SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

Oxyhydrogen Gas Production by Alkaline Water Electrolysis and the Effectiveness on the Engine Performance and Gas Emissions in an ICEs: A Mini-Review

Siti Nurul Akmal Yusof[1,*], Mat Sazilin Ayub[2], Saiful Bahri Mohamed[1,♣], Yutaka Asako[3], Wan Mohd Arif Aziz Japar[3], Mohd Sani Said[4], Mohd Shahir Kasim[5]

[1] Faculty of Innovative Design and Technology, Universiti Sultan Zainal Abidin, Kampus Gong Badak, 21300 Terengganu, Malaysia
[2] Kolej Komuniti Besut, Tingkat 3, Bangunan Baitul Ehsan, Jalan Besar, 22000 Jerteh, Terengganu, Malaysia
[3] Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia
[4] Politeknik Mukah, Km 7.5, Jalan Oya, 96400 Mukah, Sarawak, Malaysia
[5] Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka, 76100 Durian Tunggal, Melaka, Malaysia

ARTICLE INFO

Article history:
Received 19 March 2022
Received in revised form 27 May 2022
Accepted 6 June 2022
Available online 1 July 2022

Keywords:
HHO gas; alkaline water electrolysis; internal combustion engine; emissions

ABSTRACT

The excessive use of fossil fuels and the resultant dramatic increase in pollution levels have highlighted the need for a new sustainable and environmentally friendly fuel. Hence, it is necessary to research alternatives to reduce the use of fossil fuels and the emission of greenhouse gases. Utilising oxyhydrogen (HHO) gas has been proven to achieve high engine power output and efficiency with low emissions for spark-ignited internal combustion engines. HHO gas is generated from the electrolysis of water. This paper reviews the recent research findings related to the influencing factors on the production of HHO gas using alkaline water electrolysis involving electrolyte properties, electrolyte concentration, the distance between electrolytes, and the effects of HHO gas on the engine performance and gas emissions. Using an HHO gas blend in a diesel/gasoline engine could be a viable option for lowering GHG emissions and increasing engine efficiency.

1. Introduction

Energy consumption per capita is inversely proportional to living standards [1]. Oil, coal, and natural gas-based conventional energy sources have shown to be highly successful driven by economic advancement while also causing negative impacts on the environment and human health [2]. The rapid increase in energy use has prompted concerns, particularly in recent decades, as it threatens to deplete the world's petroleum supplies and other resources. The widespread usage of fossil fuels has wreaked havoc on the ecosystem in a variety of ways. Fossil fuels account for over

* *Corresponding author.*
E-mail address: snakmalyusof@unisza.edu.my
♣ *Corresponding author.*
E-mail address: saifulbahri@unisza.edu.my

https://doi.org/10.37934/arfmts.97.1.168179

90% of human energy usage [3-6]. Due to industrialization and population growth, the standard technologies used heavily depend on irreplaceable natural resources [3].

Many researchers have recently concentrated on developing renewable energies such as oxygenated fuels, biofuel (n-butanol), fuel cells and solar technology, on reducing the consumption of fossil fuels and controlling the emission of greenhouse gases (GHGs) into the atmosphere [7-10]. Additionally, pollution in the transportation industry is a source of worry. One of the most effective ways to limit GHG emissions is to reduce CO_2 emissions by reducing fossil fuel consumption in the transportation sector [5-6, 11-12]. CO_2 is directly related to the fuel's carbon content and the fuel consumption amount [12]. Other than CO_2, the production and combustion of transportation fuels emit methane (CH_4) and nitrous oxide (N_2O), which contribute to GHG emissions [3]. Diesel engines are one of the most significant contributors to environmental pollution caused by exhaust emissions and a source of various health issues. Lin *et al.,* [13] investigated the correlation between black smoke and nitrogen oxide emissions through field testing of in-use diesel vehicles. They observed that the indices of black smoke reflectivity and nitrogen oxides emitted were higher when diesel vehicles were operated at low engine speed and full engine load. Thus, better automotive engines with post-combustion emission control devices should be developed to reduce GHGs emissions and improve the efficiency of energy systems [14-17].

The use of biodiesel engines in transportation and power generation has progressed rapidly in recent decades. However, the combustion of biodiesels in the engine would produce higher NO_x, leading to poor combustion performance [11]. Thus, replacing biodiesels with oxyhydrogen (HHO) gas to fuel internal combustion engines (ICE) is gaining more attention to enhance the performance of the engine speed [18-19] and reduce the level of air pollution [20-22]. Kazim *et al.,* [23] studied the effect of HHO gas in a small-capacity diesel engine. They concluded that adding HHO and diesel in a small capacity diesel engine significantly improved all engine performance factors. The minimum percentage increases in the combustion efficiency were 2.5% and 10.5% for H6 and H10, while the minimum increases in torque were 8% and 15%, respectively. HHO gas was also used as a supplementary fuel in the internal combustion engine without any modification [21]. HHO does not have a predefined burning temperature where it reacts to the substances when burned [24]. HHO would begin imploding rather than exploding since it mainly contains hydrogen (66.67%) and oxygen (33.33%). Furthermore, when HHO is combined with diesel or gasoline, it can significantly improve the burning efficiency. The flame propagation of HHO gas is faster than that of standard liquid fuel because hydrogen possesses a fast-burning velocity [25].

The current effort aims to review the effect of HHO gas on the engine performance and gas emissions of a diesel/gasoline engine. The primary focuses of this paper were concentrated on the previous works related to the production of HHO gas using the water electrolysis process and their effect on the engine performance and gas emission in diesel/gasoline engines in recent years. Then, the possible future research direction of HHO gas as the alternative fuel in internal combustion engines is emphasized.

2. Water Electrolysis Process

The HHO gas, also known as Brown's Gas, is a gas that results from water electrolysis. Water electrolysis is the process of breaking down water molecules (H_2O) into hydrogen (H_2) and oxygen (O_2) using energy from an electric current passing through the water [26-28]. Direct production of HHO gas is straightforward using the existing power in the vehicle (i.e., battery) [29]. Two water molecules react by capturing two electrons at the cathode, then reduced to H_2 gas and hydroxide ions (OH^-). Meanwhile, two more water molecules decompose into gaseous oxygen at the anode, releasing 4 H+ ions and conducting electrons to the cathode. Then, both H+ and OH- ions undergo neutralisation so that some water molecules are reformed. Water electrolysis is usually governed by several factors: electrolyte quality, temperature, pressure, electrolyte resistance, electrode material, and separator material [30-34].

Furthermore, electrolyte usage influences the rate of chemical reactions that support decomposing water into hydrogen and oxygen since electrolyte ions can affect the stability of water molecules into H+ and OH- ions, facilitating the electrolysis process [27]. When dissolved in a polar solvent, an electrolyte generates an electrically conductive solution. As a result, cations and anions are separated from the dissolved electrolyte and evenly disseminated throughout the solvent. Cations are attracted to electrodes with many electrons, while anions are attracted to electrodes with deficient electrons (Table 1).

This reaction produces HHO gas, which forms gas bubbles near the electrode that can be collected. This approach is then used to produce hydrogen for use as hydrogen car fuel. H2O can also be split into diatomic molecules of hydrogen and oxygen using battery power, as shown in Figure 1 [35].

Table 1
Electrolysis of water produces gaseous products [35]

Electrolyte		Electrode Reaction
Acidic electrolyte	~ at the anode:	$H_2O \rightarrow ½\, O_2 + 2H^+ + 2e^-$
	~ at the cathode:	$2H^+ + 2e^- \rightarrow H_2$
Total		$H_2O \rightarrow H_2 + ½\, O_2$
Free-acidic electrolyte	~ at the cathode:	$2H_2O + 2e^- \rightarrow H_2 + 2H^-$
	~ at the anode:	$2OH^- \rightarrow ½\, O_2 + H_2O + 2e^-$
Total		$H2O \rightarrow H_2 + ½\, O_2$

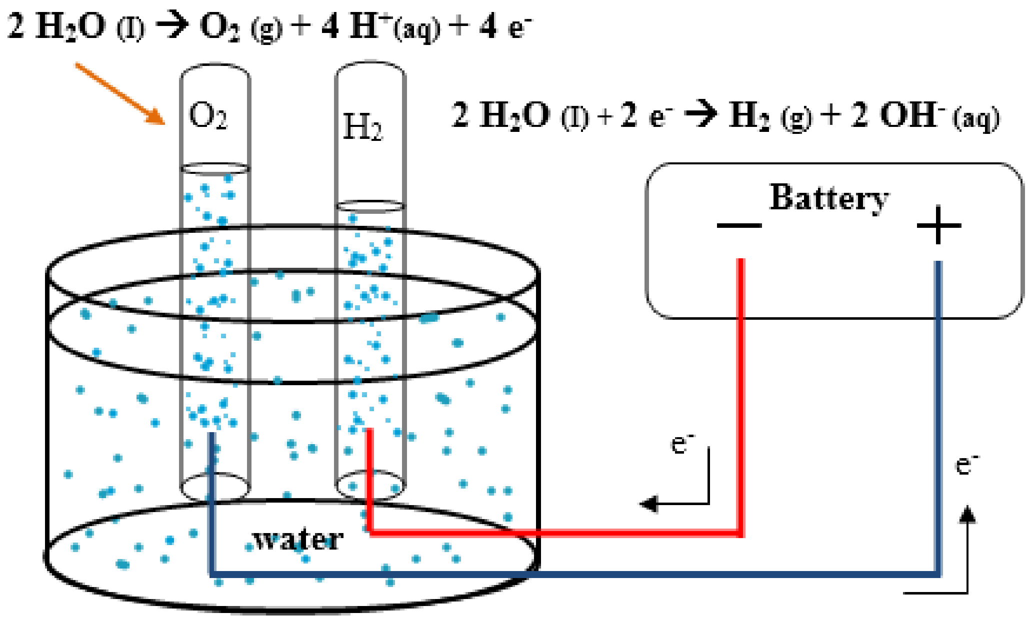

Fig. 1. A schematic diagram of water electrolysis [35]

There are three methods of water electrolysis for producing HHO gas: alkaline, proton exchange membrane (PEM), and solid oxide electrolyzers (SOE). Table 2 tabulates the various characteristics and different stages of development for alkaline, PEM, and SOE electrolyzers. In terms of efficiency, SOE is known as the best electrolyzer. In comparison, efficiencies of around 98% have been proved for SOE operating at 650 °C [41-42]. At the same time, alkaline water electrolyzers have efficiencies exceeding 80% and PEM around 83.4%. They are, however, they are the least developed among the others (alkaline and PEM electrolyzers) [43]. They also encounter durability issues as a result of the severe conditions [44]. In terms of efficiency, PEM electrolyzers performed better than alkaline electrolyzers however, PEM is more expensive than alkaline electrolyzers [43,45]. The alkaline electrolyzers is being the most economic option because of their relatively cheaper materials and low production cost [46].

Table 2
Specifications of alkaline, PEM and SOE electrolyzers [36-38]

Specification	Alkaline	PEM	SOE
Technology maturity	Widespread commercialization	Commercialization	Research & Development
Cell temperature (^oC)	60–80	50–80	900–1000
Cell pressure (bar)	< 30	< 30	< 30
Current density (A/cm^2)	< 0.45	1.0–2.0 [a]	0.3–1.0
Cell voltage (V)	1.8–2.4	1.8–2.2	0.95–1.3
Voltage efficiency (%)	62–82	67–82	81–86
Specific energy consumption (kWh/Nm^3) [b]	4.2–4.8	4.4–5.0	2.5–3.5
Minimum partial load (%)	10–40	0–10 [c]	-
Cell area (m^2)	3–3.6	< 0.13	< 0.06
Hydrogen production per stack (Nm^3/h) [d]	< 1400	< 400	< 10
Stack lifetime (kh)	55–120	60–100	8–20 [e]
System lifetime (year)	20–30	10–20	-
Hydrogen purity (%)	> 99.8	99.999	-
Cold start-up time (min)	15	< 15	> 60
Investment costs (€/kW)	800–1500	1400–2100	> 2000 [e]

[a] Typical commercial value, although laboratory experiments with a current density up to 20 A/cm2 are reported [39].
[b] Excluding rectifier and utilities (0.4-0.8 kWh/Nm3).
[c] Vendors do not report a technical limit but it is known that there is gas contamination at high pressures and low current density that prevent reaching values ?? close to 0 [40].
[d] According to a recent market survey.
[e] High uncertainty due to pre-commercial status of SOE.

3. HHO Gas Generator Design
3.1 Wet Cell Type

The wet cell type has a positive and negative electrode plate immersed in an electrolyte solution made up of water and a catalyst [47] as shown in Figure 2. In the wet-cell type, all the electrode areas of the plate are immersed in water for the electrolysis process to produce HHO gas. Using an electronic control unit, Yilmaz *et al.,* [48] evaluated the rate of hydroxy gas production in wet cells with different electrolyte solutions of potassium hydroxide (KOH), sodium chloride (NaCl), and sodium hydroxide (NaOH). These wet cells have both advantages and disadvantages. The advantages of the HHO gas generator wet cell types are that gas production is more plentiful and stable; second, generator maintenance is more manageable; and third, HHO simplifies generator design. The disadvantages of using wet cells are more heat generation by the cell and a higher current (ampere) is required. Due to the larger plate exposed surface to the electrolyte, the wet fuel cell causes higher electrode corrosion than the dry fuel cell. The catalyst was added to the water solution as a powder and dissolved [49]. Recently, Soly *et al.,* [50] performed a study to investigate the HHO production rate using dry and wet cells. They used different plates configuration to make a comparison between dry and wet cells. For the same design parameters, wet cells produce more HHO gas than dry cells because all electrodes are immersed in the electrolyte solution. The active surface area of the electrodes is enhanced. Dry cells generate less heat, have fewer electrodes that corrode, and take up less space than wet cells.

Fig. 2. Wet cell type [47]

3.2 Dry Cell Type

A dry cell HHO gas generator is where most of the electrodes are not embedded in the electrolyte. The electrolyte only fills the gap between the electrode themselves as shown in Figure 3. The advantages of dry cell HHO generators include i) waterless electrolysis, where only water is trapped between the cell plates; ii) minimum heat generation due to hot and cold-water circulation inside the HHO generator; iii) the smaller electric current used due to electricity is converted to less heat [50-54]. The advantage and disadvantages of the dry and wet cells for HHO production were listed in Table 3.

As listed in Table 3, wet cells have several advantages, including enhanced gas output, stability, maintenance, and fabrication ease. The disadvantages of the wet cells include a higher HHO flow rate and higher current required, increased cell heat, corrosion of the positive electrodes (anodes), required larger occupation space and more expensive than dry cells. The advantages of dry HHO cells outweigh the disadvantages of wet HHO cells. Both types of HHO gas provide the same outcome. However, the difference is due to the electrolyte reservoir and electrode plate displacement. Due to the volumetric size of the electrolyte within the closed chamber, a dry HHO cell has various advantages, including requiring less current per cell and being cheaper than wet cells. Recently, HHO dry cell generator designed and applied to 110 cc engine vehicles to reduce gas emissions was done by Puspitasari *et al.,* [51]. They focused only on the number of holes on the electrode plate. Several parameters such as voltage, electric current, electrolyte temperature in the reservoir tank, electrolyte temperature in the HHO gas cylinder, and HHO gas exhaust are measured. Based on their findings, the hole plate electrode 2 has the best HHO generator variant, with a necessary power of 180.78 watts and a 63.8% efficiency. The lowest CO emission level (4.01%) was found in the 2-hole version, and the lowest HC emission level (892 ppm) was found in the 4-hole variation.

El Soly *et al.,* [50] redesigned and fabricated the HHO dry cell to produce maximum gas flow rate and enhance the electrolyzer efficiency. They concluded that HHO dry cell is more economical and efficient to be applied to the engine. Meanwhile, Chinguwa *et al.,* [52] investigated the optimal design of a hydroxyl booster dry cell for enhancing the efficiency of an internal combustion engine (ICE). Due to the explosive and diffusive nature of hydrogen, and the presence of water, the introduction of hydroxyl gas from the dry cell into the combustion chamber of an ICE initiates complete combustion which subsequently decreases the potential for NOx generation. Their findings show good agreement with Ismail *et al.,* [53].

Fig. 3. Dry cell type [47]

Table 3
Advantages and disadvantages of wet and dry HHO cells [47]

Parameter	Dry	Wet
HHO flow rate	Low	High
Current consumption	Low	High
Heat and energy loss	Less	More
Electrodes corrosion	Less	More
Cell size	Small	Large
Cell life	More	Less
Engine adaption	Easy	Difficult
Occupation space	Small	Large
Cost	Low	High

4. Factors Affecting Efficiency of Water Electrolysis
4.1 Types of Electrolytes

An electrolyte is known as a substance that conducts electricity when dissolved in water [49, 54]. In the electrolysis process, electrolyte substances like acids and salts can transfer electric currents. These electrolytic ions can affect the stability of water molecules to H^+ and OH^- ions. The partial reaction at the electrodes is given in Table 1. In laboratory conditions, the required voltage (also known as the equilibrium voltage) for splitting a water molecule is approximately 1.23 V. Higher voltage, on the other hand, is required in practical electrolysis cells. This is due to the overpotential of electrochemical.

Different concentration of KOH, NaOH, and $NaHCO_3$ was prepared within the range of 0.010–0.030 M. The results of the experiments revealed that increasing electrolyte strength, voltage, and time enhanced the yield of HHO gas proportionately. When the generator was run at 13 V and 0.025 M KOH, an ideal yield rate of 2.27 cm^3/s of HHO gas was obtained.

4.2 Electrolyte Concentration

The concentration of the electrolyte significantly affected the electrolyser performance. Sun and Hsiau [59] studied the effect of electrolyte concentration on electrolysis. They used two different electrolytes which were acidic and alkaline solutions. The electrolytes concentrations varied between 5-20 wt% aqueous solution of H_2SO_4 and 10-40 wt% aqueous solution of KOH. Musmar *et al.,* [60] investigated KOH concentration in an electrolyte solution on engine performance and emissions. The electrolytes concentrations were 1 g/L, 1.5 g/L, 5 g/L and 6.5 g/L. Their findings revealed that the electrolyte concentration shows a significant effect on engine performance parameters and the best concentration range for KOH in distilled water was within the range of 1-2 g/L. Mohamed and Ali [61] used KOH solutions for producing HHO gas. The electrolyte concentrations varied from 0.07 M to 0.32 M. The study found that as the electrolysis concentration increased, the hydrogen production increased as well. This could be related to the amount of current flowing through the electrodes, determined by their conductivity and electrolyte content. Abhilash *et al.,* [62] evaluated the performance of an IC engine using HHO gas as an alternative fuel at different electrolyte concentrations. The application of NaOH electrolyte resulted in a 4% increase in brake thermal efficiency, with the efficiency rising to 75% of the engine-rated load.

4.3 Spacing Between Electrolytes

The spacing between the anode and the cathode affects HHO performance. Since the resistance is related to the spacing between the electrodes, hence by shortening the space, the resistance can be reduced. As a result, decreasing the spacing between the electrodes would reduce the resistance, thus a minimum spacing should be maintained to prevent the gap from rupturing [21]. Nagai *et al.,* [34] investigated the effect of optimum space between electrodes on hydrogen production by water electrolysis. The experimental results revealed that the current density and space between electrodes have significant effects on the efficiency of water electrolysis. These results are in good agreement with the findings of Leroy *et al.,* [63]. Both experimental results showed the importance of the space between electrodes over water electrolysis efficiency. The position of the electrodes helps the expulsion of bubbles formed during electrolysis, and introducing ultrasonic fields or supergravity conditions can accelerate the explosion of bubbles [63]. Opu [64] had successfully proved that the performance of alkaline water electrolysis is significantly affected by the distance between the electrode, electrolyte concentration and operating temperature. Lavorante *et al.,* [65] analysed two different distances between electrodes which were 6.1 and 5.30 mm. Results showed that the distance between electrodes of 6.1 mm showed the best performance during the study.

Overall, to produce a high yield of HHO gas, the efficiency of water electrolysis is essential. Based on the above kinds of literature, researchers have contradictory observations regarding the types of electrolytes, the electrolyte concentration, and the spacing between the electrodes. Therefore, it is recommended that more studies should be conducted on the factors affecting water electrolysis efficiency to optimize the process outcome.

5. Recent Studies on the HHO Gas to Fuel the ICE Engine

Several researchers used HHO gas as an alternate energy source blended with air and diesel/gasoline fuel to boost engine performance while lowering the danger of harmful gas emissions [66-71]. Gad *et al.,* [66] recently studied the impact of HHO gas on diesel engine performance and emissions. They conducted the test at the different engines from 1750 to 2750 rpm. Based on their finding, the thermal efficiency increased by 7% compared to diesel oil, and the specific fuel consumption decreased by 15% at full load. Using hydroxyl gas, the HC emissions were reduced by 25% on average. When compared to pure diesel, the CO emissions were reduced by 18% on average. The addition of hydroxyl gas increased NOx by around 8% at full load. HHO gas was suggested as a good additive to substitute diesel oil for improving performance and reducing emissions. While Sharma *et al.,* [67] investigated the energy, exergy, and emission analysis for the hydroxyl fuelled compression ignition (CI) engine under dual fuel mode. In their study, they used different mass flow rates of HHO which were 0.25, 0.5 and 0.75 LPM. Overall, it can be concluded that HHO is a viable alternative fuel with higher exergy and reduced emissions. The experimental results from Sharma *et al.,* [67] were in good agreement with that obtained by Subramanian and Thangavel [68].

Jakliński and Czarnigowski [69] investigated the effects of adding HHO gas in automotive engines operating at idle speed. When using HHO gas as a fuel additive, CO and HC concentrations in exhaust gases were lowered in the majority of cases; NOx concentrations were reduced in SI engines but increased in diesel engines. Aydin and Kenanoglu [70] investigated the performance of four-stroke, two-stroke, and single-stroke engines after introducing various designs of commercially available HHO fuel cells without a storage tank. Their findings show a significant improvement in brake power, brake torque, and brake-specific fuel consumption of gasoline engines of up to 27%, 32.4% and 16.3%, respectively. In addition, a reduction in hydrocarbon emissions was demonstrated at all engine speeds, with a maximum reduction of 12.5% at 3500 rpm. Sazilin *et al.,* [71] performed the experiment to evaluate the effect of electrode plate characteristics on the engine speed performance. The results revealed that the engine rpm has been increased by 30%-50% with the use of HHO gas compared to fossil fuel. In short, HHO gas can be used as a supplementary fuel in conjunction with air in the inlet manifold to reduce emissions while increasing performance.

6. Conclusions

This paper reviews the effects of HHO gas on the engine performance and gas emissions in an internal combustion engine. The application of the HHO gas blend in an internal combustion engine can serve as a potential approach to reducing GHG emissions and improving engine efficiency. Water electrolysis is currently one of the most promising methods to produce HHO gas when the energy source is renewable. The use of HHO gas in an internal combustion engine increased the engine braking power which is likely due to the presence of hydrogen in HHO gas. The presence of hydrogen in HHO gas has a high calorific value that is much higher than fossil fuels. The parameters in producing HHO gas such as types of electrolytes, electrolyte concentration and distance between electrolytes significantly affect the process. As a whole, the addition of HHO gas in diesel/gasoline plays an important role in enhancing engine performance and reducing exhaust emissions. Hence it was thought that most of the results are favourable because this method has numerous advantages including the fact that it produces no pollution into the environment. The gaseous products obtained only hydrogen and oxygen with a high degree of purity which makes them appealing for use in fuel cells. However, more aspects need to consider since the HHO gas production rate depends on many factors such as the amount of current passed, material, geometry, types and electrolyte composition. Further study is therefore needed to optimize these parameters to improve the efficiency and concern of conducting research on low-cost materials or modifying existing ones.

Acknowledgement

This research was funded by a grant from Malaysia's Ministry of Higher Education (FRGS Grant: FRGS/1/2015/TK10/JPP/03/1).

References

[1] Caruso, Giulia, Emiliano Colantonio, and Stefano Antonio Gattone. "Relationships between renewable energy consumption, social factors, and health: A panel vector auto regression analysis of a cluster of 12 EU countries." *Sustainability* 12, no. 7 (2020): 2915.https://doi.org/10.3390/su12072915

[2] Lipman, Timothy E., Jennifer L. Edwards, and Daniel M. Kammen. "Fuel cell system economics: comparing the costs of generating power with stationary and motor vehicle PEM fuel cell systems." *Energy Policy* 32, no. 1 (2004): 101-125.https://doi.org/10.1016/S0301-4215(02)00286-0

[3] Iuga, Anca N., Vasile N. Popa, and Luminița I. Popa. "Comparative analysis of automotive products regarding the influence of eco-friendly methods to emissions' reduction." *Energies* 12, no. 1 (2018): 6.https://doi.org/10.3390/en12010006

[4] Yusof, Siti Nurul Akmal, Yutaka Asako, Mohammad Faghri, Lit Ken Tan, Nor Azwadi Bin Che Sidik, and Wan Mohd Arif Bin Aziz Japar. "Energy equation of swirling flow in a cylindrical container." *International Communications in Heat and Mass Transfer* 108 (2019): 104288.https://doi.org/10.1016/j.icheatmasstransfer.2019.104288

[5] Ghassemieh, Elaheh. "Materials in automotive application, state of the art and prospects." *New trends and developments in automotive industry* 20 (2011): 365-394.https://doi.org/10.5772/13286

[6] Davies, John, Michael Grant, John Venezia, and Joseph Aamidor. "Greenhouse gas emissions of the US transportation sector: Trends, uncertainties, and methodological improvements." *Transportation research record* 2017, no. 1 (2007): 41-46.https://doi.org/10.3141/2017-06

[7] Uyumaz, Ahmet. "An experimental investigation into combustion and performance characteristics of an HCCI gasoline engine fueled with n-heptane, isopropanol and n-butanol fuel blends at different inlet air temperatures." *Energy Conversion and Management* 98 (2015): 199-207.https://doi.org/10.1016/j.enconman.2015.03.043

[8] He, Bang-Quan, Mao-Bin Liu, and Hua Zhao. "Comparison of combustion characteristics of n-butanol/ethanol–gasoline blends in a HCCI engine." *Energy conversion and management* 95 (2015): 101-109.https://doi.org/10.1016/j.enconman.2015.02.019

[9] Kahveci, Elif Eker, and Imdat Taymaz. "Experimental study on performance evaluation of PEM fuel cell by coating bipolar plate with materials having different contact angle." *Fuel* 253 (2019): 1274-1281.https://doi.org/10.1016/j.fuel.2019.05.110

[10] Taymaz, Imdat, and Merthan Benli. "Emissions and fuel economy for a hybrid vehicle." *Fuel* 115 (2014): 812-817. https://doi.org/10.1016/j.fuel.2013.04.045

[11] Yusof, Siti Nurul Akmal, Nor Azwadi Che Sidik, Yutaka Asako, Wan Mohd Arif Aziz Japar, Saiful Bahri Mohamed, and Nura Mu'az Muhammad. "A comprehensive review of the influences of nanoparticles as a fuel additive in an internal combustion engine (ICE)." *Nanotechnology Reviews* 9, no. 1 (2020): 1326-1349. https://doi.org/10.1515/ntrev-2020-0104

[12] Shaheen, Susan A., and Timothy E. Lipman. "Reducing greenhouse emissions and fuel consumption: Sustainable approaches for surface transportation." *IATSS research* 31, no. 1 (2007): 6-20. https://doi.org/10.1016/S0386-1112(14)60179-5

[13] Lin, Cherng-Yuan, Lih-Wei Chen, and Li-Ting Wang. "Correlation of black smoke and nitrogen oxides emissions through field testing of in-use diesel vehicles." *Environmental monitoring and assessment* 116, no. 1 (2006): 291-305. https://doi.org/10.1007/s10661-006-7402-2

[14] Yusof, Siti Nurul Akmal, Yutaka Asako, Mohammad Faghri, Lit Ken Tan, and Nor Azwadi bin Che Sidik. "Numerical analysis for irreversible processes in a piston-cylinder system." *International Journal of Heat and Mass Transfer* 124 (2018): 1097-1106. https://doi.org/10.1016/j.ijheatmasstransfer.2018.04.008

[15] Yusof, Siti Nurul Akmal, Yutaka Asako, Tan Lit Ken, and Nor Azwadi Che Sidik. "Piston surface pressure of piston-cylinder system with finite piston speed." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 44, no. 1 (2018): 55-65.

[16] Yusof, Siti Nurul Akmal, Yutaka Asako, Mohammad Faghri, Lit Ken Tan, Nor Azwadi bin Che Sidik, and Wan Mohd Arif bin Aziz Japar. "Numerical analysis of irreversible processes in a piston-cylinder system using LB1S turbulence model." *International Journal of Heat and Mass Transfer* 136 (2019): 730-739. https://doi.org/10.1016/j.ijheatmasstransfer.2019.03.007

[17] Singh, Baljit Singh Bhathal, Nor Amelia Shafikah Mat Noh, Muhammad Fairuz Remeli, and Amandeep Oberoi. "Experimental Study On Waste Heat Recovery from an Internal Combustion Engine Using Thermoelectric Generator." *Journal of Advanced Research in Applied Mechanics* 72, no. 1 (2020): 25-36. https://doi.org/10.37934/aram.72.1.2536

[18] Sazilin, Mat, S. B. Mohamed, A. Endut, M. F. M. Alkbir, R. Bwsar, A. Rosdi, and A. Syafiq. "Evaluation effect of plate electrode characteristics on engine speed performance in application of HHO generator for four-stroke engine."

In *AIP Conference Proceedings*, vol. 2030, no. 1, p. 020304. AIP Publishing LLC, 2018. https://doi.org/10.1063/1.5066945

[19] Ayub, Mat Sazilin, Siti Nurul Akmal Yusof, Saiful Bahri Mohamed, Mohd Sani Said, Yutaka Asako, Nor Azwadi Che Sidik, Mohd Shahir Kasim, and Ahmad Tajuddin Mohamad. "Effect of Electrode Plates on the Engine Performance and Gas Emissions of a Four-Stroke Petrol Engine." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 90, no. 2 (2022): 90-108. https://doi.org/10.37934/arfmts.90.2.90108

[20] Gad, M. S., M. K. El-Fakharany, and E. A. Elsharkawy. "Effect of HHO gas enrichment on performance and emissions of a diesel engine fueled by biodiesel blend with kerosene additive." *Fuel* 280 (2020): 118632. https://doi.org/10.1016/j.fuel.2020.118632

[21] Subramanian, Balaji, and Saleel Ismail. "Production and use of HHO gas in IC engines." *International Journal of Hydrogen Energy* 43, no. 14 (2018): 7140-7154. https://doi.org/10.1016/j.ijhydene.2018.02.120

[22] Wang, Chia-Nan, Min-Tsong Chou, Hsien-Pin Hsu, Jing-Wein Wang, and Sridhar Selvaraj. "The efficiency improvement by combining HHO gas, coal and oil in boiler for electricity generation." *Energies* 10, no. 2 (2017): 251. https://doi.org/10.3390/en10020251

[23] Kazim, Ali Hussain, Muhammad Bilal Khan, Rabia Nazir, Aqsa Shabbir, Muhammad Salman Abbasi, Hamza Abdul Rab, and Nabeel Shahid Qureishi. "Effects of oxyhydrogen gas induction on the performance of a small-capacity diesel engine." *Science Progress* 103, no. 2 (2020): 0036850420921685. https://doi.org/10.1177/0036850420921685

[24] Taib, Norhidayah Mat, Mohd Radzi Abu Mansor, and Wan Mohd Faizal Wan Mahmood. "Simulation of Hydrogen Fuel Combustion in Neon-oxygen Circulated Compression Ignition Engine." *Journal of Advanced Research in Numerical Heat Transfer* 3, no. 1 (2020): 25-36.

[25] Huang, Zuohua, Yong Zhang, Qian Wang, Jinhua Wang, Deming Jiang, and Haiyan Miao. "Study on flame propagation characteristics of natural gas− hydrogen− air mixtures." *Energy & Fuels* 20, no. 6 (2006): 2385-2390. https://doi.org/10.1021/ef060334v

[26] Brown, Y., “Welding,” U.S. Patent 4,014,777, 1977.

[27] Harman, Arif E., and Duma Hasan. "Pengaruh Penambahan Gas Oksihidrogen Terhadap Unjuk Kerja Motor Bensin Berbahan Bakar Pertamax." *Jurnal Teknik Mesin, Universitas Hasanuddin Makassar* (2013).

[28] Mutlu, Rasiha Nefise, Ibrahim Kucukkara, and Ahmet Murat Gizir. "Hydrogen generation by electrolysis under subcritical water condition and the effect of aluminium anode." *International Journal of Hydrogen Energy* 45, no. 23 (2020): 12641-12652. https://doi.org/10.1016/j.ijhydene.2020.02.223

[29] Kwasi-Effah, C. C., A. I. Obanor, and F. A. Aisien. "A review on electrolytic method of hydrogen production from water." *American Journal of Renewable and Sustainable Energy* 1, no. 2 (2015): 51-57.

[30] Millet, P., F. Andolfatto, and R. Durand. "Design and performance of a solid polymer electrolyte water electrolyzer." *International journal of hydrogen energy* 21, no. 2 (1996): 87-93. https://doi.org/10.1016/0360-3199(95)00005-4

[31] Badwal, S. P. S., S. Giddey, and F. T. Ciacchi. "Hydrogen and oxygen generation with polymer electrolyte membrane (PEM)-based electrolytic technology." *Ionics* 12, no. 1 (2006): 7-14. https://doi.org/10.1007/s11581-006-0002-x

[32] Nikolic, Vladimir M., Gvozden S. Tasic, Aleksandar D. Maksic, Djordje P. Saponjic, Snezana M. Miulovic, and Milica P. Marceta Kaninski. "Raising efficiency of hydrogen generation from alkaline water electrolysis–Energy saving." *International Journal of Hydrogen Energy* 35, no. 22 (2010): 12369-12373. https://doi.org/10.1016/j.ijhydene.2010.08.069

[33] Mansouri, Khaled, Karim Ibrik, Nasr Bensalah, and Ahmed Abdel-Wahab. "Anodic dissolution of pure aluminum during electrocoagulation process: influence of supporting electrolyte, initial pH, and current density." *Industrial & engineering chemistry research* 50, no. 23 (2011): 13362-13372. https://doi.org/10.1021/ie201206d

[34] Nagai, N., M. Takeuchi, T. Kimura, and T. Oka. "Existence of optimum space between electrodes on hydrogen production by water electrolysis." *International journal of hydrogen energy* 28, no. 1 (2003): 35-41. https://doi.org/10.1016/S0360-3199(02)00027-7

[35] Yuvaraj, A. L., and D. Santhanaraj. "A systematic study on electrolytic production of hydrogen gas by using graphite as electrode." *Materials Research* 17, no. 1 (2014): 83-87. https://doi.org/10.1590/S1516-14392013005000153

[36] David, Martín, Carlos Ocampo-Martínez, and Ricardo Sánchez-Peña. "Advances in alkaline water electrolyzers: A review." *Journal of Energy Storage* 23 (2019): 392-403. https://doi.org/10.1016/j.est.2019.03.001

[37] Dincer, Ibrahim, and Canan Acar. "Review and evaluation of hydrogen production methods for better sustainability." *International journal of hydrogen energy* 40, no. 34 (2015): 11094-11111. https://doi.org/10.1016/j.ijhydene.2014.12.035

[38] Buttler, Alexander, and Hartmut Spliethoff. "Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review." *Renewable and Sustainable Energy Reviews* 82 (2018): 2440-2454. https://doi.org/10.1016/j.rser.2017.09.003

[39] Lewinski, Krzysztof A., Dennis van der Vliet, and Sean M. Luopa. "NSTF advances for PEM electrolysis-the effect of alloying on activity of NSTF electrolyzer catalysts and performance of NSTF based PEM electrolyzers." *Ecs Transactions* 69, no. 17 (2015): 893. https://doi.org/10.1149/06917.0893ecst
[40] Grigoriev, S. A., V. I. Porembskiy, S. V. Korobtsev, V. N. Fateev, F. Auprêtre, and P. Millet. "High-pressure PEM water electrolysis and corresponding safety issues." *International journal of hydrogen energy* 36, no. 3 (2011): 2721-2728. https://doi.org/10.1016/j.ijhydene.2010.03.058
[41] Schiller, G., R. Henne, P. Mohr, and V. Peinecke. "High performance electrodes for an advanced intermittently operated 10-kW alkaline water electrolyzer." *International Journal of Hydrogen Energy* 23, no. 9 (1998): 761-765. https://doi.org/10.1016/S0360-3199(97)00122-5
[42] Wang, Zhenwei, Masashi Mori, and Takuto Araki. "Steam electrolysis performance of intermediate-temperature solid oxide electrolysis cell and efficiency of hydrogen production system at 300 Nm3 h− 1." *International journal of hydrogen energy* 35, no. 10 (2010): 4451-4458. https://doi.org/10.1016/j.ijhydene.2010.02.058
[43] Kalamaras, Christos M., and Angelos M. Efstathiou. "Hydrogen production technologies: current state and future developments." In *Conference papers in science*, vol. 2013. Hindawi, 2013. https://doi.org/10.1155/2013/690627
[44] Laguna-Bercero, M. A. "Recent advances in high temperature electrolysis using solid oxide fuel cells: A review." *Journal of Power sources* 203 (2012): 4-16. https://doi.org/10.1016/j.jpowsour.2011.12.019
[45] Gago, Aldo Saul, Philipp Lettenmeier, Svenja Stiber, Asif Syed Ansar, Li Wang, and Kaspar Andreas Friedrich. "Cost-effective PEM electrolysis: The quest to achieve superior efficiencies with reduced investment." *ECS Transactions* 85, no. 13 (2018): 3. https://doi.org/10.1149/08513.0003ecst
[46] Birol, Fatih. "The future of hydrogen: seizing today's opportunities." *IEA Report prepared for the G* 20 (2019).
[47] Sudarmanta, Bambang, Sudjud Darsopuspito, and Djoko Sungkono. "Application of dry cell HHO gas generator with pulse width modulation on sinjai spark ignition engine performance." *International Journal of Research in Engineering and Technology* 5, no. 2 (2016): 105-112. https://doi.org/10.15623/ijret.2016.0502019
[48] Yilmaz, Ali Can, Erinç Uludamar, and Kadir Aydin. "Effect of hydroxy (HHO) gas addition on performance and exhaust emissions in compression ignition engines." *international journal of hydrogen energy* 35, no. 20 (2010): 11366-11372. https://doi.org/10.1016/j.ijhydene.2010.07.040
[49] Gad, M. S., and SM Abdel Razek. "Impact of HHO produced from dry and wet cell electrolyzers on diesel engine performance, emissions and combustion characteristics." *International Journal of Hydrogen Energy* 46, no. 43 (2021): 22277-22291. https://doi.org/10.1016/j.ijhydene.2021.04.077
[50] El Soly, A. K., M. A. El Kady, Ahmed El Fatih Farrag, and M. S. Gad. "Comparative experimental investigation of oxyhydrogen (HHO) production rate using dry and wet cells." *International Journal of Hydrogen Energy* 46, no. 24 (2021): 12639-12653. https://doi.org/10.1016/j.ijhydene.2021.01.110
[51] Puspitasari, Indah, Noorsakti Wahyudi, Yoga Ahdiat Fakhrudi, and Galih Priyo Wicaksono. "Design of Generator HHO Dry Cell Type and Application on 110 Cc Engined Vehicles Towards Gas Emissions." In *Journal of Physics: Conference Series*, vol. 1845, no. 1, p. 012002. IOP Publishing, 2021. https://doi.org/10.1088/1742-6596/1845/1/012002
[52] Chinguwa, Simon, Tien-Chien Jen, and Esther T. Akinlabi. "Conceptualization of the optimal design of a hydroxyl booster dry cell for enhancing efficiency of internal combustion engines." *Procedia CIRP* 91 (2020): 819-823. https://doi.org/10.1016/j.procir.2020.03.118
[53] Ismail, Tamer M., Khaled Ramzy, M. N. Abelwhab, Basem E. Elnaghi, M. Abd El-Salam, and M. I. Ismail. "Performance of hybrid compression ignition engine using hydroxy (HHO) from dry cell." *Energy conversion and Management* 155 (2018): 287-300. https://doi.org/10.1016/j.enconman.2017.10.076
[54] Ahmed, Rana M., Ahmed K. Abdelsalam, and Motaz Amer. "Off-grid diesel generators enhanced performance using photovoltaic powered on-board HHO generation: Experimental validation." In *2017 IEEE Second International Conference on DC Microgrids (ICDCM)*, pp. 428-433. IEEE, 2017. https://doi.org/10.1109/ICDCM.2017.8001080
[55] White, Ralph E. *Comprehensive treatise of electrochemistry*. Edited by John O'M. Bockris, Brian E. Conway, and Ernest Yeager. Vol. 1. New York: Plenum press, 1980.
[56] Masjuki, H. H., A. M. Ruhul, Nirendra N. Mustafi, M. A. Kalam, M. I. Arbab, and IM Rizwanul Fattah. "Study of production optimization and effect of hydroxyl gas on a CI engine performance and emission fueled with biodiesel blends." *International Journal of Hydrogen Energy* 41, no. 33 (2016): 14519-14528. https://doi.org/10.1016/j.ijhydene.2016.05.273
[57] Baltacıoğlu, Mustafa Kaan. "A novel application of pulse width modulation technique on hydroxy gas production." *International Journal of Hydrogen Energy* 44, no. 20 (2019): 9726-9734. https://doi.org/10.1016/j.ijhydene.2018.10.228
[58] Essuman, Samuel Pamford Kojo, Andrew Nyamful, Vincent Agbodemegbe, and Seth Kofi Debrah. "Experimental studies of the effect of electrolyte strength, voltage and time on the production of brown’s (HHO) gas using

oxyhydrogen generator." *Open Journal of Energy Efficiency* 8, no. 02 (2019): 64. https://doi.org/10.4236/ojee.2019.82005
[59] Sun, Cheng-Wei, and Shu-San Hsiau. "Effect of electrolyte concentration difference on hydrogen production during PEM electrolysis." *Journal of Electrochemical Science and Technology* 9, no. 2 (2018): 99-108. https://doi.org/10.33961/JECST.2018.9.2.99
[60] Musmar, Sa'ed A., Ammar A. Al-Rousan, Musa AlAjlouni, and Khalid Alzoubi. "Quantitative Assessment of Potassium Hydroxide Concentration in Oxyhydrogen Cell for Optimal Gasoline Fuel Engine Performance and Emissions." *Journal of Energy Resources Technology* 143, no. 5 (2021). https://doi.org/10.1115/1.4048505
[61] Mohammed, Haleemah J., and Nathera A. Ali. "Fabricating and study effect of the concentrations electrolyte for an alkaline electrolysis cell." In *AIP Conference Proceedings*, vol. 2144, no. 1, p. 030002. AIP Publishing LLC, 2019. https://doi.org/10.1063/1.5123072
[62] Abhilash, R., K. Gopalakrishna, and K. Venkatesh. "Performance evaluation of an IC engine using oxyhydrogen as a fuel supplement." (2015).
[63] LeRoy, Rodney L., Christopher T. Bowen, and Donald J. LeRoy. "The thermodynamics of aqueous water electrolysis." *Journal of the Electrochemical Society* 127, no. 9 (1980): 1954. https://doi.org/10.1149/1.2130044
[64] Opu, Md S. "Effect of operating parameters on performance of alkaline water electrolysis." *Int. J. Therm. Environ. Eng* 9 (2015): 53-60.
[65] Lavorante, María J., Carla Y. Reynoso, and Juan I. Franco. "Straight-Parallel Electrodes and Variable Gap for Hydrogen and Oxygen Evolution Reactions." *International Journal of Electrochemistry* 2019 (2019). https://doi.org/10.1155/2019/5392452
[66] Gad, M. S., Mahmoud MA Sayed, and Tarek A. Mahmoud. "Impact of HHO gas on diesel engine performance and emissions." In *2020 IEEE Aerospace Conference*, pp. 1-10. IEEE, 2020. https://doi.org/10.1109/AERO47225.2020.9172357
[67] Sharma, Pushpendra Kumar, Dilip Sharma, Shyam Lal Soni, Amit Jhalani, Digambar Singh, and Sumit Sharma. "Energy, exergy, and emission analysis of a hydroxyl fueled compression ignition engine under dual fuel mode." *Fuel* 265 (2020): 116923. https://doi.org/10.1016/j.fuel.2019.116923
[68] Subramanian, Balaji, and Venugopal Thangavel. "Analysis of onsite HHO gas generation system." *International Journal of Hydrogen Energy* 45, no. 28 (2020): 14218-14231. https://doi.org/10.1016/j.ijhydene.2020.03.159
[69] Jakliński, Piotr, and Jacek Czarnigowski. "An experimental investigation of the impact of added HHO gas on automotive emissions under idle conditions." *International Journal of Hydrogen Energy* 45, no. 23 (2020): 13119-13128. https://doi.org/10.1016/j.ijhydene.2020.02.225
[70] Aydin, Kadir, and Raif Kenanoğlu. "Effects of hydrogenation of fossil fuels with hydrogen and hydroxy gas on performance and emissions of internal combustion engines." *international journal of hydrogen energy* 43, no. 30 (2018): 14047-14058. https://doi.org/10.1016/j.ijhydene.2018.04.026
[71] Sazilin, Mat, S. B. Mohamed, A. Endut, M. F. M. Alkbir, R. Bwsar, A. Rosdi, and A. Syafiq. "Evaluation effect of plate electrode characteristics on engine speed performance in application of HHO generator for four-stroke engine." In *AIP Conference Proceedings*, vol. 2030, no. 1, p. 020304. AIP Publishing LLC, 2018. https://doi.org/10.1063/1.5066945