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HYDROXY GAS AS AN ADDITIVE FOR IMPROVEMENT OF EXHAUST EMISSIONS OF INTERNAL COMBUSTION ENGINES – A REVIEW

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Abstract
Lowering emissions expelled from internal combustion engines has been the focus of researchers worldwide. Adding hydroxy gas to current internal combustion engines can be an effective way of lowering CO_2, CO, HC and particle emissions, as well as improve combustion. Because of this, a review of previously conducted research on the addition of hydroxy gas to different internal combustion engines has been produced. During this review, it was concluded that addition of hydroxy gas can be an effective way of lowering fuel consumption and CO, CO_2 and HC emissions in petrol engines, as well as fuel consumption and CO and HC emissions in diesel engines.
Key words: Hydrogen, Hydroxy, Emissions, Exhaust gases, Internal combustion engine.

Introduction

Worldwide, the total amount of motor vehicles is constantly increasing. According to the International Energy Outlook 2021, liquid fuels such as petroleum fuel remain as the largest energy source (Energy Information Administration, 2021). International Energy Outlook 2019 has projected that liquid fuel consumption is expected to increase by approximately 50% between 2019 and 2050 (Energy Information Administration, 2019). Fossil fuels are the main fuels used in the automotive sector, both in personal vehicles and industrial machinery. The biggest drawbacks of these fuels are the large amounts of toxic components in the exhaust. Besides of that the source of fossil fuels, crude oil, is being depleted at a fast pace. Since the demand of energy is constantly increasing, but the source of this energy is depleting rapidly, the use of alternative and renewable energy sources is required.

A good alternative to traditional fossil fuels is hydrogen gas. It contains zero carbon, making it a clean burning fuel. Additionally, it has a high combustion efficiency (Ma *et al.*, 2007). Hydrogen gas can be generated from various sources, such as water, coal, biomass, and fossil fuels. Hydrogen fuel is renewable, and it is an efficient and clean fuel that can be used for multiple applications, mainly as an additive or substitute for fossil fuels. However, the usage of hydrogen gas in vehicles can be challenging because of the difficulty of storing hydrogen gas in its liquid state at low temperatures or in its gaseous state at high pressure. Moreover, any damage caused to such systems can have disastrous consequences as hydrogen gas is highly flammable. Because of these safety concerns, researchers are proposing the use of a different form of hydrogen gas that can be created on-board of the vehicle, such as hydroxy gas, also known as Brown's gas.

Hydroxy or HHO gas consists of a mix of hydrogen and oxygen with a stoichiometric ratio of 2:1. HHO gas is mainly produced via water electrolysis (Newborough & Cooley, 2021). It has been used as a fuel additive in various researches using both petrol and diesel engines. Researchers have found that using HHO gas as an additive in regular internal combustion engines has resulted in a 10% increase in thermal efficiency, up to 34% decrease in fuel consumption and a reduced concentration of nitrogen oxides (NO_x), carbon monoxide (CO) and hydrocarbon (HC) emissions in petrol engines (El-Kassaby *et al.*, 2016) and 41% reduction of particle emissions, 13.5% reduction of CO emissions and 5% reduction of HC emissions in diesel engines (Bari *et al.*, 2022; Yilmaz *et al.*, 2010).

Materials and Methods

A monographic research method has been used in this research, in order to summarize and analyze the impact of adding hydroxy gas to internal combustion engines in order to reduce toxic emissions. This research combines scientific literature from various journals and authors. Articles from scientific journals published from 2007 to 2023 were used, while more recent research was favored. The use of research that was recent and contained the use of dry cell hydroxy generators was favored, as this method is better suited for use in automotive applications. Multiple articles were analyzed, and articles that contained similarly conducted research were selected for the review.

Results and Discussion

Hydroxy gas

Hydroxy gas is extracted from water by splitting water into two molecules of hydrogen and one molecule of oxygen via the process of electrolysis. The process is caried out in an electrolytic cell. Hydroxy gas has a low density of 0.5378 $kg \cdot m^{-3}$. That means, hydroxy gas is lighter than air, and in open environment it will rapidly disperse (Paparao & Murugan, 2021).

The comparison between hydroxy gas and other gaseous fuels can be seen in Table 1. Based on the data in Table 1 it can be concluded that hydroxy gas can be used as a gaseous fuel in internal combustion engines in a wide array of air-fuel ratios. As it contains hydrogen, it also requires less energy to be ignited. Since hydrogen has high diffusivity, hydroxy gas can mix well in the air-fuel mixture, resulting in a uniform mixture. A major drawback for hydroxy gas is that it has a low quenching distance, which creates a large possibility for backfire. And finally, since hydroxyl gas contains hydrogen, it has higher flame speeds, that require a safer engine operation to avoid damage.

Hydroxy generators

The easiest way to produce hydroxy gas on-board a vehicle is by electrolysis of water mixed with an electrolyte, for example sulfuric acid (H_2SO_4), potassium hydroxide (KOH) or sodium hydroxide (NaOH).

Table 1

Comparison between gaseous fuels (Paparao & Murugan, 2021)

Properties	Hydroxy	Hydrogen	Methane	Propane	Butane	Biogas
Chemical Formula	HHO	H2	CH4	C3H8	C4H10	-
Density ($kg \cdot m^{-3}$) at 16 °C and 1.01 bar	0.5	0.1	0.7	0.5	2.5	0.7-0.9
Molecular weight	12.0	2.0	16.0	44.1	58.1	16.6
Lower heating value ($MJ \cdot kg^{-1}$)	13.2	119.9	47.1	45.6	45.3	23
Higher heating value ($MJ \cdot kg^{-1}$)	25.9	142.2	52.2	50.36	49.1	-
Flame Velocity ($cm \cdot s^{-1}$)	265-325	265-325	42	46	87	20
Diffusivity in air ($cm^2 \cdot s^{-1}$)	0.6	0.6	0.3	-	-	-
Stoichiometric Air-Fuel Ratio	-	34.3	17.2	15.7	15.5	17
Octane Number	-	130+	100	105	92	130
Motor Octane Number (MON)	-	-	120	97	-	-
Auto-ignition temperature (°C)	-	585	565	490	287	650
Flash Point (°C)	-	-253	-188	-104	-60	>230
Boiling Point (°C)	-	-253	-161.5	-42	-0.5	-
Melting Point (°C)	-	-259	-182	-188	-135	--
Flammability limits (Volume % in air)	4-95	4-75	5-15	2.1-10.1	-	-

The gas can be produced via a dry cell HHO gas generator, principles of which are shown in Figure 1, or wet cell hydroxy generators, shown in Figure 2.

As seen in Figure 1, the water and electrolyte mixture is filled into the tank. The mixture then fills up the HHO generator. Power is supplied to the generator from the vehicle battery, and the process of electrolysis begins. The gas, containing both hydroxy and water/electrolyte vapors is then transported back to the tank, where vaporized water and electrolyte mixes back into the liquid water/electrolyte mixture, but the hydroxy gas rises to the top and is expelled from the tank. This gas is ready to be injected into the engine.

In the case of wet cell hydroxy generators, the cathode and anode are submerged in the tank containing the water and electrolyte mixture, and power is supplied to them from the battery. The HHO gas emitting from the electrolysis process rises above the water level, and then is ready for injection into the engine.

When compared, the dry cell generator has a smaller volume, so a smaller amount of water and electrolyte mixture is needed for the reaction to happen. However, using wet cells, the electrical connections are submerged in the water and electrolyte mixture, reducing the time it takes for the connections to corrode (Shah *et al.*, 2018).

Overall, comparing both generators, the dry cell generator would be more acceptable for the use in automotive applications, as the tank for water and electrolyte mixture can be stored separately and the generator itself and the whole assembly can be better integrated in the vehicle.

As seen in Table 2, the addition of hydroxy gas in engines can be an effective way for reduction of CO, HC and NOx emissions, and decreasing the fuel consumption in petrol engines and smoke opacity in diesel engines.

However, to achieve optimal results, the modification of engine control parameters is necessary, mainly the modification of fuel delivery.

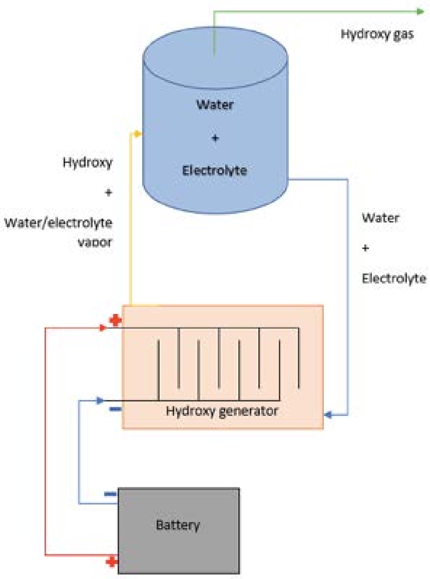

Figure 1. Operation of a dry cell hydroxy generator.

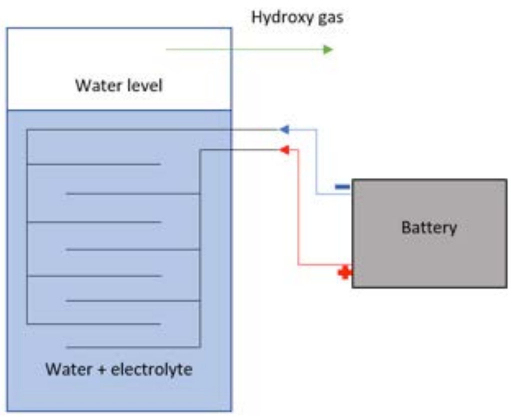

Figure 2. Operation of a wet cell hydroxy generator.

Results of adding hydroxy gas to internal combustion engines

Table 2

Results of adding hydroxy to engines

Author	Vehicle/engine used	Fuels used	Results obtained
Mohamed M. EL-Kassaby (El-Kassaby *et al.*, 2016)	Skoda Felicia 1.3l GLXi	Petrol Petrol + HHO gas	10% increase in thermal efficiency 34% decrease in fuel consumption 15% reduction in NO_x emissions 18% decrease in CO emissions 14% decrease in HC emissions
František Synak (Synák *et al.*, 2021)	Skoda Felicia 1.3 MPI	Petrol LPG Petrol + HHO gas LPG + HHO gas	No effect on CO concentration Slight increase in HC concentration When driving on petrol, no effect on CO_2, O_2 and NO_x. On LPG and HHO gas, CO_2 concentration increased.
	Skoda Fabia 2 1.4 MPI	Petrol LPG Petrol + HHO gas LPG + HHO gas	Adding HHO gas to both petrol and LPG resulted in slight decrease in CO concentration.
	Kia Ceed 1.6 CVVT	Petrol E85 Petrol + HHO gas E85 + HHO gas	Adding HHO gas resulted in slight decrease of engine power and torque. Specific fuel consumption increased after adding HHO gas. When used with E85, the addition of HHO gas did not result in changes to engine power and torque.
	Skoda Felicia 1.9D	Diesel Diesel + HHO gas	Engine power and torque were not affected. Increase in NO_x levels from 8 ppm to 29 ppm. Slight reduction in smoke opacity.
	Kia Sportage 1.6 CRDI	Diesel Diesel + HHO gas	Slight decrease in engine power and torque. Slight increase in HC from 8 ppm to 11 ppm. 14.46% reduction in CO_2 emissions. CO and NO_x levels are unchanged.

Continuation of the Table 2

Zhe Zhao (Zhao *et al.*, 2022)	VW EA888 engine	Petrol Petrol + HHO gas	With λ = 1, CO emissions decrease by 18%. With λ = 1.1, CO emissions decrease by 91.67%. With λ = 1.4, CO emissions decrease by 92.38%. With λ = 1, HC emissions decrease by 17.18%. With λ = 1.1, HC emissions decrease by 20.52%. With λ = 1.4, HC emissions decrease by 32.8%. NO emissions increase when th mixture is lean (λ = 1.1 and λ = 1.4).
Sa'ed A. Musmar (Musmar & Al-Rousan, 2011)	Honda G200 0.7l single cylinder engine	Petrol Petrol + HHO gas	Increase in thermal efficiency with HHO gas added. Decrease in specific fuel consumption with HHO gas added. 50% reduction in NO emissions 20% reduction in CO emissions 54% reduction in NO_x emissions
Saiful Bari (Bari *et al.*, 2022)	Cummins 6BT5.9-G2 engine	Diesel Diesel + HHO gas	Average 41% reduction in particle matter No impact on performance parameters No significant reduction in CO_2 emissions CO emissions were reduced by 5.5%, 3.4% and 2.32% (at 0.42 LPM, 0.84 LPM and 1.25 LPM hydroxy addition). No significant change in NO_x emissions.
Ali Can Yilmaz (Yilmaz *et al.*, 2010)	3567 cm^3 4-cylinder direct-injection diesel engine	Diesel Diesel + HHO gas	19.1% Increase in engine power 14% reduction in specific fuel consumption is achieved 5% reduction in HC emissions 13.5% reduction in CO emissions
Jorge M. Rodriguez Matienzo (Rodríguez Matienzo, 2018)	LISTER PETTER LPW2 engine	Diesel Diesel + HHO gas	3.81% increase in engine power 2.79% increase in engine torque At low and medium load, brake specific fuel consumption is reduced in a range of 2.66% to 9.29%. Lower vibration levels that indicate smoother combustion.
Mohamed F. Al-Dawody (Al-Dawody *et al.*, 2023)	Kirloskar TAF-1 0.553 l diesel engine	Diesel Diesel + 10% HHO gas	9% to16% increase in brake power (from 1500 to 3500 RPM) 31.5% increase in thermal efficiency 20% reduction in fuel consumption Decrease in NOx emissions
Mohammad Sabeghi (Sabeghi *et al.*, 2022)	8CRZ 2800 cm^3 diesel engine	Diesel Diesel + HHO gas	66% reduction in CO emissions 33% reduction in CO_2 emissions 38% decrease in HC emissions 11% decrease in NO_x emissions
Piotr Jaklinski (Jakliński & Czarnigowski, 2020)	Fiat Cinquecento 170A.000	Petrol Petrol + HHO gas	1% increase in NO_x emissions 24% reduction in HC emissions 34% increase in CO emissions
	Renault Twingo 1149 cm^3	Petrol Petrol + HHO gas	17% reduction in NO_x emissions 45% reduction in HC emissions 20% reduction in CO emissions
	Opel Corsa 1398 cm^3	Petrol Petrol + HHO gas	50% reduction in NO_x emissions 35% reduction in HC emissions No change in CO emissions
	Skoda Octavia 1896 cm^3	Diesel Diesel + HHO gas	10% increase in NO_x emissions 80% increase in HC emissions 95% decrease in CO emissions
	Opel Combo 1248 cm^3	Diesel Diesel + HHO gas	100% increase in NO_x emissions 37% decrease in HC emissions No change in CO emissions

Comparing results, it can be observed, that in cases where the fuel delivery system has been left unmodified, the obtained improvements are significantly reduced.

Hydroxy gas contains hydrogen that is a type of fuel by itself. Therefore leaving an engine unmodified and adding hydroxy gas could result in an overall increase in fuel delivery without leaving significant decrease in emissions, fuel consumption or smoke opacity.

Adding hydroxy gas to the air-fuel mixture can reduce specific fuel consumption, thanks to the additional oxygen contained in hydroxy gas. This results in enhanced combustion efficiency and lower fuel consumption. Hydroxy gas also provides a more homogenous mixture with air and dissolves better with the fuel-air mixture which further increases efficiency of combustion (Aydin & Kenanoğlu, 2018).

Multiple researchers claimed that the addition of hydroxy gas resulted in reduced vibration and smoother work of the test engines. This is due to the fact that hydrogen has a very high flame speed that positively affects the combustion process. Hydrogen has a high auto-ignition temperature, which means the main fuel is ignited first, and that ignites the hydrogen gas that then ignites the remaining unburnt fuel, resulting in smoother and more complete combustion.

Exhaust gas emissions

Consumption of fossil fuels creates a large number of harmful and toxic pollutants that are one of the main causes of global warming. These pollutants include carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), particulate matter (PM).

The consumption of 1 liter of petrol in an internal combustion engine creates at least 2.28 kg of carbon dioxide. In diesel engines, at least 2.76 kg of CO_2 is emitted from each liter of diesel fuel (Pinto & Oliver-Hoyo, 2008). Carbon monoxide is produced from partial oxidation of carbon. CO production is higher if the engine is in poor technical condition, there is limited oxygen or if the engine has not reached proper working temperature. Nitrogen oxides are created in high pressure and high temperature conditions, especially if the air-fuel mixture is lean. Nitrogen oxides include nitrous oxide (N_2O), that depletes the ozone layer and is toxic, nitrogen oxide (NO) that is responsible for the creation of smog and acid rains and nitrogen dioxide (NO_2) that is irritating and also causes smog. Particulate matter is produced in cases of local oxygen deficiency, resulting in free carbon molecules that connect with free hydrocarbons and form larger particles. Particulate matter can cause respiratory diseases in humans (Synák *et al.*, 2021).

The use of hydroxy gas additive can be used to improve emissions, resulting in a decrease in smog formation, decrease in greenhouse gas emissions and slow down global warming.

Adding hydroxy gas to diesel engines can result in an increase in NO_x emissions, because the added hydrogen increases the total amount of fuel and energy. The combustion speed is increased, and so is the temperature and pressure inside the cylinder, which results in an increase in NO_x emissions. In petrol engines, at low load conditions the addition of hydroxy gas does not increase the temperature significantly, so no major changes in NO_x emissions can be observed (Jakliński & Czarnigowski, 2020). If the fuel management system is adjusted for the added hydrogen and the air/fuel mixture is made leaner, NOx emissions can be reduced.

CO and CO_2 emissions are byproducts of combustion, resulting from the oxidizing of carbon present in the fuel. Hydroxy gas does not contain carbon, which causes the reduction in CO and CO_2 emissions. Additionally, the addition of hydroxy gas makes the air-fuel mixture burn faster and more completely, resulting in further reduction in CO and CO_2 reduction (Yilmaz *et al.*, 2010).

At higher engine rotation speeds, the reduction of HC emissions becomes less visible. The time, intake valves are kept open, is becoming shorter, so sufficient amount of air cannot be supplied to the engine. This results in a decrease in combustion efficiency and lower improvements in HC emissions (Aydin & Kenanoğlu, 2018).

Diesel engines contain particle matter emissions, that are comprised of carbon soot particles. They are created inside the cylinder during combustion in fuel rich areas. Adding hydroxy gas adds oxygen that helps in combustion of soot particles in fuel rich areas, as well as hydrogen that increases the temperature of combustion and accelerates the oxidation of particle matter, resulting in an increased amount of CO_2 emissions (Bari *et al.*, 2022). Since hydroxy gas does not contain carbon, the overall amount of CO_2emissions still remains lower when compared to traditional petrol or diesel combustion without added hydroxy gas.

Conclusions

The following conclusions can be drawn from the analysis of addition of hydroxy gas to internal combustion engines:

1. Addition of hydroxy gas can be an effective way of lowering fuel consumption and CO, CO_2 and HC emissions in petrol engines.
2. Addition of hydroxy gas can be an effective way of lowering fuel consumption and CO and HC emissions in diesel engines, as well as a reduction in smoke opacity.
3. When used in diesel engines, the addition of

hydroxy gas could increase NO_x emissions.
4. Specific fuel consumption can be reduced via the addition of hydroxy gas.
5. Thermal efficiency of both petrol and diesel engines can be improved via the addition of hydroxy gas.
6. Smoother combustion can be observed with the addition of hydroxy gas.

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