Isolation of hydrogen from water and its utilization as a co-fuel for trucks into fuel-efficient vehicles

Sittichot Kradang-nga[1], Pongsakorn Kachapongkun[1], Thee Chowwanonthapunya[2]
[1]Rattanakosin College for Sustainable Energy and Environment, Rajamangala University of Technology Rattanakosin, Phutthamonthon, Thailand
[2]Faculty of International Maritime Studies, Kasetsart University Sriracha, Chonburi, Thailand

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ABSTRACT

This research focused on the separation of hydrogen gas from water and its utilization as a supplementary fuel blended with the primary fuel of an internal combustion engine. The test was divided into two steps: evaluating the energy efficiency of the electrolyzer and conducting experiments on pickup trucks (common rail diesel engine, 2,499 cc) to determine energy savings and pollution emission. The results showed that the efficiency of the electrolysis system with an average electricity consumption of 125.74 W was 84.83 kWh/kgH_2 and the theoretical efficiency of the electrolyzer in separating hydrogen gas from water was 45.97%. Results from the test on a pickup truck using 100% diesel fuel and hydrogen-diesel dual fuel with loads of 1,850 and 2,100 kg over a distance of 11 km showed that using a hydrogen-diesel dual system resulted in fuel savings of 27.8% and 16.70%, as compared to that of using pure diesel fuel system. Besides, levels of black smoke, PM2.5, and PM10 of the hydrogen-diesel dual fuel system were lower than those of the pure diesel fuel system.

Corresponding Author:

Pongsakorn Kachapongkun
Rattanakosin College for Sustainable Energy and Environment
Rajamangala University of Technology Rattanakosin
Phutthamonthon, Nakhon Pathom 73170, Thailand
Email: pongsakorn.kerd@rmutr.ac.th

1. INTRODUCTION

In the current situation, fossil fuel reserves are diminishing, and prices are increasing. As a result, this trend is expected to continue as oil and gas fuels are non-renewable energy. Thus, the rising need for alternative renewable energy sources is obvious. Among many, an interesting choice is energy derived from separating hydrogen gas from water. In recent years, many countries around the world have faced significant issues with toxic dust, PM2.5 smog, and greenhouse gases [1]. A portion of these harmful emissions originates from the incomplete combustion in internal combustion engines. Nowadays, hydrogen fuel obtained from water presents a new alternative energy for automobile energy. The process involves separating hydrogen gas from water to be used as a supplementary fuel in conjunction with primary fuels such as gasoline and diesel. This hydrogen gas separation system is designed to produce hydrogen gas in quantities that match its consumption, thereby eliminating the need for a hydrogen gas storage tank. This system is simple to install and requires minimal space. It operates semi-automatically, controlled by a microcontroller [2]. The hydrogen gas separation from water, intended for blending with the main fuel of an internal combustion engine, utilizes the electrolysis process. Equipment is developed and designed to separate hydrogen gas from water, allowing it to be blended with either gasoline or diesel without the modification of existing engine configurations.

Because of its usefulness, the test of hydrogen gas as an alternative fuel for engines become a center of attention. Zhang *et al.* [3] and Tang *et al.* [4] measured the laminar flame speed of fuel blended with hydrogen in a constant volume container. Their results revealed that the laminar flame speed of hydrogen gas can reach up to 15 m/s. Sun *et al.* [5] investigated the effects of direct hydrogen injection on particulate number emissions. They reported that the hydrogen addition significantly reduced particulate number emissions, resulting in an increase in the sensitivity to ignition timing. Raviteja *et al.* [6] presented that adding hydrogen gas as a co-fuel to a gasoline engine reduced fuel consumption and simultaneously decreased greenhouse gas emissions. Luo *et al.* [7] studied the combustion knock in hydrogen internal combustion engines and their results indicated that combustion knock occurred at a relatively higher engine speed (more than 3,000 r/min) as compared to that taking place on gasoline engines. The results from previous studies indicate the effectiveness of the hydrogen gas used as an alternative fuel, particularly the important information related to internal combustion. However, the investigation on the use of hydrogen gas as a supplementary fuel in a common rail diesel engine is still limited, especially, the engine efficiency with the use of the electrolysis process with varying loads, energy consumption saving, and emission.

Therefore, this study aims to fill the gap by investigating the efficiency of the electrolysis process used in the pickup truck with no-load and load conditions. In this study, hydrogen gas was separated from water and then utilized as a supplement to the primary fuel of the internal combustion engine. The hydrogen gas separator was designed to produce hydrogen to meet the engine's requirements without the storage tank. All processes related to the hydrogen gas-producing system were controlled by the electronic control unit (ECU). The power control system and backfire flame control system were properly installed in the testing system to ensure the safe operation of this investigation. The electronic system was used to control the acceleration rate of the engine. When the engine stopped working, the system immediately shut down the gas production and the rest remained water stored in the water tank. The efficiency of the engine performance with the hydrogen fuel gas blended with oil fuel provided by this gas separator was then studied. At the same time, energy consumption savings and emissions were also investigated. This self-made hydrogen gas separator can distribute hydrogen gas to engines according to the actual operating conditions of the engine with the precise control of ECU. This system can be a prototype that can be further developed to be an alternative choice for automotive energy.

2. METHOD

Hydrogen gas (dihydrogen or molecular hydrogen) [8] is highly flammable and burned in the air at a very wide range of concentrations between 4% and 75% by volume [9]. The molar enthalpy of combustion for hydrogen was -286 kilojoules per mole (kJ/mol), as indicated by (1) [10]. Hydrogen gas forms explosive mixtures with air within a broad range of concentrations between 4% and 74% and with chlorine over an extensive range of concentrations between 5% and 95% [11]. The mixtures spontaneously explode by spark, heat, or sunlight. The hydrogen autoignition temperature in the air was 500 °C [12]. The pure hydrogen-oxygen flame emites ultraviolet light and is barely visible to the naked eye.

$$2\ H_2\ (g) + O_2\ (g)\ 2\ H_2O\ (l) + 572\ kJ\ (286\ kJ/mol) \quad (1)$$

Hydrogen gas is characterized as the smallest and lightest atoms among elements, and it is abundant in various compounds on Earth. Under normal conditions, hydrogen exists in a gaseous state. However, when the temperature decreases to -217 °C, hydrogen changes to a liquid state, similar to natural gas vehicles (NGV) [13]. Further lowering the temperature to -160 °C [14] results in the formation of liquid hydrogen normally referred to as liquefied natural gas (LNG). Hydrogen energy has been increasingly recognized as an alternative energy source due to its favorable physical and chemical properties. It combusts easily and produces no pollution because its combustion results in the formation of water (H_2O). Hydrogen is readily available as a basic element found abundantly in nature [15]. Current technologies have enabled the transformation of hydrogen in various forms into hydrogen gas for use as fuel [16], [17]. These technologies included thermal systems that converted natural gas into hydrogen [18], electrolysis that separated water using electricity, and other processes. To understand more about the usefulness of hydrogen, important parameters, i.e. heating value and molecular weight, of hydrogen and other commonly used fuels are given in Tables 1 and 2.

It is obvious from Tables 1 and 2 that among the listed fuels, hydrogen has the highest heating value and the lowest molecular weight. Thus, hydrogen has a high energy-to-weight ratio compared to other fuels. Apart from that, hydrogen has the highest flame speed and a wider ignition range in the air compared to other fuels [12]. Hence, hydrogen possesses several advantageous properties, which make it well-suited for blending with other fuels in appropriate ratios and subsequently enhancing combustion efficiency and pollution reduction.

Table 1. Heating value of hydrogen and different fuel types [12]

Fuel	State at 25 °C	Heating value (MJ/kg)
H_2	Gas	121.0
Natural gas	Gas	47.1
Gasoline	Liquid	44.41
Diesel	Liquid	39.6

Table 2. properties of each type of fuel [12]

Properties	Unit	H_2	Natural gas	Gasoline	Diesel
Molecular weight		2.02	16.04	100-105	200
Density at standard condition	kg/m^3	0.0838	128	718-778	848
Boiling point	C	-253	-162 to -88	27-225	360-160
Flash point	C	<-253	-184	-43	80-60
Flammability limit	vol %	4.0-75.0	0.15-3.5	1.4-7.6	0.6-0.1
Auto-ignition temperature	C	500	632-482	257	315
Flame speed	m/s	2.83	45.0	N/A	

Note: Standard conditions serve as the reference point for comparing gases.
These conditions refer to a gas at a temperature of 15 °C and a pressure of 1 atm

2.1. Principle and efficiency of the electrolysis of water

The process of separating hydrogen from water through electrolysis is an electrochemical process that involves essential components: the anode terminal, cathode terminal, power source, and an electrolyte solution. During the operation, a reduction reaction takes place at the cathode terminal, resulting in the production of hydrogen gas. Simultaneously, the generation of oxygen gas occurs at the anode terminal. The reactions in the electrolysis process can be summarized (2)-(4) [16]-[18].

- At the cathode

$$2H_2O\,(l) + 2e^- \; H_2\,(g) + 2OH^-(aq) \tag{2}$$

- At the anode

$$H_2\,(g) + 2OH^-(aq) \; \tfrac{1}{2}\,O_2\,(g) + H_2O + 2e^- \tag{3}$$

- Combination reaction

$$H_2O \; H_2 + \tfrac{1}{2}\,O_2 \tag{4}$$

2.2. Efficiency of the electrolysis process

Since the process of electrolysis requires a certain amount of electrical energy to separate hydrogen from water, the efficiency of the electrolysis process can be determined by comparing the high heating value (HHV) [6] of the hydrogen produced with the electrical energy input required. It can be expressed as follows: The energy efficiency of hydrogen-water electrolysis is inversely related to the voltage applied across 1 cell (electrode pair) in the electrolysis process. In theory, increasing the efficiency of the electrolyzer requires the use of a higher voltage closer to 1.482 volts, representing 100% efficiency. However, practical considerations such as electrical and thermal losses mean that the actual efficiency of the electrolyzer is lower than 100% due to higher voltages [19], [20]. Therefore, designing the voltage to 1 cell as close as possible to 1.482 volts maximizes efficiency in electrolysis processes.

2.3. Methodology

This research aims to develop a system for separating hydrogen gas (H_2) from clean water and using it as a supplementary fuel blended with the primary fuel in internal combustion or IC engines. This experiments differ from previous research because it can produce hydrogen gas according to the needs of the engine. All processes were controlled through ECU with the installation of the power control system and safety backfire system to ensure safety during operation. ECU regulated hydrogen production to meet the engine's needs. The electronic system controlled the acceleration rate of the engine. When the engine stopped working, the system immediately shut down the gas production and the remaining water was stored in the water tank, as shown in Figure 1.

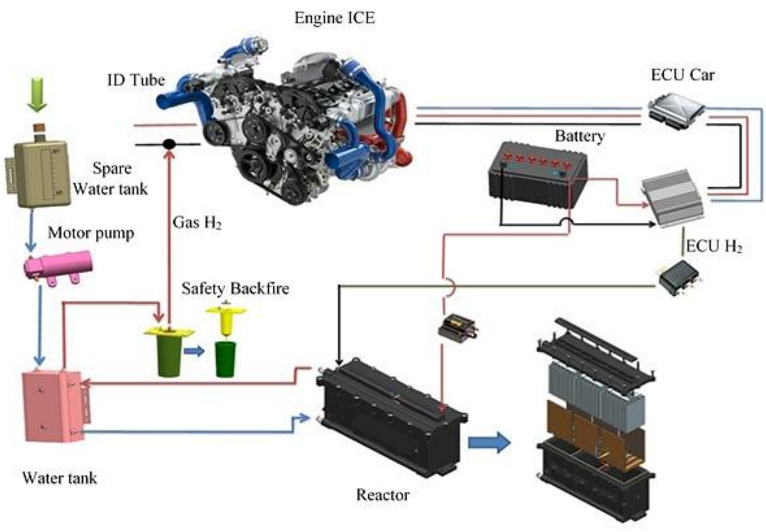

Figure 1. Diagram of hydrogen fuel in an engine

The hydrogen isolation set was designed as a system for separating hydrogen from water for blending with engine fuel. It was specifically constructed for use with a 2,500 cc engine (a small set suitable for engines not exceeding 3,500 cc). The system comprised one set, equipped with a control apparatus, featuring STL 316L metal cell plates. In total, there are three sets of hydrogen separators. Each set contains three channels and 14 electrodes (seven cathodes and seven anodes) with 42 plates. The hydrogen isolation set is depicted in Figure 2. Its results were also used for the comparison of fuel consumption rates between the pure diesel fuel and hydrogen-diesel dual fuel systems.

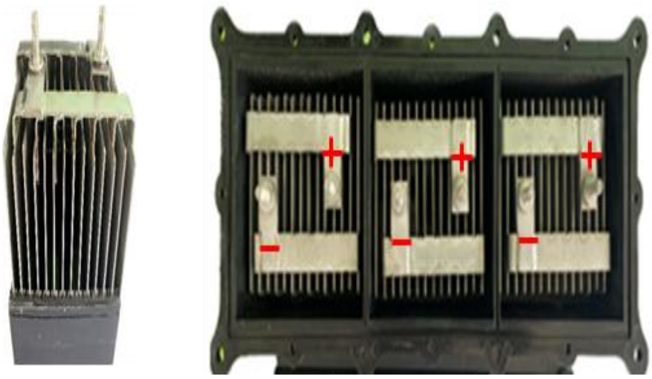

Figure 2. Set of equipment for separating hydrogen gas from water, using STL 316L stainless steel sheets, with a total of 3 sets

2.4. Results and discussion

In this study, a hydrogen separator from water was designed based on the “Safety Standard for Hydrogen and Hydrogen Systems: Guidelines for Hydrogen System Design, Materials Selection, Operations, Storage, and Transportation" by the National Aeronautics and Space Administration (NASA), United States [21]. The efficiency of hydrogen gas separation from water was measured using measuring instruments and electrolyzers. The positive poles of these devices were connected to the battery's positive terminals, while the negative poles were connected to the battery's negative terminals [22]-[24]. The values were recorded every minute for three hours. Electrical voltage was measured in volts, and current was measured in amps. Subsequently, after recording the lost water weight, the electrical energy consumption used in hydrogen production from the electrolyzer was determined by multiplying the measured electrical voltage and current. The quantity of lost water weight was then compared over time, as shown in Figure 3.

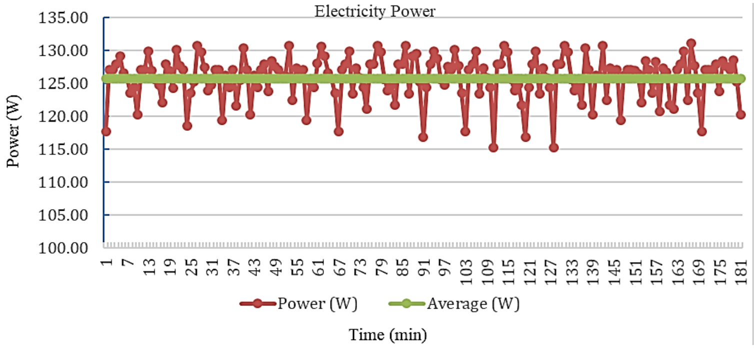

Figure 3. The electric power consumed by hydrogen gas separator from water

Figure 3 shows the electric power consumed by a hydrogen gas separator from water. The values were recorded every minute for three hours. It was found that the average electric power used in the process of separating hydrogen gas from water was 125.74 W, with a maximum value of 131.70 W and a minimum of 115.90 W. The average power was 14.00 V and 9.00 A. Hydrogen production from the electrolyzer led to a gradual reduction in the water level. In this experiment, the electrolyzer contained three liters of water, with an additional 1 liter in the storage tank. Consequently, the weight of the water in the storage tank was measured every minute for three hours, as illustrated in Figure 4.

Figure 4 shows the weight of water loss during the separation of hydrogen gas from water. It was found that in 3 hours, the weight of water loss was 40.02 g. The energy efficiency of the electrolyzer was calculated using following concepts. Since one gram of water contains approximately 1/9 g of hydrogen, in this case, the weight of water loss is 40.02 g, which can be converted to 40.02/9 gram of hydrogen in three hours. The average electrical power consumption was then calculated to be 125.74 W. Therefore, the energy efficiency of the electrolyzer in separating hydrogen gas from water was determined to be 84.83 kWh/kgH_2. Consequently, the theoretical efficiency of the electrolyzer in accordance with the hydrogen separation theory from water was at 45.97%. The flame characteristics from the electrolyzer were continuous, with an average flow rate of 0.89 cm^3/sec and an average hydrogen speed of 2.84 m/sec. Figure 5 shows images captured with a regular camera and images captured with an infrared thermometer.

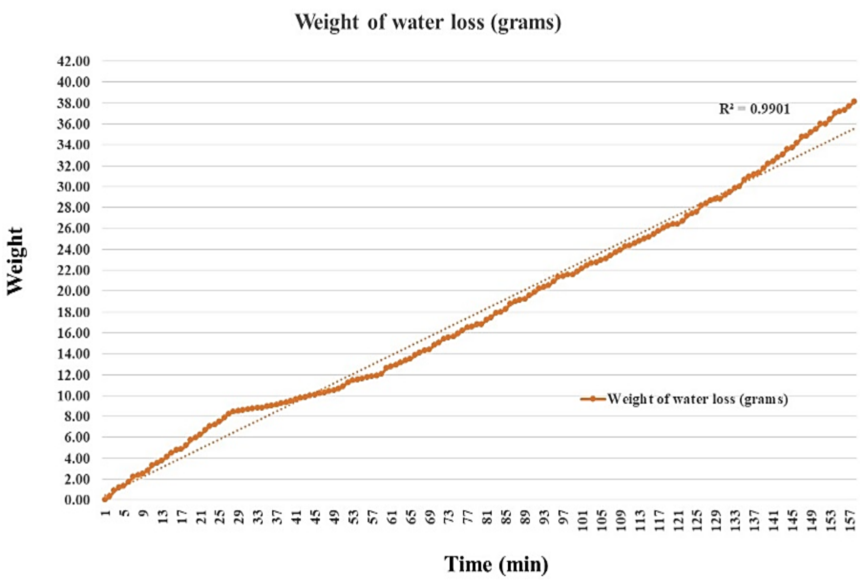

Figure 4. The weight of water lost during the separation of hydrogen gas from water

To evaluate the performance of the hydrogen separator, the actual test on the pickup truck, a common rail diesel engine with a displacement of 2,499 cc, was conducted. ECU was adjusted to match the engine's size and speed. To perform the test, the loads of the test ranging from from 1,850 to 2,100 kg were prepared from the arrangement of cement bags on the truck, as displayed in Figure 6(a). The test covered an 11-km distance along the same route. This test involved a comparative study between using pure diesel fuel and a hydrogen-diesel blend to determine fuel efficiency over the same route. The installation of a hydrogen separator from water in a car included several key components: a hydrogen production tank, a 1-liter water storage tank, a flashback arrestor, and an electronic control unit (ECU) for the engine, as shown in Figure 6(b). ECU for hydrogen production utilized a computer to adjust the system, reducing the amount of fuel injection and replacing it with the produced hydrogen. The design of the control system is shown in Figure 7. Figure 8 exhibits the control system tunning to gain the desired amount of fuel injection in the test.

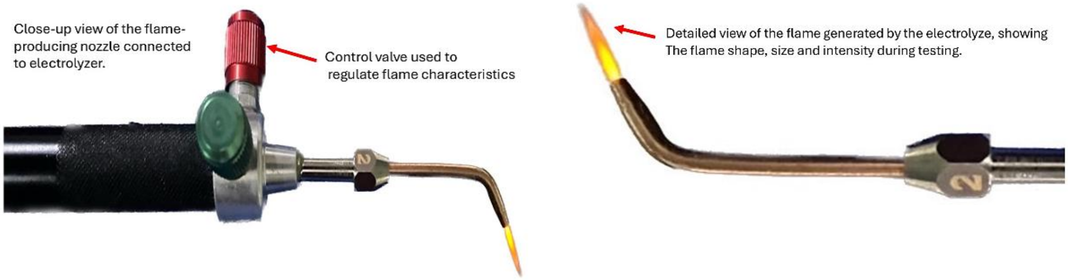

Figure 5. Characteristics of the hydrogen flame obtained from the electrolyzer

(a) (b)

Figure 6. Testing of pickup truck (common rail diesel engine 2,499 cc):
(a) load arrangement and (b) configuration of key components

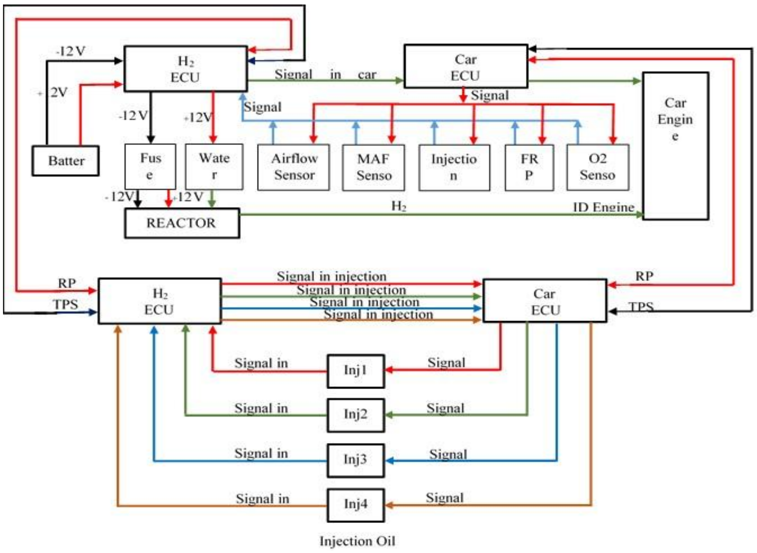

Figure 7. Control system design diagram to reduce signals in equipment and sensors in order to reduce fuel injection by using hydrogen gas as a replacement

The comparison of fuel consumption rates between using only diesel fuel and using diesel fuel combined with H_2 with a loaded weight of 1,850 and 2,100 kg at 11 km is shown in Figures 9 and 10. Figure 9 presents the fuel consumption rate over a distance of 11 km. The results indicate that at a load weight of 1,850 kg, using diesel fuel combined with H_2 results in greater fuel savings compared to using pure diesel fuel, with an average savings of 27.8%. For an increased load weight of 2,100 kg, the diesel fuel combined with H_2 achieves higher fuel savings than using pure diesel fuel, with an average savings of 16.70%. As the load weight increases, the engine requires more power, thereby increasing the need for fuel energy. Thus, the average fuel savings of the diesel fuel combined with H_2 system with the load weight of 2,100 kg is lower than that of the pure diesel fuel system.

Figure 8. The computer system tuning to control the amount of fuel injection

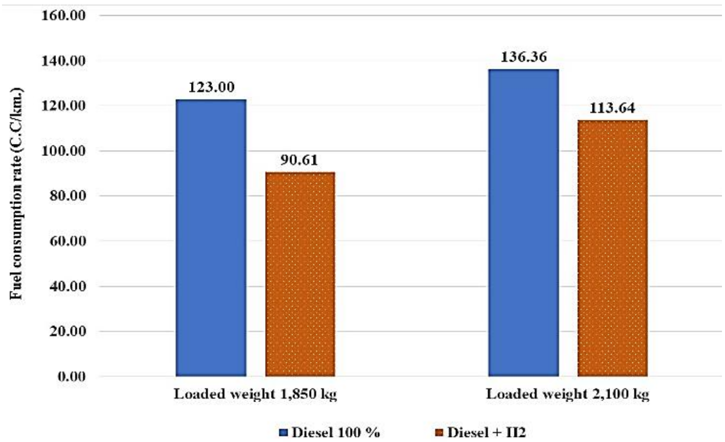

Figure 9. Fuel consumption rate test at a distance of 11 km

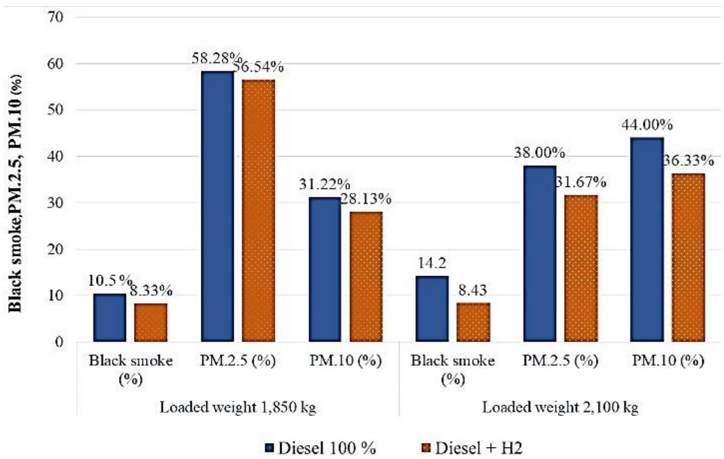

Figure 10. Testing levels of black smoke, PM 2.5, and PM 10 at a distance of 11 km

Testing the levels of black smoke, PM2.5, and PM10 with a load weight of 1,850 to 2,100 kg reveals that levels of black smoke, PM2.5, and PM10 of the hydrogen-diesel dual fuel system are lower than those of the pure diesel fuel system. As the load increases, black smoke emissions tend to increase, but the release of PM2.5 and PM10 decreases. These findings are agreeable with the results of the works provided by Wu *et al.* [25], indicating that the higher loads increased black smoke emissions. In this present work, the black smoke emission at a load weight of 2,100 kg was 8.43% when the hydrogen-diesel dual fuel was tested. This black smoke emission value is under the limitation given by the work conducted by Castro *et al.* [18].

3. CONCLUSION

An investigation on the efficiency of the electrolysis process used in the pickup truck was conducted. Based on the obtained results, the significant conclusions and suggestions are: i) The tests revealed that the energy efficiency of using electrolyzers, with an average electricity consumption of 125.74 W, was 84.83 kWh/kgH_2. In addition, the theoretical efficiency of the electrolyzer in separating hydrogen gas from the water was 45.97 %; and ii) Testing on pickup trucks with loads of 1,850 and 2,100 kg over a distance of 11 kilometers exhibited that using hydrogen-diesel dual system resulted in fuel savings of 27.8% and 16.70%, as compared to that of using pure diesel fuel system. Besides, levels of black smoke, PM2.5, and PM10 of the hydrogen-diesel dual fuel system were lower than those of the pure diesel fuel system. Thus, the use of hydrogen gas as a supplementary fuel by the self-made hydrogen gas separator in a common rail diesel engine can be an alternative choice for automobile energy. To achieve this goal in the future, the self-made hydrogen gas separator as the present prototype should be further developed for the higher engine capacity, and applying a new control-oriented method to control the amount of fuel injection in accordance with the actual use of the engines should also be performed in the near future.

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BIOGRAPHIES OF AUTHORS

Sittichot Kradang-nga received his bachelor's degree in industrial engineering from King Mongkut's University of Technology North Bangkok and master's degree in business administration from Ramkhamhaeng University in 1995 and 1998, respectively. He has more than 20 years of experience as an engineer and a production manager in the manufacturing industry. Currently, he is continuing his doctoral program at Rattanakosin College for Sustainable Energy and Environment Rajamangala University of Technology Rattanakosin, Nakhon Pathom, Thailand. His major research is related to renewable energy, power electronics, and energy storage. He can be contacted at email: sittichot.kra@rmutr.ac.th.

Pongsakorn Kachapongkun is an assistant professor at Rattanakosin College for Sustainable Energy and Environment Rajamangala University of Technology Rattanakosin, Nakhon Pathom, Thailand with over 20 years of experience in energy conservation. Dr. Pongsakorn Kachaponkul has contributed as an expert to the energy conservation project of the Department of Alternative Energy Development and Efficiency, Ministry of Energy, Thailand. His research interests include renewable energy, modeling, simulation, and energy efficiency analysis. He has experience in reviewing articles for peer-reviewed journals including SAU Journal of Science and Technology, Applied Science, and Engineering Progress. He can be contacted at email: pongsakorn.kerd@rmutr.ac.th.

Thee Chowwanonthapunya is an associate professor in the Faculty of International Maritime Studies, Kasetsart University, Sriracha Campus. He has more than 10 years of professional experience in petrochemical plants and power plants. He has a Doctor of Engineering in material science and engineering from the University of Chinese Academy of Science. He has published more than 30 papers in peer-reviewed journals including Corrosion Science, Journal of Materials Science and Technology, Journal of Alloys and Compounds, Construction and Building Materials, Chemical Engineering Journal, Progress in Organic Coatings and Colloids and Surfaces A: Physicochemical and Engineering Aspect. His major interests are materials, electrochemistry, and renewable energy. He can be contacted at email: thee.c@ku.th.