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# Effects of hydrogenation of fossil fuels with hydrogen and hydroxy gas on performance and emissions of internal combustion engines

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ABSTRACT

Energy security is an important consideration for development of future transport fuels. Among the all gaseous fuels hydrogen or hydroxy (HHO) gas is considered to be one of the clean alternative fuels. Hydrogen is very flammable gas and storing and transporting of hydrogen gas safely is very difficult. Today, vehicles using pure hydrogen as fuel require stations with compressed or liquefied hydrogen stocks at high pressures from hydrogen production centres established with large investments.

Different electrode design and different electrolytes have been tested to find the best electrode design and electrolyte for higher amount of HHO production using same electric energy. HHO is used as an additional fuel without storage tanks in the four strokes, 4-cylinder compression ignition engine and two-stroke, one-cylinder spark ignition engine without any structural changes. Later, previously developed commercially available dry cell HHO reactor used as a fuel additive to neat diesel fuel and biodiesel fuel mixtures. HHO gas is used to hydrogenate the compressed natural gas (CNG) and different amounts of HHO-CNG fuel mixtures are used in a pilot injection CI engine. Pure diesel fuel and diesel fuel + biodiesel mixtures with different volumetric flow rates are also used as pilot injection fuel in the test engine. The effects of HHO enrichment on engine performance and emissions in compression-ignition and spark-ignition engines have been examined in detail. It is found from the experiments that plate type reactor with NaOH produced more HHO gas with the same amount of catalyst and electric energy. All experimental results from Gasoline and Diesel Engines show that performance and exhaust emission values have improved with hydroxy gas addition to the fossil fuels except $NO_x$ exhaust emissions. The maximum average improvements in terms of performance and emissions of the gasoline and the diesel engine are both graphically and numerically expressed in results and discussions. The maximum average improvements obtained for brake power, brake torque and BSFC values of the gasoline engine were 27%, 32.4% and 16.3%, respectively. Furthermore, maximum improvements in performance data obtained with the use of HHO enriched biodiesel fuel mixture in diesel engine were 8.31% for brake power, 7.1% for brake torque and 10% for BSFC.



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## Introduction

In recent years, the threat of environmental security and global warming has been taken into account by the vast majority of scientists and numerous studies have been undertaken to slow down or stop the adverse effects of these factors [1–10]. Due to the depletion of fossil fuel sources and harmful environmental effects of their utilization, sustainable energy sources and energy carriers have become an important subject and hydrogen will have a crucial role to reduce dependency of fossil fuels [11–14]. When emissions are considered, it is known that hydrogen or hydroxy (HHO) gas is the cleanest source of energy among all alternative fuels. Hydroxy Gas (HHO) is formed by separating the atoms in the water molecule by electrolysis (theoretically 67% H and 33% O) as understood from the abbreviation [15]. Its calorific value is extremely high with respect to diesel and gasoline. For instance, the calorific value of 1 kg of HHO is 3 times and 3.2 times greater than gasoline and diesel fuel, respectively [16].

Dincer, I. [17], expressed that the most effective method known for producing almost pure hydrogen is water electrolysis. The electrolysis phenomena were discovered by Sir Anthony Carlisle and William Nicholson in early 1800s. They used a pair of conducting wires to connect electrodes of the Volta battery and the other ends immersed separately in the saline solution. As a result, hydrogen and oxygen have begun to accumulate at the tip of the electrode due to the water acting as a conductor [18]. There are three main different types of electrolysis, such as alkaline water, solid oxide and PEM (polymer electrolyte membrane) water electrolysis [19]. Three major issues, low partial load range, limited current density and low operating pressure, are related with alkaline electrolyzers. In this study, alkaline water electrolysis method was used. SOECs (solid oxide electrolyzer cells) gain importance because while they are producing hydrogen with high efficiency, they can convert electrical energy into chemical energy. PEMs discovered by Grubb, and they used solid sulfonated polystyrene membrane as an electrolyte [20,21]. It is known as water electrolysis by proton exchange membrane or polymer electrolyte membrane. Besides, they called solid polymer electrolyte (SPE) water electrolysis rarely [19].

PEMs also used as a fuel cell. Fuel cells operate with pure hydrogen gas, natural gas and biogas fuels. The ability of fuel cells to be used in vehicles varies according to their power generation capacity [22]. In the USA, Fuel cells have been studied for use with hydrocarbon fuels depending on the operating temperature of 500–800 °C [23–25]. Granovskii et al. [26] fuel cells stacks and ion conductive membranes applications on gas turbine cycles allow increasing electricity generation efficiency and decreasing air pollution emissions.

In recent years, exhaust emissions, which play a significant role in the hole of the ozone layer and in global warming, have been restricted by various agreements. Because of these situations, many researchers have tended to alternative fuels in internal combustion engines. Although many alternative fuels have been tried by these researchers, it appears that alternative fuel with the best performance is hydrogen. Hydrogen has many advantages over fossil fuels. The absence of carbon and other harmful substances in the first place and the abundance of compounds in nature are some of these. All exhaust emissions, except nitrogen, can be regulated by using hydrogen as a fuel. The fuel properties of hydrogen are given in Table 1 [27].

Pure hydrogen could be used as a fuel in S.I. engine solely with higher efficiency and higher power outputs [28]. But there are some severe disadvantages of using hydrogen as a fuel in S.I. engine e.g. engine knock, pre-ignition and $NO_x$ emission [29]. The using of hydrogen as an alternative in C.I. engines is defined as a new concept. Due to the high ignition temperature (858K) hydrogen cannot be ignited without any spark or additives. The methods of hydrogen usage in CI engines are air enrichment with hydrogen, directly injection into the intake system and in-cylinder injection [30].

Other researchers have examined the use of hydrogen, natural gas and their mixtures in internal combustion engines in terms of second law analysis [31]. Rakopoulos et al. were investigated the exergy efficiency of hydrogen and natural gas fuel blends for direct injection CI engine. The results showed that as the engine load increased, the irreversibility generation of the engine decreased [32].

Many studies have performed on dual fuel engines to investigate performance and emission characteristics of different alternative energy sources with diesel as a pilot source of ignition. Saravanan et al. used hydrogen as a source of energy and diesel as a source of ignition in their work. Their results indicated that CO, $CO_2$ and HC values were reduced at negligible concentrations, although engine efficiency was increased [27]. Shitole at al. used HHO gas for the air enrichment in C.I. engine by 1 lpm. Their results were indicated that thermal efficiency, power and specific fuel consumption values were improved however, $NO_x$ formation was increased due to high flammability of hydrogen [33]. Verde and Frame performed a research about dual fuel mode. They obtained some improvements of performance parameters.

Kumar et al. investigated the combustion process effects of hydrogen enrichment on single-cylinder diesel-engine using biodiesel from vegetable oil in their study. The experimental results showed that the brake thermal efficiency was improved by 2% when used 7% of hydrogen by mass at

**Table 1 – The properties of hydrogen.**

| Properties | Diesel | Unleaded gasoline | Hydrogen |
|---|---|---|---|
| Autoignition temperature (K) | 530 | 533–733 | 858 |
| Minimum ignition energy (mJ) | – | 0.24 | 0.02 |
| Flammability limits (volume % in air) | 0.7–5 | 1.4–7.6 | 4–75 |
| Stoichiometric air–fuel ratio on mass basis | 14.5 | 14.6 | 34.3 |
| Limits of flammability (equivalence ratio) | – | 0.7–3.8 | 0.1–7.1 |
| Density at 16 °C and 1.01 bar (kg/m$^3$) | 833–881 | 721–785 | 0.0838 |
| Net heating value (MJ/kg) | 42.5 | 43.9 | 119.93 |
| Flame velocity (cm/s) | 30 | 37–43 | 265–325 |
| Quenching gap in NTP air (cm) | – | 0.2 | 0.064 |
| Diffusivity in air (cm$^2$/s) | – | 0.08 | 0.63 |
| Research octane number | 30 | 92–98 | 130 |
| Motor octane number | – | 80–90 | – |

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