container costs are high and a high level of energy is needed to convert gaseous hydrogen into liquid [24]. In order to eliminate hydrogen storage problem, hydrogen could be produced on-board through the electrolysis of water. In this way, there will be no need for a high pressure tank. In the on-board hydrogen production systems, hydrogen is only produced while the engine is being operated and the produced gas has just been sent into the intake manifold.

Water electrolysis technology is easily classified into three approaches, with each approach conducting one of three ionic species across the electrolyte: liquid alkaline electrolytes, which transport hydroxide (OH^-) ions; proton exchange membranes, typically polymers that transport protons (H^+); and ceramic solid oxide membranes, which conduct oxygen (O^{2-}) ions [25]. Among three methods alkaline water electrolysis has the advantage of simplicity [26]. Nagai et al. [27] studied on efficiency of alkaline water electrolysis to obtain optimum conditions. Nagai developed a model and conducted some experiments to verify it. As a result, KOH solution with different concentration such as 8.5, 17, 25.5 wt% was used and changed electrode spacing in the range of 1–20 mm. Current density was ranged from 0.1 to 1.6 A/cm^3 and DC current up to 100 A and DC voltage up to 35 V was used in their study. Theoretical and experimental findings showed that electrode spacing between 1.5 and 2.5 mm was optimum when concentration was 8.5 wt%.

In the literature, most of the studies focus on investigating effect of hydrogen addition, which is supplied by high pressure tanks, on emissions and performance of ICEs. Also, the studies which are about optimization of electrolyser's operating condition haven't been tested on engines as supplementary fuel. In this study, the emissions and the performance of SI engines were investigated considering the existing knowledge in the literature by using hydrogen as a supplementary fuel which was produced by electrolysis of water in the alkaline solution. Although PEM electrolysers are promising one as their outstanding and environmentalist technology, they are expensive, capacious extremely and have also limited economic life for automotive sector. For these reasons, alkaline water electrolysers can serve as a bridge during the transitional stage. The alkaline water electrolyzer was used as an on-board system on test setup. The aqueous potassium hydroxide solutions of 10 wt%, 20 wt%, 28 wt% were used with controlling the voltage and gap between plates. The advantage and importance of this system is to suppress need of a storage system and to eliminate all the hydrogen storage problems as using it directly. Hydrogen was produced by alkalinde water electrolyser and consumed simultaneously in the SI engine. The aim of this study is determining the optimum operating conditions of alkaline water electrolyser in terms of energy efficiency initially, then using produced hyrogen in this electrolyser operating condition as supplementary fuel in the SI engine to investigate the performance and emissions of the engine. In the literature, there is not enough study about testing the effect of hydrogen as additional fuel which was produced by an optimized alkaline water electrolyser in terms of energy efficiency on the SI engine. For this reason, firstly alkaline water electrolyser was optimized in terms of energy efficiency, then brake power, brake thermal efficiency, brake specific fuel consumption and emissions (CO, THC, NO_x) were tested with additional hyrogen and without additional hydrogen cases on the SI engine.

Materials and methods

Engine modifications and specifications

The studies were carried out on a 1.1 L Peugeot engine. The main engine specifications are summarized in Table 1. The test cell was adapted to work with hydrogen gas. H_2/O_2 gas mixture (as supplementary fuel) and gasoline were supplied separately to the engine.

Table 1 – Specifications of the original engine.

Definiton	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 distributorless
Fuel System	Multi-point fuel injection
Cylinder arrangement	In-line

Hydrogen production and fuel system

An alkaline water electrolyser is designed and manufactured in order to generate hydrogen and oxygen as supplementary fuel. The main units of an electrolyzer are an anode, a cathode, and an electrolyte which transmits the ions between anode and cathode (electrodes). When the power is turned on, water decomposes into positively charged hydrogen ions and negatively charged oxygen ions. The positive hydrogen ions move to the negatively charged electrode (cathode) and form as hydrogen gas (H_2) and the negative oxygen ions move to the positively charged electrode (anode) and form as oxygen gas (O_2). The fundamental reactions at the electrodes of an alkaline electrolyzer are as follows:

$$\text{Cathode Reaction}: \quad 4H_2O(l) + 4e^- \rightarrow 4H_2(g) + 4OH^-(aq) \tag{1}$$

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

$$\text{Overall Reaction}: \quad 2H_2O(l) \rightarrow 4H_2(g) + O_2(g) \tag{3}$$

Fig. 1 shows schematic diagram of hydrogen line. Material of regulator and hydrogen line is 316 stainless steel. A relief valve was used to prevent an overpressure. A check valve was used before intake manifold to prevent backfire. A second regulator was installed to regulate pressure. A pressure gauge was installed to check line pressure. A thermal mass-flow meter calibrated for hydrogen was used with a measurement uncertainty of 1%. A buffer tank was used in order to reduce H_2/O_2 mixture flow fluctuations. H_2/O_2 mixture was delivered into engine with an additional fuel supplement system; also H_2/O_2 mixture was injected into the intake port of each cylinder using a multipoint sequential injection system.

Electronic management system

The original ECU of engine was not changed. A power supply with constant current capability was used both to control the current and the voltage of electrolyser. Since current level determines the hydrogen production, power supply was set to be a constant current value. A self-developed ECU was used to control hydrogen injectors. The self developed ECU triggered to gas injectors and flow rate of gas injectors was controlled according to signal width. During experiments, all data were

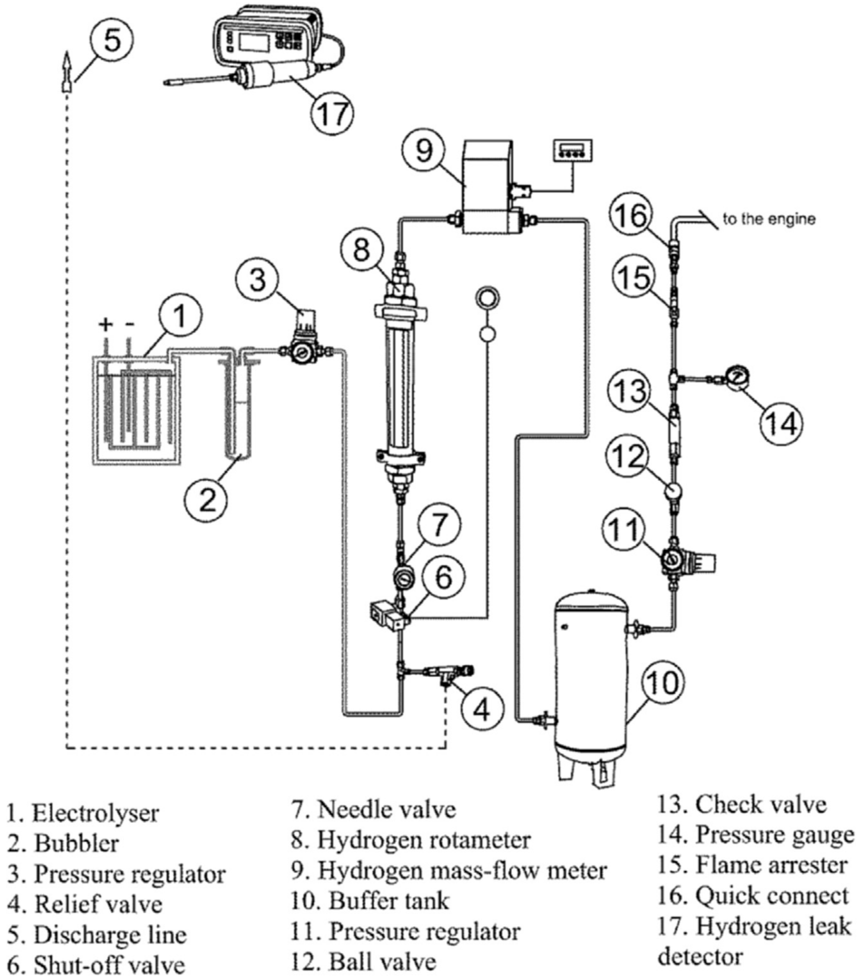

Fig. 1 – Schematic diagram of hydrogen fuel system.

acquired with a DAS (data acquisition system) at a sampling rate of 1 Hz.

Experimental setup

The schematic of experimental system was illustrated in Fig. 2. A hydrokinetic dynamometer was used to measure engine brake torque. The torque control of hydrokinetic dynamometer is controlled by a servo motor. Also, hydrokinetic dynamometer has 112 kW loading capacity to brake an engine. A Sika VZ0.2 turbine type flow meter was used to measure gasoline flow rate (measurement uncertainty 1%). The exhaust emissions (CO, THC and NO_x) were measured by AVL DiCom 4000 exhaust gas analyser which CO and THC are measured with infrared gas sensor (NDIR), NO_x emissions are measured with electrochemical sensor (ECD). The measurement accuracies and the uncertainties are presented in Table 2. The measurement accuracies and the uncertainties were determined using Kline and McClintock method [28] taking into account entire engine operating speed range. On the other hand, some measures were taken in terms of safety issues in the laboratory. The testing bed cell of the laboratory was adapted to provide safely working conditions with hydrogen. Air venting system was operated to prevent a hydrogen accumulation. A two stage hydrogen alarm unit was installed in order to determine possible hydrogen leakage.

Experimental procedure

In this study, an alkaline water electrolyser was designed to produce hydrogen to be used in ICE as a supplementary fuel. Tests were conducted with and without hydrogen conditions to observe and compare the effects of hydrogen on performance and emission values on the engine.

SS 316 plates were used as metarial of electrodes. In order to optimize electrolyser, the following parameters were controlled: voltage (3.5–4.0 V), gap between plates (2, 3, 5 and 10 mm) and concentration of KOH solution (10 wt%, 20 wt% and 28 wt%). Testing procedure began with starting the engine with unleaded gasoline fuel and warming it up until the engine reached regime temperature. All the tests were conducted at steady state condition and soichiometric air-fuel ratio, because the test engine is a typical catalyst-equipped gasoline engine. Also, engine tests were performed at 50% throttled position. The engine brake torque, brake power, brake specific fuel consumption, NO_x, THC and CO emissions

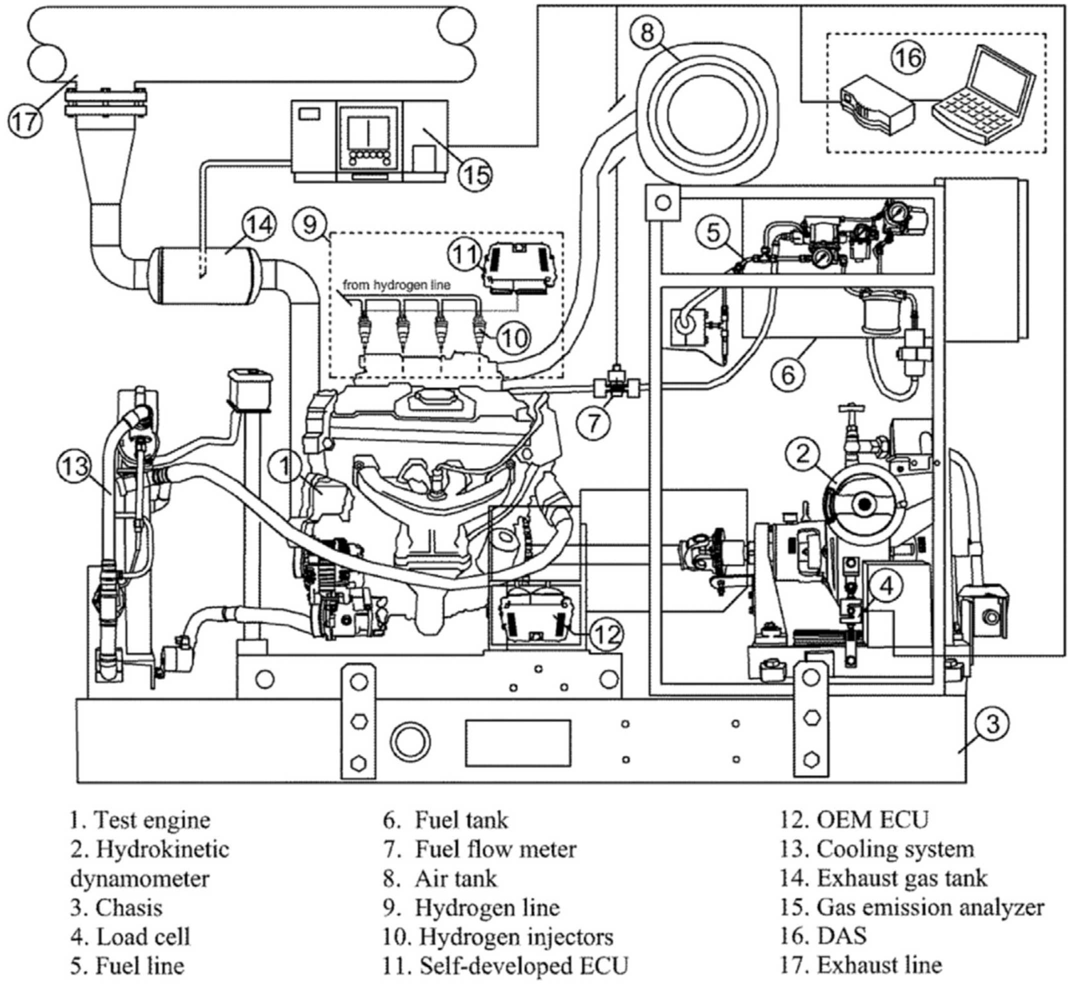

Fig. 2 – Schematic diagram of experimental system.

were measured. 0 (pure gasoline) and 20 l/min H_2/O_2 mixture as additional fuel were introduced into intake manifold at 1500, 2000, 2500, 3000 and 3500 rpm engine speeds. In this study, H_2/O_2 (hydrogen to oxygen) gas mixture has a molar ratio of 2:1. All parameters were measured and collected by a DAS each test, and mean values were calculated to minimize measurement error.

Data reduction

Energy efficiencies of alkaline water electrolyser were calculated to observe the effect of voltage values, concentration of solution and gaps between plates on electrolyser efficiency. The energy efficiency was calculated:

Table 2 – Measurement accuracies and uncertainties of calculated results.

Parameter	Device	Accuracy
Brake engine torque	Load-cell	±0.05 Nm
Engine speed	Incremental encoder	±5 rpm
Fuel mass-flow rate	Sika VZ 0.2	±1% (of reading)
Hydrogen mass-flow rate	New-flow TLF13	±1% (F.S.)
CO	AVL Dicom 4000	±0.01 vol.%
THC	AVL Dicom 4000	±1 ppm
NO_x	AVL Dicom 4000	±1 ppm
Calculated results		**Uncertainty (entire engine speed range)**
Brake power		±0.09 ÷ 0.12%
Bsfc		±1.05 ÷ 1.16%

$$Energy\ of\ efficiency = \frac{H_u \times \dot{m}_{H2}}{P_e} \tag{4}$$

where energy efficiency is the efficiency of electrolyser, Hu is the lower heating value of hydrogen in kJ/kg, $\dot{m}_{H2}$ is the produced hydrogen mass flow rate by electrolyser in kg/s and P_e is the consumed electrical power by the electrolyser in kW. Lower heating value was preffered instead of higher heating value to calculate energy efficiency of alkaline water electrolyser in equation (1), because produced hydrogen by the electrolyser is simultaneously consumed by the engine; using lower heating value in internal combustion engine calculations is more feasible than using higher heating value.

The brake torque value was obtained taking into account load cell value which joined the moment arm [29]:

$$M_e = m \times g \times L \tag{5}$$

M_e is the engine brake torque (Nm), m is the measured weigth in kg, g is the gravitiotinal acceleration (9.81) in m/s^2 and L is the length of moment arm (m).

The SI engine was loaded by hydrokinetic dynamometer and absorbed power by dynamometer was calculated depending on brake torque and angular speed [30]:

$$N_e = 2\pi\omega M_e \times 10^{-3}, \tag{6}$$

where N_e is the value of engine brake power (kW), ω is the angular engine speed (rps) and M_e is the engine brake torque (Nm).

The brake thermal efficiency is calculated as a function of brake power, fuel consumption and lower heating value of fuel [31]:

$$\eta_T = \frac{N_e}{\dot{q}_{m,g} \times LHV_g + \dot{q}_{m,H_2} \times LHV_{H_2}}, \tag{7}$$

where η_T is the engine brake thermal efficiency value, N_e is the engine brake power (kW), $\dot{q}_{m,g}$ is the mass flow rate of gasoline (kg/s), $\dot{q}_{m,H2}$ is the mass flow of additional hydrogen (kg/s), LHV_g is the lower heating value of gasoline (kJ/kg) and LHV_{H2} is the lower heating value of hydrogen (kJ/kg).

The brake specific fuel consumption was calculated taking into account equivalent gasoline amount of consumed hydrogen fuel according to lower heating values of hydrogen and gasoline. The consumed gasoline mass flow rate and equivalent gasoline mass flow rate of hydrogen were added together and bsfc were calculated according to equivalent gasoline amount as follows:

$$bsfc = \frac{\dot{m}_g + \dot{m}_{g,H_2}}{N_e} \tag{8}$$

where bsfc is the total brake specific fuel consumption according to gasoline value in g/kWh, $\dot{m}_g$ is the consumed gasoline mass flow rate in g/h, $\dot{m}_{g,H2}$ is the equivalent consumed gasoline mass flow rate of hydrogen in g/kWh and N_e is the engine brake power in kW.

Kline and McClintock method [28] applied to calculate total measurement uncertainties for whole engine speed range as follows:

$$W_R = \left[\left(\frac{\partial R}{\partial x_1}w_1\right)^2 + \left(\frac{\partial R}{\partial x_2}w_2\right)^2 + \ldots + \left(\frac{\partial R}{\partial x_n}w_n\right)^2\right]^{1/2}, \tag{9}$$

where W_R is the total uncertainity value, R is the function, x_1, x_2, …,x_n are the independent variables and w_1, w_2, … w_n are the uncertainty values of the independent variables.

Result and discussion

An experimental investigation was carried out on the performance characteristics of a H_2/O_2-gasoline fuelled SI engine. H_2/O_2 gas mixture was injected into intake port using sequential LPG-CNG system. In this work, the supplementary gas mixture (H_2:O_2) has a molar ratio of 2:1. All of the tests were performed at the ICEs Laboratory in Technical University of Yildiz. The test bench and the test engine were accommodated to work with hydrogen and oxygen gas mixture as additional fuel. In previous study, the effect of 0% hydroxygen (pure gasoline), 4.5% hydroxygen (3% H_2 + 1.5% O_2) and 9% hydroxygen (6% H_2 + 3% O_2) on performance and emissions of an SI engine of total intake air by volume addition between 1500 and 3500 rpm engine speed was observed by Karagoz et al. [32]. Hydrogen and oxygen flow rates were controlled with needle valves. In another study, Karagöz et al. [33] introduced 3.75% hydroxygen (2.5% H_2 + 1.25% O_2) and 7.5% hydroxygen (5% H_2 + 2.5% O_2) of intake air by volume between 1500 rpm and 5000 rpm engine speed. Then, 0.25 l/h water is sprayed. H_2+O_2 gas mixture used as supplementary fuel is named as hydroxygen. In both studies, a high quantity of gas mixture is introduced by the help of high pressure H_2 and O_2 tubes. In this study, unlike other studies, effect of little (20 slpm) H_2/O_2 addition with an alkaline water electrolyser is observed on engine performance and emissions. First of all, most efficient working point of alkaline water electrolyser is determined, then effect of 20 slpm H_2/O_2 gas mixture usage as supplementary fuel at most efficient working point is investigated on engine performance and emissions.

Energy efficiency of 10wt%, 20wt% and 28wt% KOH solutions are shown in Fig. 3a, Fig. 3b and c, respectively. At all KOH solution rates, energy efficiency of electrolyser increases with voltage decrease and shrinkage between plates. Energy efficiency rises when KOH solution increases from 10wt% to 28wt%. At 28wt% KOH solution, 3.5 V tension value and 3, 5 ve 10 mm plate gap; 5.2%, 6.2% and 8.5% increase is observed respectively compared to 2 mm plate gap. At 28wt% KOH solution and 2 mm plate gap, when tension value rises from 3.5 V to 5 V, an increase of 7.4% and 14.9 (3.75 V and 4 V) is observed respectively compared to 3.5 V value. With test conditions such as 2 mm plate gap, 3.5 V tension value, 20wt% KOH solution and 10wt% KOH solution, an increase of 6.6%, 15.8% respectively is seen compared to 28wt% KOH solution. According to test results, 2 mm gap between plates, 28wt% KOH solution and 3.5 V found to be the best conditions in terms of energy efficiency. If lower heating value at this condition is considered, energy efficiency value is calculated as 76.7%. The high concentration of hydroxyl (OH^-) ions in an alkaline electrolyte such as 28 wt% potassium hydroxide

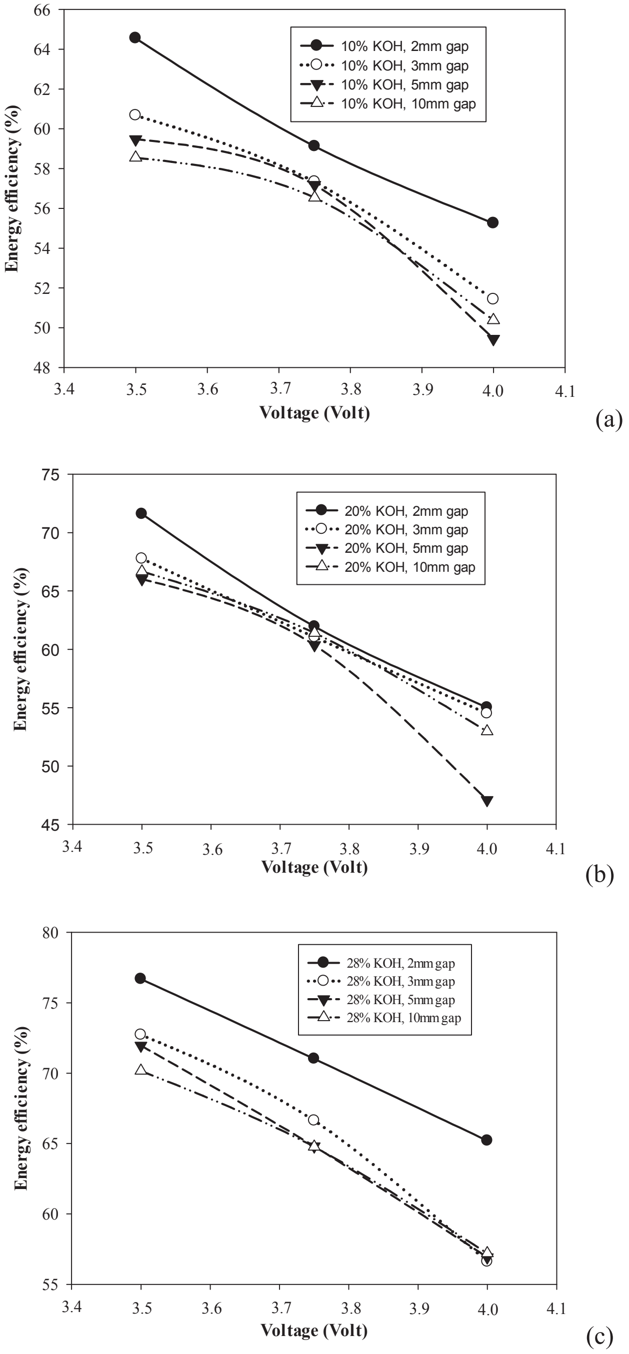

Fig. 3 – Energy efficiency for 10 (a), 20 (b) and 28 (c) wt% KOH.

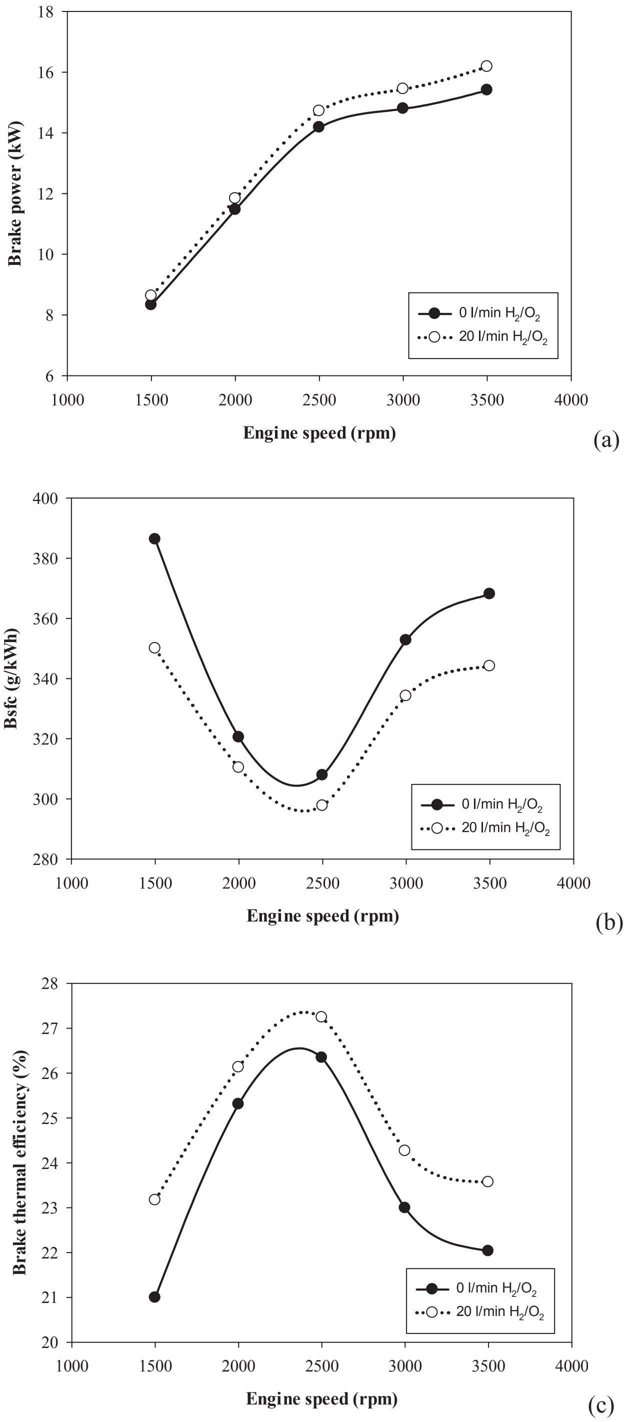

Fig. 4 – Brake power (a), Bsfc (b) and Brake thermal efficiency (c) at 50% throttled versus engine speed.

(KOH) solution promotes rapid reaction kinetics and smaller activation overvoltages, especially for oxygen evolution at the anode [25].

Test results of engine brake power at 50% throttled positon versus engine speed are shown in Fig. 4a. These tests are conducted with and without hydrogen as supplementary fuel and compared each other. A positive impact of hydrogen addition is observed on the power output of the test engine for entire speed range. According to the results, the engine performance was improved with hydrogen addition as a supplementary fuel. The maximum brake power of the engine was increased to 16.18 kW from 15.40 kW at 3500 rpm engine speed with 20 l/min H_2/O_2 enrichment. An increase of 3.6%, 3.2%, 3.8%, 4.4% and 5% was observed respectively on engine brake power with H_2/O_2 addition for 1500, 2000, 2500, 3000 and 3500 rpm engine speeds compared to only gasoline operationg condition. Hydrogen's lower heating value per kg is higher than gasoline, which procures an increase on brake power

[31]. Moreover, higher in-cylinder temperature and pressure occurred with hydrogen assisted gasoline combustion thanks to high flame speed of hydrogen. Therefore, improved engine power occurs due to increase of overall efficiency which contains both combustion efficiency and thermodynamic efficiency.

The variation of bsfc at 50% throttled position versus engine speeds is shown in Fig. 4b. Bsfc (brake spesific fuel consumption) and bsec (brake spesific energy consumption) are the most frequently used terms in the works which are related to fuel economy studies where IC engine is operated with hybrid fuels. Bsfc is explained as the quantity of equivalent gasoline consumed per kilowatt of power (produced by the engine). Equivalent gasoline amount of hydrogen was calculated by considering the lower heat value. By the sum of equivalent gasoline amount of hydrogen and gasoline consumption, the total fuel consumption was determined. Bsec is defined as the quantity of energy consumed per kilowatt of power (produced by the engine). So as to compare the fuel economy of test fuels, bsfc is better than bsec, because the bsfc is more frequently used than bsec in ICEs. For this reason, bsfc is preferred in this work. Including slight H_2/O_2 decreases bsfc irregardless engine speed. Since flame speed of hydrogen is five times as large as that of gasoline, higher flame speed of the mixture has a positive contribution on bsfc improvement [34,35]. Moreover, hydrogen has a wider flammability range than gasoline [36]. As a consequence, shorter burning duration and wider flammability range of the hydrogen gasoline mixture results with higher combustion efficiency [37]. So, completion of higher degree of constant volume combustion means that an SI engine operates much closer to its theoretical cycle [34]. Fig 4b reveals that addition of H_2/O_2 into the air intake to enhance combustion, decreases bsfc. Improvement in bsfc mainly originated by lower amount of gasoline injection is a result of engine control unit algorithm. Although, any modification was applied on the original electronic control unit of the engine, signal width of the gasoline injectors was decreased by the original ECU of the engine depending on stoichiometry based control algorithm as shown in Fig. 5. Decrease in the inducted air due to the gas phase injection of the H_2—O_2 mixture causes this situation. Bsfc value increases by 9.4%, 3.2%, 3.3%, 5.2% and 6.5% respectively for 1500, 2000, 2500, 3000 and 3500 rpm engine speed with H_2/O_2 gas mixture addition compared to only gasoline fuel. By inducting 20 l/min H_2/O_2 mixture, the maximum bsfc reduction was observed at 1500 rpm engine speed. Bsfc value was reduced from 386.3 g/kWh to 350.0 g/kWh at 1500 rpm engine speed.

Variation of brake thermal efficiency at 50% throttled position versus engine speeds is illustrated in Fig. 4c. The low percentage of H_2/O_2 as a supplementary fuel improved the combustion process. As mentioned in previous paragraph, higher flame speed of hydrogen, wider flammability range of hydrogen cause SI engine to operate much closer to its theoretical cycle. Besides, peak in-cylinder temperature and in-cylinder pressure rise with hydrogen enrichment. However, instant pressure rise and drops are seen in hydrogen added gasoline engines that limit post combustion period. Thus, reduced exhaust losses are acquired [25]. Also, shortened combustion period degrades cooling loss of engine [17]. Moreover, oxygen concentration enlarges with hydroxygen addition which enables air—fuel blends to burn completely [17]. The maximum brake thermal efficiency value of the SI engine was obtained at 2500 rpm engine speed with 20 l/min H_2/O_2 addition. The brake thermal efficiency was increased to 27.24% from 26.34% at this speed. Maximum improvement of brake thermal efficiency is attained at 1500 rpm engine speed. At this engine speed, brake thermal efficiency increases from

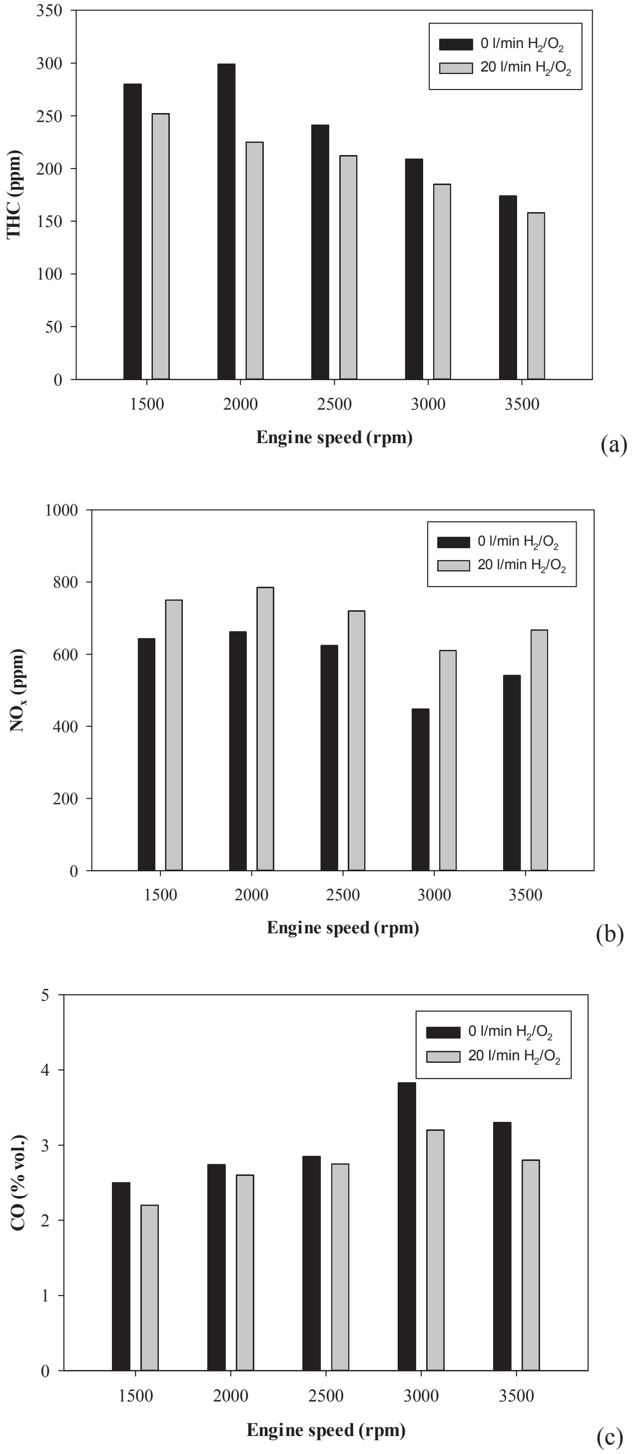

Fig. 5 — Variation of THC (a), NO_x(b) and CO (c) emissions at 50% throttled versus engine speed.

20.99% to 23.16% with H_2/O_2 addition. At 1500, 2000, 2500, 3000 and 3500 rpm engine speed, brake thermal efficiency increases by 10.4%, 3.3%, 3.4%, 5.5% and 7% respectively with H_2/O_2 enrichment.

Hydrocarbons (organic compounds) are formed because of incomplete combustion of hydrocarbon fuels. The unburned hydrocarbon in the tail-pipe gases is called as total hydrocarbon (THC) [29]. The variation of total hydrocarbons (THC) with 20 l/min H_2/O_2 addition at 50% throttled position versus engine speeds was depicted in Fig. 5a. THC emission decreased with H_2/O_2 induction because of the absence of carbon in hydrogen [7]. The total carbon mass value of total fuel was decreased to 0.855 kg C/kg fuel (for neat gasoline fuel and whole engine operating speeds),0.823 kg C/kg fuel, 0.829 kg C/kg fuel, 0.833 kg C/kg fuel, 0.836 kg C/kg fuel, 0.838 kg C/kg fuel for 1500 rpm, 2000 rpm, 2500 rpm, 3000 rpm and 3500 rpm engine speeds, respectively with H_2/O_2 addition since the original ECU of the test engine decreases gasoline injection duration depending on engine operating speed. According to literature, OH^- formation is improved with hyrogen addition [34]. Combustion efficiency increased and less THC occurred thanks to accelerated chain reaction with hydrogen addition [36]. Also, the quenching distance of hydrogen is shorter than gasoline and the crevice effect improved with hydrogen addition and therefore THC emission exhausted by the engine is reduced. The maximum THC emission emitted by engine was dropped from 299 ppm to 225 ppm at 2000 rpm engine speed with 20 l/min H_2/O_2 induction. Also, the maximum THC reduction was observed at the same engine speed (2000 rpm). The improvement level of THC emission with 20 l/min H_2/O_2 addition is 10%, 24.7%, 12%, 11.5% and 9.2% at 10%, 24.7%, 12%, 11.5% and 9.2% engine speeds, respectively compared with neat gasoline fuel.

Nitric oxide and nitrogen dioxide are named together as oxided of nitrogen (NO_x) and tail-pipe emissions of ICEs includes NO_x [29]. Nitric oxide is formed in the cylinder and its source is N_2 in air [29]. The variation of NO_x emission at 50% throttled position with 20 l/min H_2/O_2 addition is shown in Fig. 5b. According to test results, NO_x emission was increased with hydrogen addition. Formation of nitrogen oxides depends on both high temperature and oxygen availability [29]. Availability of oxygen and higher in-cylinder temperature is acquired with hydogen and oxygen gas mixture enrichment. Moreover, higher flame temperature and speed of hydrogen combustion cause higher local in-cylinder temperatures and higher NO_x emission formation [38]. If increase of NO_x emissions and improvement of engine performance are considered together, it can be understood that peak cylinder pressure and peak cylinder temperature increased with hydrogen addition. (Referans Bari and Esmail). The maximum NO_x emission rise was observed at 3000 rpm engine speed with 20 l/min H_2/O_2 addition. Besides, the maximum NO_x emission value was increased to 785 ppm from 662 ppm with 20 l/min H_2/O_2 induction at 2000 rpm engine speed. Based on engine speed (1500, 2000, 2500 and 3000 rpm), NO_x emissions increase by 16.6%, 18.6%, 15.4%, 36.2% and 23.3% respectively with H_2/O_2 addition compared to only gasoline fuel condition. Despite little H_2/O_2 addition (20 slpm), a drastic increase in NOx emissions is observed.

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 combution efficiency. If combution of carbon is complete (in the precense of planty air), CO oxidizes to CO_2 [29]. As shown in Fig. 5c, when H_2/O_2 mixture was being used, CO emission values were lower than pure gasoline due to improved combustion and lean operating condition of the engine with H_2/O_2 addition. Hydrogen assisted gasoline combustion emits less CO emission since H_2 fuel doesn't include any carbon element [7]. Furthermore, hydrogen has unique combustion properties such as high flame speed, high diffusion coefficient and wide flammability range, so combustion efficiency increases with H_2 fuel addition [16]. Higher in-cylinder pressure and temperature improve oxidation reaction and ICEs emit less CO emission with hydrogen enriched gasoline combustion [25]. The maximum CO reduction was obtained as 16.44% at 3000 rpm engine speed with 20 l/min H_2/O_2 addition. Also, the maximum CO value was observed at the same engine speed and CO value decreased to 3.2% vol. from 3.83% vol. with H_2/O_2 addition. At 1500, 2000, 2500, 3000 and 3500 rpm engine speeds, there is an improvement by 12%, 5.1%, 3.5%, 16.4% and 15.2% respectively in CO emissions with H_2/O_2 addition.

Conclusion

An experimental study, which investigates the effects of hydrogen addition on emissions and performance of gasoline engine, was conducted. During the experiments, the engine run at 50% throttled position,0 and 20 l/min H_2/O_2 mixture as supplementary fuel was introduced into intake manifold where 0 l/min is referring to without hydrogen case and 20 l/min with hydrogen case. Therefore, the engine performance has been improved, THC and CO emissions have been decreased by means of the use of hydrogen as a supplementary fuel. The main conclusions are listed below:

a) Hydrogen was produced by alkaline water electrolysis, and the electrolysis was optimized in terms of energy efficiency. According to test results, 2 mm gap between plates, 28 wt% KOH solution and 3.5 V voltage were the best conditions in terms of energy efficiency (76.7% energy efficiency).
b) The maximum brake power of the engine was increased to 16.18 kW from 15.40 kW at 3500 rpm engine speed with 20 l/min H_2/O_2 enrichment. The engine brake power value increased by 3.2%–5% with hydrogen addition at all engine speeds compared to only gasoline fuel operating condition.
c) By inducting 20 l/min H_2/O_2 mixture, the maximum bsfc reduction was observed. Bsfc value was reduced from 386.3 g/kWh to 350.0 g/kWh at 1500 rpm engine speed. Bsfc value decreased by 3.2%–9.4% with H_2/O_2 addition at all engine operating gaps. The maximum brake thermal efficiency value of the SI engine was obtained at 2500 rpm engine speed with 20 l/min H_2/O_2 addition. The brake thermal efficiency was increased to 27.24% from 26.34%. The brake thermal efficiency values improved by 3.3% ila 10.4% with H_2/O_2 addition at all engine operating gaps compared to only gasoline fuel operating condition.

d) The maximum THC emission emitted by engine was dropped from 299 ppm to 225 ppm at 2000 rpm engine speed with 20 l/min H_2/O_2 induction. THC emissions improved by 9.2%–24.7% with H_2/O_2 addition at all engine cycles. The maximum CO reduction was obtained as 16.44% at 3000 rpm engine speed with 20 l/min H_2/O_2 addition. CO emissions decreased by 3.5%–16.4% with H_2/O_2 addition at all engine speeds.

e) Maximum NO_x emission value was increased from 662 ppm to 785 ppm at 2000 rpm engine speed with 20 l/min H_2/O_2 induction. NO_x emissions increased by 36.2%–15.4% with H_2/O_2 addition based on engine speed. Despite little H_2/O_2 addition (20 slpm), a drastic increase in NO_x emissions is observed.

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Nomenclature

bsfc	brake specific fuel consumption
CNG	compressed natural gas
CO	carbon monoxide
DAS	data acquisition system
ECU	electronic control unit
EGR	exhaust gas recirculation
HC	hydrocarbons
H_2	hydrogen
ICE	internal combustion engine
KOH	potassium hydroxide
LHV	lower heat value
LPG	liquefied petroleum gas
NOx	nitrogen oxides
OH^-	hydroxyl
O_2	oxygen
PEMFC	polymer electrolyte membrane fuel cell
rpm	revolutions per minute
SI	spark ignition
THC	total hydrocarbons

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