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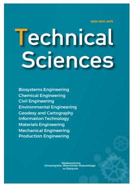

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AN ASSESSMENT OF THE POTENTIAL OF BROWN'S GAS (HHO) TO REDUCE DIESEL FUEL CONSUMPTION IN SMALL ENGINES

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K e y w o r d s: Brown’s gas, HHO, diesel engine, fuel consumption, electrolyzer, energy balance, stationary generator.

A b s t r a c t

This study evaluates the effect of Brown’s gas (HHO), produced by water electrolysis, on diesel fuel consumption in a small compression-ignition engine driving a stationary generator set. The tests were performed under six electrical load conditions and three fuelling variants: diesel fuel only, diesel with approximately 117 l/h HHO, and diesel with approximately 140 l/h HHO. Diesel fuel consumption was measured gravimetrically, while HHO flow rate and electrolyzer electrical demand were monitored during the measurements. The results indicate that HHO addition may reduce the measured diesel fuel consumption under selected operating conditions; however, the magnitude of this reduction is limited and depends on load and HHO flow rate. Moreover, the electrical power required to generate HHO exceeded the energetic benefit resulting from the observed diesel fuel savings. Therefore, the tested on-board-type HHO system should not be considered energetically or economically justified when powered from the vehicle electrical system. The study contributes a practical assessment of a commercially available HHO kit under stationary-engine operating conditions, with particular emphasis on the energy balance of the system.

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Introduction

The prevailing trend across all industries and modes of transportation today is to achieve the greatest possible environmental neutrality. This trend has not bypassed power machinery, particularly internal combustion engines. Currently, many automotive companies are striving to reduce harmful exhaust emissions. To address this issue, engineers are attempting to implement various changes, ranging from designing more efficient engines to experimenting with alternative fuels. One such option is adding HHO gas, also known as Brown's gas to a standard gasoline or diesel engine.

HHO gas, which consists of a mixture of hydrogen (H_2) and oxygen (O_2) (BASTAWISSI et al. 2022), is produced through the process of water electrolysis. This process typically involves an electrolyzer in which water (H_2O) is subjected to a direct electric current. At the molecular level, water electrolysis can be described by chemical reaction equations.

Reaction occurring at the cathode is a reduction reaction in which hydrogen ions from water are converted into gaseous hydrogen:

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \tag{1}$$

At the anode, an oxidation reaction takes place, in which hydroxide ions are converted into oxygen:

$$2OH^- \rightarrow H_2O + \frac{1}{2}O_2 + 2e^- \tag{2}$$

Combining these reactions leads to the general equation for the electrolysis of water:

$$2H_2O \rightarrow 2H_2 + O_2 \tag{3}$$

Various electrolytes are used in the electrolysis process to improve the electrical conductivity of the solution. The most commonly used are solutions of alkaline hydroxides, such as potassium hydroxide (KOH) or sodium hydroxide (NaOH), which significantly increase the reaction efficiency (NAQVI et al. 2022, DAVID et al. 2019). Experiments indicate that the efficiency of the electrolysis process is influenced by many factors, including temperature, current density, and the type of electrolyte used (EL-RAZIK et al. 2023, SCHALENBACH et al. 2016).

The use of an electrolyzer enables the production of HHO in gaseous form, which is used as an alternative energy source, including in internal combustion engines (SUBRAMANIAN, ISMAIL 2018). Gas production efficiency depends not only on the type of electrolyte used, but also on the type of electrodes and the design of the device itself (SUBRAMANIAN et al. 2022, WANG et al. 2022).

In terms of emissions, the use of HHO in diesel engines has shown a significant reduction in harmful substances. Studies indicate that HHO supplementation can reduce emissions of carbon monoxide (CO) and hydrocarbons (HC) by an average of 18% and 14%, respectively (NGUYEN et al. 2021, YANG et al. 2022, THANGARAJ, NAGARAJAN 2022). The increase in combustion efficiency is attributed to the oxidizing properties of oxygen radicals in HHO, which accelerate the breakdown of harmful substances during combustion (LIU et al. 2016). Furthermore, experiments conducted by GOHAR and RAZA demonstrated that HHO contributes to cleaner combustion, thereby achieving a nearly smoke-free emission profile, thanks to its carbon-free composition (GOHAR, RAZA 2017).

Optimal applications of HHO were analyzed, particularly with regard to engine modifications and operating parameters. For example, studies have successfully implemented HHO in both single- and dual-fuel configurations, often with diesel acting as a pilot fuel, highlighting the role of HHO in enhancing combustion stability and efficiency under varying engine loads (MULK et al. 2025, GOVINDHAN et al. 2021, MORENO-GAMBOA et al. 2023). Furthermore, the integration of HHO with exhaust gas recirculation (EGR) systems has also been analyzed, demonstrating improved combustion characteristics and further reductions in NOx emissions (KATHIRVEL et al 2022).

Safety and practicality issues related to the production and storage of HHO were also discussed. The on-site production of HHO via electrolysis eliminates the risks associated with storing hydrogen under high pressure, as it allows the gas to be generated directly on demand (THANGARAJ, NAGARAJAN 2017). Various studies detail safety protocols related to the implementation of HHO systems in vehicles, ensuring that additional risks are minimized while leveraging the benefits of improved fuel efficiency (NABIL 2019).

Research is ongoing, focusing on optimizing HHO injection parameters, including flow rates and mixing ratios with standard diesel fuels. Furthermore, comparative analyses of the impact of both hydrogen and HHO on exhaust emissions suggest that HHO may offer even more favorable results than hydrogen alone, mainly due to the dual chemical properties of oxygen and hydrogen during combustion processes (SUBRAMANIAN et al. 2020, RIMKUS et al. 2012).

Previous studies have widely investigated the influence of hydrogen or HHO addition on engine performance and exhaust emissions. However, fewer studies focus on the practical limitations of compact, commercially available HHO generators intended for vehicle installation, especially when their electrical power demand is included in the overall assessment. In real applications, the potential reduction in diesel fuel consumption should be evaluated together with the energy required to operate the electrolyzer, because this demand is ultimately supplied by the engine-driven electrical system. Therefore, the novelty of this study lies not in demonstrating the general combustibility of HHO, but in assessing whether a small on-board-type HHO generator can provide a net practical benefit when applied to a simple stationary compression-ignition engine under controlled load conditions.

The purpose of this study was to analyze the influence of HHO addition on diesel fuel consumption in a compression-ignition engine and to assess the net energy balance of using a compact electrolyzer powered under vehicle-like electrical conditions. Additionally, tests were conducted to determine the relationship between HHO flow rate, engine load, diesel fuel consumption, and electrolyzer power demand.

Research methodology and procedures

Methodology

The experimental methodology was based on comparing diesel fuel consumption of a small compression-ignition engine operating under controlled electrical load conditions. Three fuelling variants were investigated: diesel fuel only, diesel fuel with approximately 117 l/h HHO, and diesel fuel with approximately 140 l/h HHO. The HHO generator was powered from an external power supply to enable independent determination of its electrical power demand and to avoid interference with the generator load.

Test stand and measurement equipment

The test stand consisted of a KIPOR/KIPOR KDE 3500 E single-phase generator set equipped with a single-cylinder, four-stroke compression-ignition engine with direct fuel injection. According to the technical specification, the generator operated at 3000 rpm and had a nominal electrical power of 2.8 kW and a maximum power of 3.2 kW. The engine nominal and maximum powers were 3.68 kW and 4.42 kW, respectively.

The electrical load was generated using five resistive 500 W loads connected independently, which allowed the generator load to be changed from 0 to 2500 W in 500 W steps. HHO was supplied to the intake system from an OGO-DC43721 electrolyzer. The electrolyzer was powered by an external Telwin Computer 48/2 power supply operating at 12 V. During the tests, the current drawn by the electrolyzer was recorded in order to determine its electrical power demand.

Diesel fuel consumption was determined gravimetrically. The external fuel tank was placed on a scale with a resolution of 1 g. Fuel mass was recorded before each 10-minute measurement cycle and after the cycle; an additional reading was taken after 5 minutes to check the stability of fuel consumption during the test. HHO flow rate was controlled using rotameters and was set to approximately 117 l/h and 140 l/h in the two HHO-assisted test variants.

Procedures

The laboratory tests were conducted on a KIPOR KDE 3500 E generator set powered by a compression-ignition engine. The internal combustion engine was controlled by a mechanical governor, whose function is to maintain a constant crankshaft speed. A load system consisting of five 500-watt loads, each activated by individual switches, was connected to the generator. This setup allowed for loading the generator in 500-watt increments within the range of 0–2500 watts. An HHO gas supply line from the OGO-DC43721 electrolyzer was connected to the engine's intake system. The HHO generator used in the study was taken from a kit designed for installation in internal combustion engine vehicles. To avoid interference with the entire measurement system, it was decided to power the electrolyzer from an external power supply, which allowed for the reading of voltage values and the current drawn by the electrolyzer. The fuel tank was placed on a scale. The mass of diesel fuel consumed by the engine during each measurement cycle was monitored. Before each measurement series, the engine was warmed up and operated until stable speed and generator voltage were obtained. Measurements were then performed at constant electrical load. For each fuelling variant, three independent measurement series were carried out. Each series included six load points: 0, 500, 1000, 1500, 2000 and 2500 W. At each load point, the engine operated for 10 minutes. Fuel mass was recorded at the beginning, after 5 minutes, and after 10 minutes. The HHO flow rate was monitored throughout the measurement cycle. The HHO generator was powered from an external supply to avoid direct interference with the generator electrical load and to allow independent determination of voltage, current and power demand of the electrolyzer. The temperature of the electrolyte and detailed in-cylinder combustion parameters were not measured; therefore, the study focuses on external fuel consumption and system energy balance rather than on a detailed combustion analysis.

The main source of measurement uncertainty was the gravimetric determination of diesel fuel consumption. Since the fuel mass was measured with a scale resolution of 1 g, the relative uncertainty was highest at low loads, where the 10-minute fuel consumption was the lowest. For example, at idle conditions the measured fuel consumption was approximately 50 g per cycle; therefore, a 1 g resolution corresponds to about 2% of the measured value. At the highest load, where the fuel consumption exceeded 120 g per cycle, the relative influence of scale resolution was below 1%. Consequently, small differences between test variants at low loads should be interpreted with caution. The repeatability of the results was assessed by performing three measurement series for each fuelling variant.

Results and their analysis

After conducting the tests and compiling the results from all of them, graphs of diesel fuel consumption were plotted for a given Brown gas dosage. Figure 1 shows the results of diesel fuel consumption measurements during all test series as a function of the generator's load.

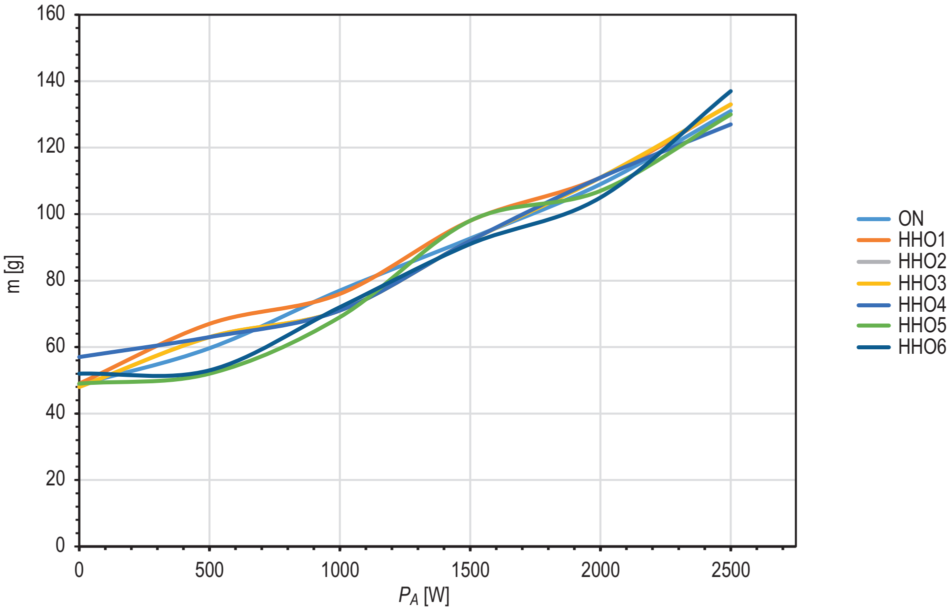

Fig. 1. Mass of diesel fuel consumed M during the measurement cycle as a function of the generator set's load P_A

For each load and fuelling variant, the mean diesel fuel consumption and standard deviation were calculated from three repeated measurement series. The standard deviation was used as a measure of repeatability of the obtained results and was calculated according to the following equation:

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{(n-1)}} \tag{4}$$

where:
SD – standard deviation;
x_i – value obtained in an individual measurement series;
$\bar{x}$ – arithmetic mean;
n – number of repeated measurements.

This allowed the repeatability of the measurements to be assessed and made it possible to compare the observed fuel-consumption differences with the measurement scatter. The results are summarized in Table 1.

Table 1
Mean diesel fuel consumption and standard deviation for each engine load and fuelling variant

Generator load [W]	Diesel only [g/10 min]	HHO 117 l/h [g/10 min]	HHO 140 l/h [g/10 min]
0	52.0 ± 0.0	48.3 ± 0.6	48.7 ± 3.5
500	63.0 ± 1.0	62.7 ± 0.6	54.7 ± 3.8
1000	77.0 ± 1.0	71.7 ± 1.2	71.3 ± 2.1
1500	92.7 ± 1.5	92.3 ± 0.6	89.7 ± 1.5
2000	109.0 ± 1.0	111.3 ± 0.6	106.7 ± 1.5
2500	131.0 ± 1.7	133.3 ± 0.6	129.7 ± 1.5

Source: own elaboration.

The standard deviation values were generally low, which indicates acceptable repeatability of the gravimetric measurements. However, at low loads the relative effect of the scale resolution was higher; therefore, small differences between fuelling variants at these operating points should be interpreted with caution.

Based on the amount of diesel fuel consumed, the engine crankshaft speed, and the duration of the measurement cycle, the fuel injection volume per cycle was determined using the following equation:

$$d_{ON} = \frac{m}{C \cdot \rho_{ON}} = \frac{m}{\frac{n \cdot t}{2} \cdot \rho_{ON}} = \frac{2m}{n \cdot t \cdot \rho_{ON}} \left[\frac{l}{cycle}\right] \tag{5}$$

where:
m – amount of fuel consumed [g];
C – number of operating cycles [–];
n – engine crankshaft speed [rev/min];
ρ_{ON} – fuel density [g/l];
t – cycle duration [min].

The amount of HHO gas per operating cycle of the tested engine was determined using the following equation:

$$d_{HHO} = \frac{V}{C} = \frac{\frac{Q}{6}}{\frac{n \cdot t}{2}} = \frac{2Q}{6 \cdot n \cdot t} \quad [l/cycle] \tag{6}$$

where:

V – volume of gas consumed HHO [l];
Q – gas flow HHO [l/h].

To determine the proportions of the two fuels during individual measurement cycles, a measure in the form of a coefficient λ_{HHO} was introduced, expressed by the following equation:

$$\lambda_{HHO} = \frac{d_{HHO}}{d_{ON}} [-] \tag{7}$$

where:

d_{HHO} – volume of HHO gas per engine cycle [l/cycle];
d_{ON} – the volume of diesel fuel per engine cycle [l/cycle].

Based on the recorded fuel consumption and the average power output of the generator set during the measurement cycle, the specific diesel fuel consumption of the generator set's engine was calculated using the following equation:

$$g_{eON} = \frac{G_{eON}}{P} = \frac{\frac{m_{ON}}{T}}{P} \quad \left[\frac{\text{g}}{\text{kWh}}\right] \tag{8}$$

where:

G_{eON} – hourly diesel fuel consumption [g/h];
P – average load capacity of the unit [kW];
m_{ON} – mass of diesel fuel consumed during the measurement cycle [g];
T – duration of the measurement cycle [h].

Figure 2 shows the changes in specific fuel consumption as a function of the fuel ratio coefficient λ_{HHO} for different load conditions.

Analysis of the graph shown in Figure 2 indicates that, for every set load value, it is possible to determine a value of the λ_{HHO} coefficient at which specific fuel consumption reaches its minimum. The results suggest that HHO addition influences the measured diesel fuel consumption of the tested engine. However, because the observed differences are relatively small, their interpretation should take into account the repeatability of the measurements and the uncertainty of the gravimetric method.

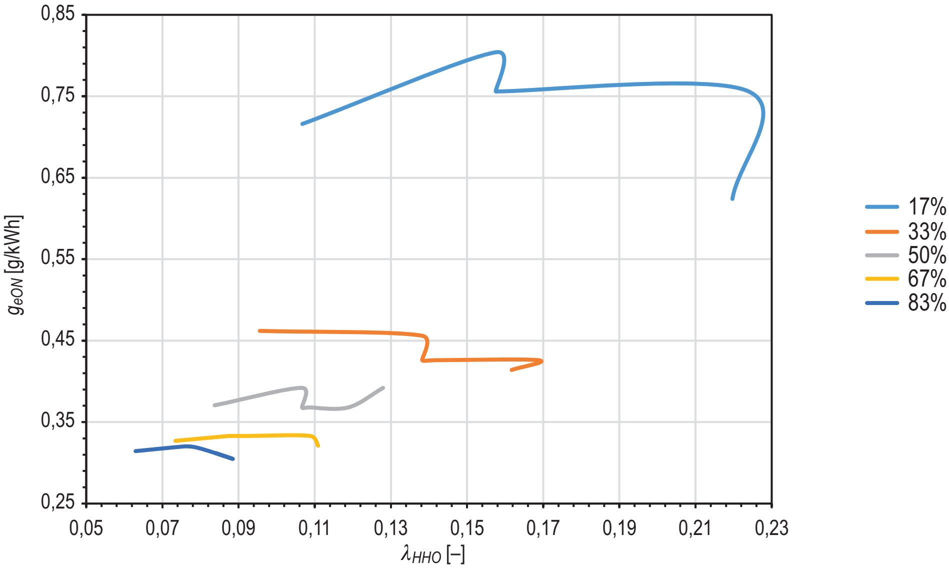

Fig. 2. The relationship between the specific fuel consumption g_{eON} and the fuel ratio λ_{HHO} and the percentage load of the test engine

An analysis was also conducted of the effect of engine load P and the flow rate Q of HHO gas supplied to the engine on the specific fuel consumption g_{eON}, as illustrated by the graph shown in Figure 3.

An analysis of the graph (Fig. 3) shows that specific diesel fuel consumption decreases as engine load increases. The decrease in specific diesel fuel consumption with increasing load is typical for small diesel engines operating at low and medium loads. Under higher loads, the results indicate a relationship between HHO flow rate and the measured diesel fuel consumption. However, because in-cylinder combustion parameters and exhaust emissions were not measured in this study, the observed reduction in fuel consumption should not be interpreted as direct evidence of improved combustion efficiency.

The profitability of installing an HHO gas generation system in vehicles was also calculated. To this end, the power consumption of the electrolyzer was determined. Given that the most favorable results were obtained at the highest flow rates of added HHO gas, the analysis focused on the power consumption values of the electrolyzer operating at flow rates in the range of 117–140 [l/h]. For a flow rate of 117 [l/h], the current draw was 16 [A], while for a flow rate of 140 [l/h], the current draw was 24 [A]. In all cases, the voltage supplied by the power supply was 12 [V], similar to that found in the electrical systems of most motor vehicles. In both cases, the power was determined based on the following relationship:

$$P = U \cdot I \qquad [W]$$

where:

U – the device's supply voltage [V];

I – current drawn by the device [A].

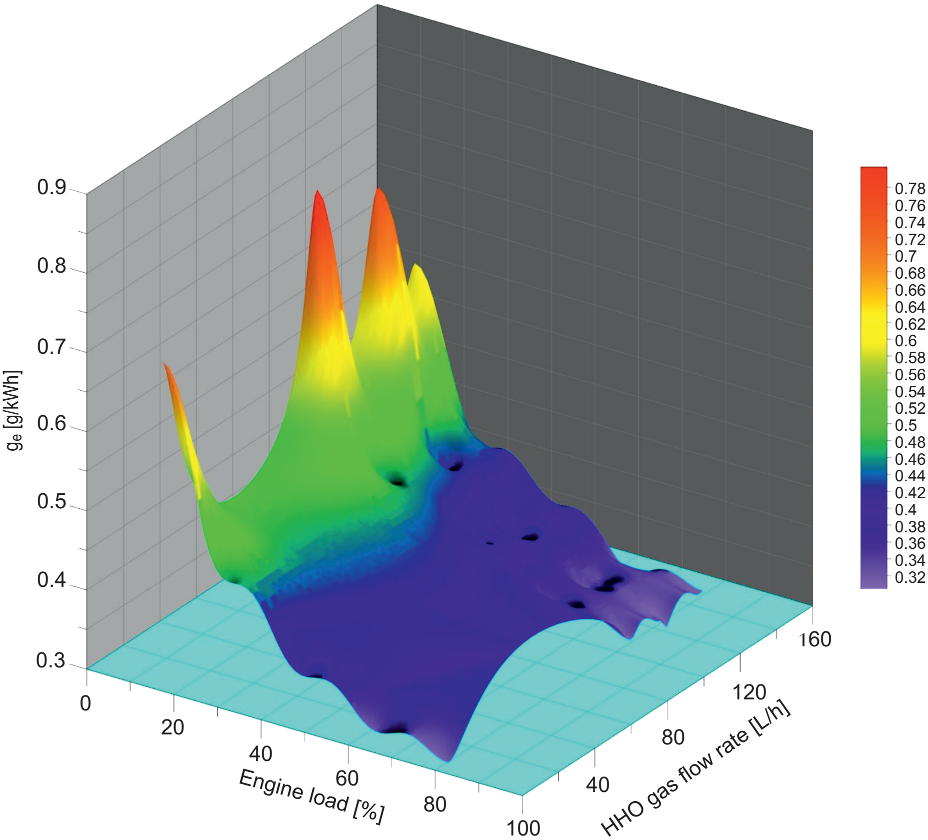

Fig. 3. The relationship between the specific fuel consumption g_{eON} and the engine load P_A and the HHO gas flow rate Q

The measured power consumption values indicate relatively high power draw, which may have a significant impact on the vehicle's electrical system. At a flow rate of 117 [l/h], the electrolyzer operates at 192 [W], while at a flow rate of 140 [l/h], the system draws 288 [W]. Considering that during a 10-minute measurement cycle, the diesel fuel savings resulting from the use of HHO gas in the engine average 4 g, which represents approximately 4% of the fuel consumed, while the power consumed by the electrolyzer accounts for about 12%

of the engine's load power, it follows that installing an HHO generator powered by the vehicle's electrical system is disadvantageous from the perspective of the overall balance of potential gains and losses.

Summary and conclusions

The experimental results showed that the addition of HHO to the intake system of the tested compression-ignition engine affected the measured diesel fuel consumption. The magnitude and direction of this effect depended on engine load and HHO flow rate. The most favorable results were observed at higher HHO flow rates and selected load points; however, the observed fuel savings were moderate and should be interpreted in relation to measurement uncertainty and repeatability.

The electrical power required to operate the electrolyzer was 192 W at an HHO flow rate of approximately 117 l/h and 288 W at approximately 140 l/h. Therefore, when the HHO generator is considered as a system powered by a vehicle electrical installation, the energetic cost of gas production is significant compared with the diesel fuel savings observed during the tests.

Consequently, although HHO addition may reduce the measured diesel fuel consumption under selected operating conditions, the overall energy balance of the tested system is unfavorable. The installation of such an HHO system in a diesel-powered vehicle should therefore not be considered energetically or economically justified if the electrolyzer is powered by the vehicle on-board electrical system.

The study was limited to fuel-consumption and energy-balance measurements. Exhaust emissions, combustion stability and in-cylinder combustion parameters were not measured; therefore, further work should include exhaust-gas analysis, engine-speed stability, temperature monitoring and tests on engines equipped with modern electronic fuel-injection control.

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