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## Article

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## Research paper

# Experimental study, energy assessment and improvement of hydroxy generator coupled with a gasoline engine

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## ABSTRACT

In this paper, retrofitting of a hydroxy (HHO) cell which is coupled to a gasoline engine is performed by investigating the effects of electrodes' shape and distances and the impacts of improvement technologies ultrasonic waves, DC pulsed power with various frequencies and magnetic field on the cell's bubble pumping efficiency and rate of HHO gas production. Subsequently, an energy analysis was performed to provide a comparison between different improvement technologies. As a result, by applying DC pulsed power with 300 kHz frequency to the HHO cell, highest HHO gas production rate, energy efficiency and lowest energy intensity is achieved among other technologies, however, it will allocate lowest surface intensity which leads to requiring more electrode surface area. In addition, employment of ultrasonic waves improves HHO gas production rate from approximately 6.4% to 52.4%, and it is possessed the highest surface intensity which result in requiring lowest electrode surface among other methods. Finally, the effects of superior improvement methods on the overall cost and weight of an HHO generator and its impacts on engine parameters are studied.

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## 1. Introduction

These days, Air pollutants such as CO and NO<sub>x</sub> caused lots of environmental problems. Scientist and engineers are trying to find the ways to overcome such problems which caused by them. Transportation system is one of the main sources of pollutant producer systems which generates large amount of pollutants every day.

Using clean fuels such as Hydrogen as an alternative of fossil fuels in transportation systems is recommended by many researchers as a solution which will reduce air pollutants made by internal combustion engines, sufficiently (EL-Kassaby et al., 2016; Chen et al., 2019; Ren et al., 2019; Polverino et al., 2019; Musmar and Al-Rousan, 2011; Al-Rousan, 2010; Karagöz et al., 2018). Furthermore, hydrogen gas is burned faster than other fossil fuels in engines, so it provides higher thermal efficiency and lower pollutant production than them. However, some dangerous obstacles are caused by mounting hydrogen fuel tank and injection system on vehicles. In addition, the risks of explosion of hydrogen tank mounted on a car or truck is a critical problem and it may cause life threat for passengers (Rodionov et al., 2011).

There are many types of water electrolyzers which can produce hydrogen gas. Moreover, production of large amount of hydrogen gas which can be fed to engine as its main fuel by water

electrolysis process is costly, because the electrolysis equipment is required high cost materials one of which is semi-permeable membrane. Semi-permeable membrane is employed in most of the mentioned electrolyzers to separate hydrogen and oxygen in convectonal electrolysis cells (Fig. 1a) and pure hydrogen and oxygen are generated at the end of the process (García-Valverde et al., 2012; Schmidt et al., 2017). In spite of that, by removing mentioned membrane from the cell (Fig. 1b), hydrogen and oxygen are mixed together and HHO gas will be generated (Masjuki et al., 2016; Yilmaz et al., 2010) which is noticed in this paper. One of the brilliant benefits of HHO electrolyzers is their lower cost materials compared to other types. Furthermore, HHO generator is used as a lightweight electrolyzer which can be mounted on vehicles to produce HHO gas exactly when it is demanded by engine to modify its combustion process (EL-Kassaby et al., 2016; Musmar and Al-Rousan, 2011; Karagöz et al., 2018). Injection of HHO gas to the engine improves its combustion performance and reduces engine emissions. There is a hypothesis which tells hydroxyl or HHO gas has higher heating value than the pure hydrogen gas (Santilli, 2003, 2006; Yang et al., 2013).

The energy efficiency of HHO electrolyzers plays key role in HHO on-board injection systems that researchers did not payed much attention to it. Nevertheless, most of mechanical engineering researchers focused on HHO injection in combustion chambers and investigating its effects on combustion characteristics.

Some researchers investigated employment of rod shape electrodes in electrolysis process (Mazloomi et al., 2013; Mandal

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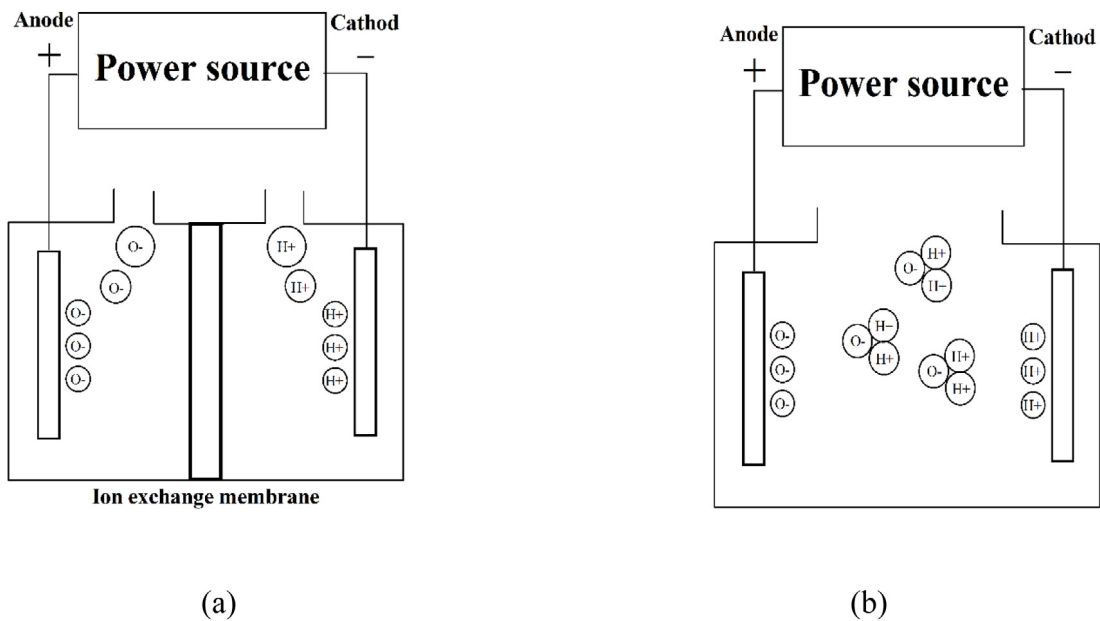


Fig. 1. Pure hydrogen (a) and HHO (b) gas production setups.

et al., 2012). Mandal et al. (2012) Examined the effects of Rod shape and flat shape electrodes on electrolysis efficiency. Besides, they have found that employment of Rod shape electrodes increases electrolysis efficiency by approximately 25% to 30%. In addition, Cylindrical shape electrodes and their application in water electrolysis are investigated by Chambers (2000) and Meyer (1990). Based on their claims, better performance was achieved by cylindrical cells than flat plate ones in water electrolysis process, however, they did not provide any scientific report for their claims.

There are too many researchers who believe employing power pulsation technology improves electrolysis performance efficiently (Mazloomi et al., 2013; Mandal et al., 2012; Demir et al., 2018; Shimizu et al., 2006; King, 2011). The majority of them focused on determining the effects of power pulsation on the cell's electrical properties. Additionally, Demir et al. (2018) has examined an alkaline electrolysis cell which has by power pulsation technology. They applied pulsed power with various frequencies to an alkaline cell. Based on their results, power pulsation technology reduces cell energy consumption (for production of 1 mol hydrogen) between almost 20% and 25%. Besides, Shimizu et al. (2006) has examined ultra-short power pulsation effects on cell efficiency and has found that the increase of power will not decrease electrolysis performance.

The ultrasonic waves were caused considerable increase in electrolysis efficiency reported by many researchers (Zadeh, 2014; Wang and Chen, 2009; Lin and Hourng, 2014). Ultrasonic waves with various field strength and its effects on cell performance is examined by Lin and Hourng (2014). They mentioned that marked growth of cell bubble pumping efficiency may occur by employment of ultrasonic waves which increases overall efficiency of electrolysis performance. Zadeh (2014) also used a sound horn to examine the effects of ultrasonic waves on an alkaline electrolysis cell which improved cell's gas production and energy efficiencies by 4.5% and 1.3%, consecutively. Substantially, it was found that the ultrasonic waves reduce cell power consumption and increases its production efficiency.

Lin et al. (2017, 2016) evaluated the effects of external magnetic field on water electrolysis performance. They used permanent magnets which produces magnetic fields with 4.5 tesla

strength. Moreover, magnetic waves increases cell hydrogen bubble pumping efficiency and hydrogen production performance by nearly 25%.

All in all, the most of the retrofitting parameters were examined by mentioned researchers for investigation of their effects on an alkaline electrolysis cell efficiency which has semi-permeable membrane. Therefore, the effects of them on HHO cells are not investigated yet. In this paper, HHO gas production of an HHO cell is evaluated by employing two flow meters, simultaneously, to provide high accurate measurement of HHO gas production. At the start of the experiment, electrolysis chambers, cylindrical and flat plate cells are built and the electrolysis performance of each cell with different electrode distances are examined by applying DC power to the cells which are mounted in electrolysis chambers. Then, the best shape and distance for electrodes is chosen according to the results. At next, the effects of ultrasonic waves, magnetic field and pulsed power on superior cell's electrolysis and bubble pumping efficiency and HHO gas production rate are tested. Following that, the energy analysis is employed to compare the effects of each parameter on electrolysis efficiency and other matters including power density and surface intensity of electrolyzer. Finally, the impacts of mentioned technologies employment in an on-board HHO injection system on engine output parameters are investigated.

## 2. Experimental setup

### 2.1. DC experiments

An experimental setup was designed for examination of the impact of mentioned parameters on an HHO cell hydroxyl gas production efficiency. Moreover, two types of electrolysis chamber were built for cylindrical shape and flat plate shape electrodes (Shown in Fig. 2). Fig. 2 indicates the experimental setup used for DC experiment on electrodes geometry which contains; (1) DC power supply, (2) Bubbler and (3) cylindrical and (4) flat electrodes electrolysis chambers. The changes of HHO cell's electrolysis efficiency by employing different electrode shapes with different distances were determined and a comparison between various cases was made by applying DC power to the cell. Then, the best electrode shape and distance were chosen, and other



Fig. 2. Different electrolysis chambers for cylindrical and flat plate electrodes experiments.

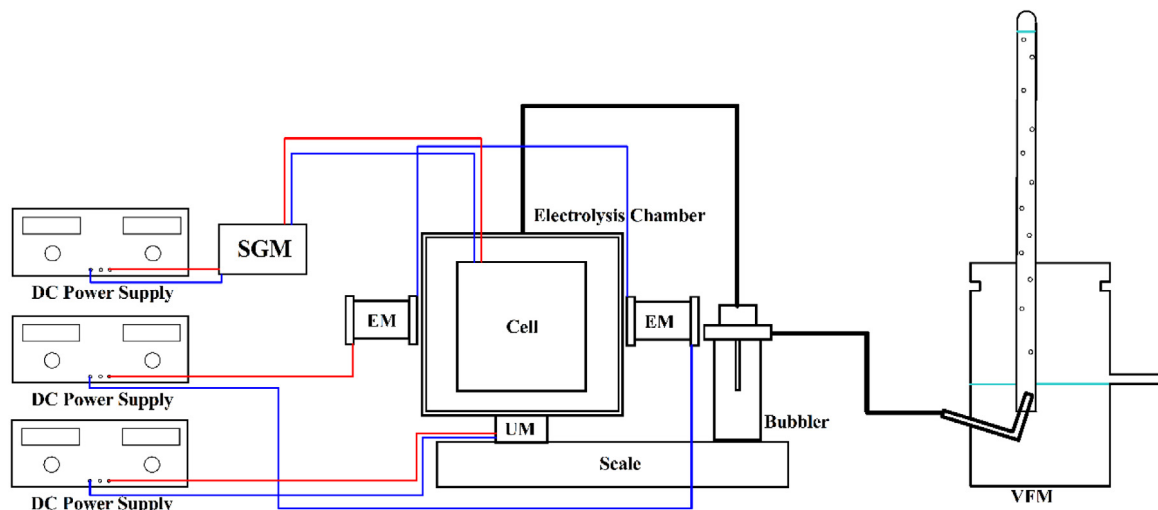


Fig. 3. Block diagram of experimental setup.

**Table 1**  
Cylindrical and flat plate Cells dimensions and their electrodes' distances.

Cell	Distance between electrodes [mm]	Cathode electrode dimensions [mm]	Anode electrode dimensions [mm]
A-F	2		160 * 160
B-F	3		160 * 160
C-F	6.5		160 * 160
A-C	2	32∅ * 200	25∅ * 200
B-C	3	38∅ * 200	32∅ * 200
C-C	6.5	38∅ * 200	25∅ * 200

efficiency improvement equipment were mounted on its chamber to examine of each improvement parameters' effects on cell's electrolysis efficiency. The dimension of flat plate and cylindrical cells and their electrodes' distances in experiments were given in Table 1.

## 2.2. Improvement technologies' experiments

The effects of improvement technologies such as ultrasonic waves, magnetic field and DC pulsed power on the cell' electrolysis efficiency and production rate were determined by adding external equipment to the cell chamber. Consequently, the experimental setup was upgraded as shown in Figs. 3 and 4 one of which has presented a block diagram of the upgraded experimental setup. In addition, as shown in Figs. 3 and 4, experimental setup consists of: (1) DC power supply, (2) Electrolysis chamber, (3) Bubbler, (4) Electrical magnet, (5) Scale, (6) Ultrasonic module

and (7) Signal generator (SGM). However, HHO Volume flow meter is not shown in Fig. 4.

As shown in Figs. 1 and 2, a digital scientific scale and a volume flow meter (VFM) were used for measuring the amount of HHO gas production in HHO cell, simultaneously. Additionally, by employing mentioned measurement equipment, amount of HHO gas production can be determined more accurately.

External magnetic field is created by two electrical magnets which are mounted at the outside of electrolysis chamber. Due to rising of electrolyte temperature and avoiding its effects on magnets, the magnets are mounted at the outside of the electrolysis chamber. Besides, electrical type magnets were chosen to investigate the effects of both permanent and non-permanent magnets in energy efficiency of the cell. Hence, the power consumption of electrical magnets was measured and considered in energy efficiency calculation when magnetic field is assumed to be made by non-permanent magnets. To examine the effects of ultrasonic waves on cell' electrolysis efficiency, an ultrasonic module was mounted at the bottom of electrolysis chamber. Moreover, a signal generator module (SGM) which was coupled to an amplifier was used to generate pulsed power with various frequencies in the experimental setup (Fig. 5). Furthermore, specifications of electrical magnets, ultrasonic module and signal generator module which were used in experiments are provided in Tables 2–4, respectively. Uncertainty of measurement devices are presented in Table 5.



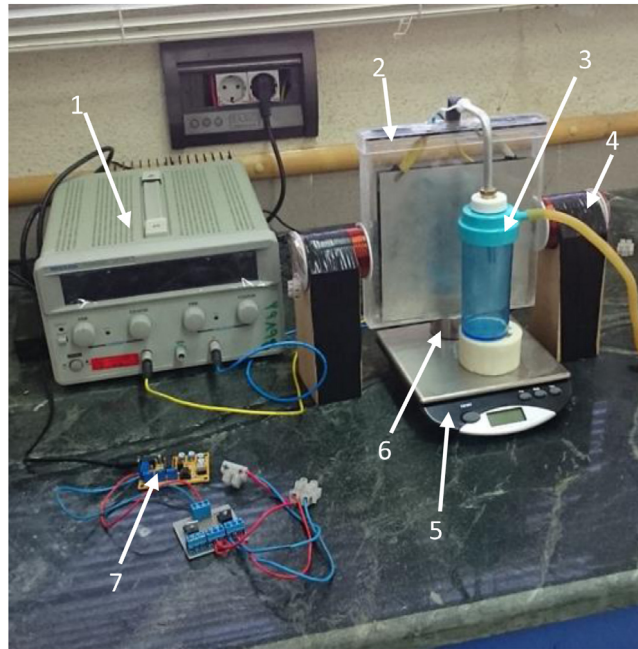


Fig. 4. Experimental setup equipment.

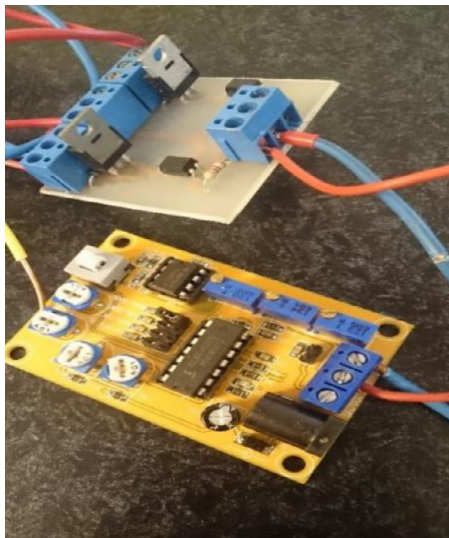


Fig. 5. SGM and amplifier.

Table 2  
Specifications of electrical magnets.

Parameter	Unit	Value
Material of wires		Copper
Material of core		Iron
Number of loops of wire around the iron core		600
Maximum voltage	V	4
Maximum strength of magnetic field	mT	32

### 3. Engine experimental data

Falahat et al. (2014) have been studied the effects of HHO gas injection in such a gasoline engine output parameter as brake thermal efficiency, specific fuel consumption, CO and NOx production. Hence, various amount of HHO gas were injected to the engine in different RPMs. Fig. 7 indicates the amount of each output parameter before and after the injection. The rate of

Table 3  
Ultrasonic module specifications.

Parameter	Unit	Value
Type		XQPA550-12
Size	mm	45*40
Working frequency	MHz	1.7
Working temperature	K	274–323
Power	W	20
Diameter of piezo-ceramics	mm	20

Table 4  
Signal generator module specs.

Parameter	Unit	Value
Frequency range	Hz	10 to 300 000
Duty range	%	2 to 98
Low temperature drift	ppm/K	50
Power supply	V	12 to 24
Amplifier maximum output	V	12

HHO gas injection was approximately 2 LPM. The specification of tested engine and the experimental setup which is used by Falahat are presented in Table 6 and Fig. 6, respectively.

### 4. Applied mathematical correlations

Some mathematical correlations are provided in this section to perform energy analysis of HHO cell:

$$PD = \frac{V \times I \times DU}{A_{cathod}} \quad (1)$$

where  $V$ ,  $I$  and  $DU$  are the applied Voltage and current and duty cycle of the power source and  $A_{cathod}$  is the area of cell's cathodic electrode.

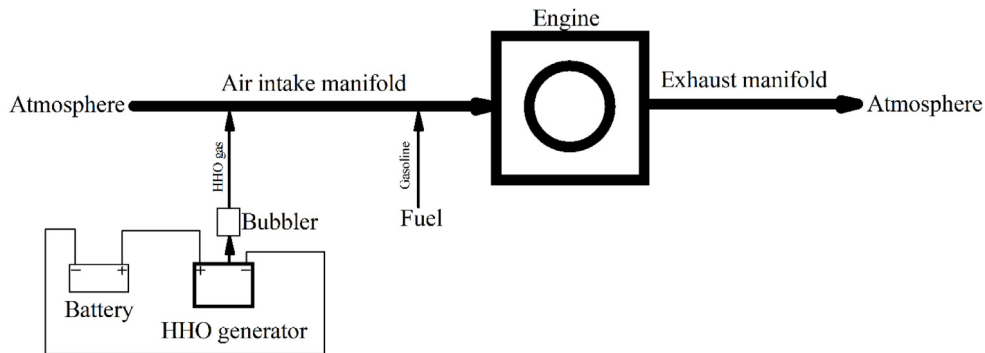
$$EE = \frac{\dot{m}_H \times LHV_H}{V \times I \times DU + E_{AUX}} \quad (2)$$

$$EI = \frac{V \times I \times DU + E_{AUX}}{\dot{V}_{HHO}} \quad (3)$$

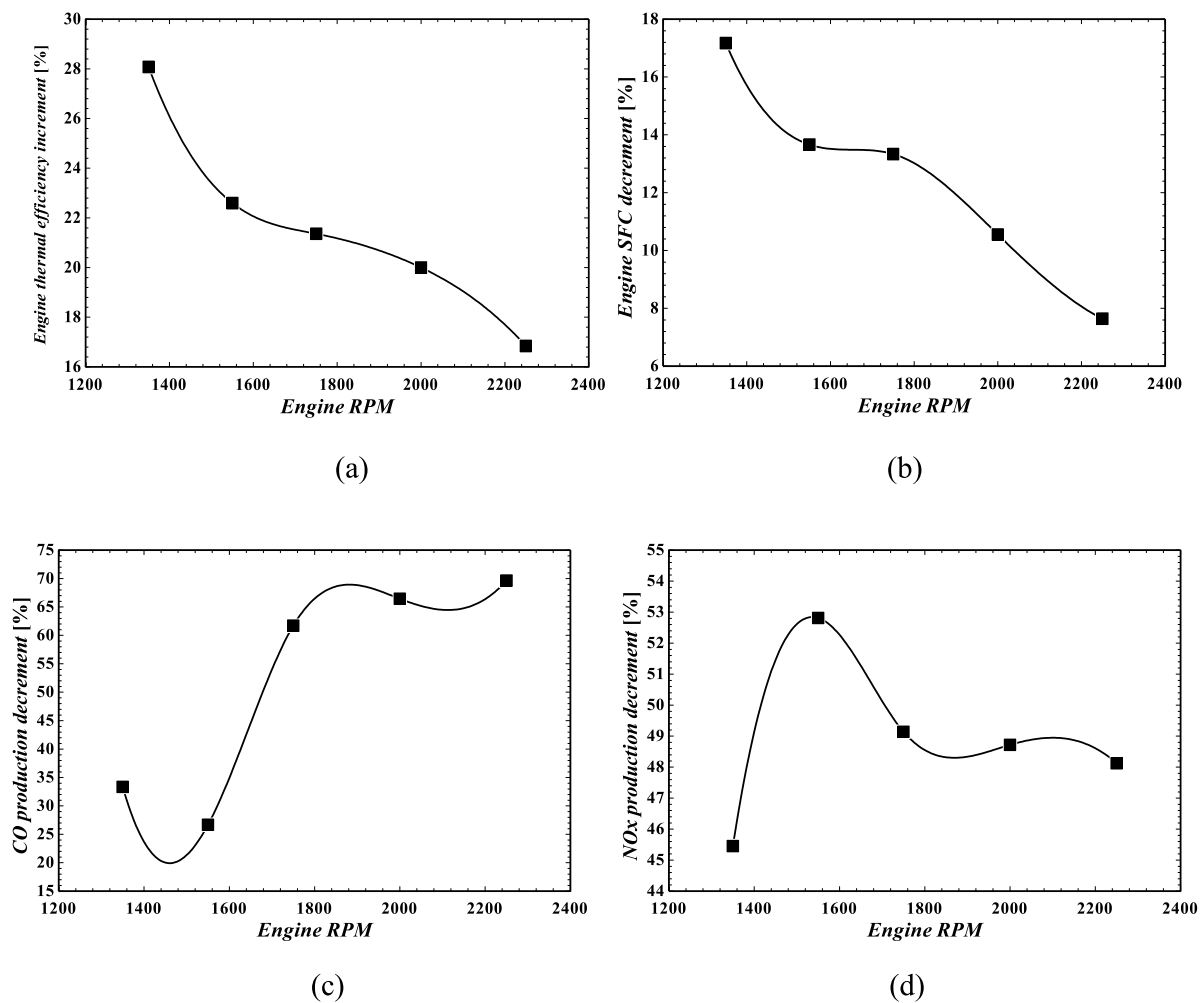
$$SI = \frac{A_{cathod}}{\dot{V}_{HHO}} \quad (4)$$

**Table 5**  
Uncertainties of the measurement instruments.

Parameter name	Unit	Measuring equipment	Nominal value range	Uncertainty	Maximum relative uncertainty [%]
Voltage	V	Multi-meter	3.5-6	$\pm 0.1$	2.8
Current	I	Multi-meter	5-10	$\pm 0.1$	2
Electrodes length	mm	Coulis	150	$\pm 0.02$	0.013
Volume	cc	Volume meter	10-50	$\pm 0.1$	1
Time	s	Stopwatch	60-180	$\pm 0.5$	0.27
Mass	gr	Scale	0.04-0.15	$\pm 0.002$	5



**Fig. 6.** Experimental set up which was used for determination of HHO generator effect on engine (Falahat et al., 2014).



**Fig. 7.** The impacts of HHO injection on engine: (a) brake thermal efficiency, (b) specific fuel consumption, (c) CO and (d) NOx generation in various RPMs.

**Table 6**

Technical specifications of engine Falahat et al. (2014).

Parameter	Unit	Value
Engine displacement	cc	197
Engine type	-	4 stroke
Bore	mm	67
Stroke	mm	56
Compression ratio	-	6.5
Rated speed	RPM	3600
Maximum power at rated RPM	kW	3.7

$\dot{m}_H$ ,  $LHV_H$  and  $\dot{V}_{HHO}$  are the mass flow rate, lower heating value of produced hydrogen and HHO volume flow rate in electrolysis process, respectively.  $E_{AUX}$  is the auxiliary device's power consumption.

## 5. Results and discussion

### 5.1. The impacts of cell's geometry and distance

The experiment setup which was discussed earlier, is used for investigation of each improvement parameters on electrolysis efficiency. At first, the concentration of KOH in electrolysis chamber electrolyte was set to lowest amount (5 wt) to neglect the effects of KOH on electrolysis efficiency. Next, Cell's geometry examination has been performed to determine the superior shape of electrodes. Accordingly, Electrodes which were illustrated in Table 1 were put in electrolysis chamber and a DC power applied to them. Next, the rate of produced HHO gas in various power densities and current densities were measured by flow meters. Moreover, maximum relative uncertainty of dependent parameters which are used in energy analysis such as volume flow rate, current density, energy intensity and surface intensity are calculated as 3.12%, 4.563%, 5.84% and 0.12%, respectively. Therefore, according to the results of experimental measurement error analysis which is performed during the tests, maximum uncertainty of experimental measurements and tests are below 10 percent.

Fig. 8 shows the rate of HHO gas production by each cell in various power densities. It can be inferred by Fig. 8 that the rate of HHO gas production has increased by the decrease of electrode distances. Consequently, distances between anode and cathode electrodes has affected cell's HHO production, significantly. The distance between electrodes has direct relation to cell's electrical resistance which can decrease by reducing electrodes' distance. On the other hand, the shape of each electrode has caused considerable effects on cell's gas production rate. It can be obviously determined by Fig. 8 that the HHO production rate of flat plate shape electrodes are higher than cylindrical ones. Therefore, flat plate cell which has 2 mm electrodes' distance (A-F) gained the highest HHO production rate among others.

The energy intensity of each cell in various current densities are indicated by Fig. 9. It can be clearly seen from Fig. 9 that by the increase of electrodes' distances, the amount of cell's energy intensity has risen steeply. Furthermore, A-F electrode's energy intensity which has the highest HHO production rate, has increased from 2.5 W/LPH to nearly 4 W/LPH by rising of cell's current density from approximately 100 A/m<sup>2</sup> to 400 A/m<sup>2</sup>. Additionally, it can be concluded that the cell's energy intensity is not sensitive to its shape.

As a result, A-F electrode was chosen as the best test sample among other samples which are provided in Table 1. At next, the concentration of KOH in electrolyte was changed to 25 wt which is the optimum value of KOH concentration mentioned by other researchers (Karagöz et al., 2018; Wang and Chen, 2009; Lin and Hourng, 2014).

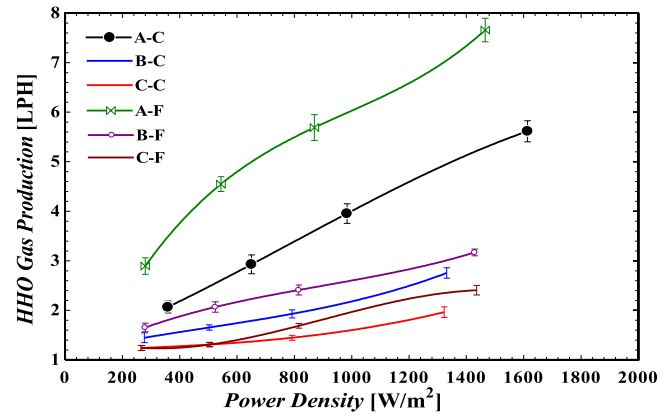


Fig. 8. HHO Gas production of each cell in various power densities.

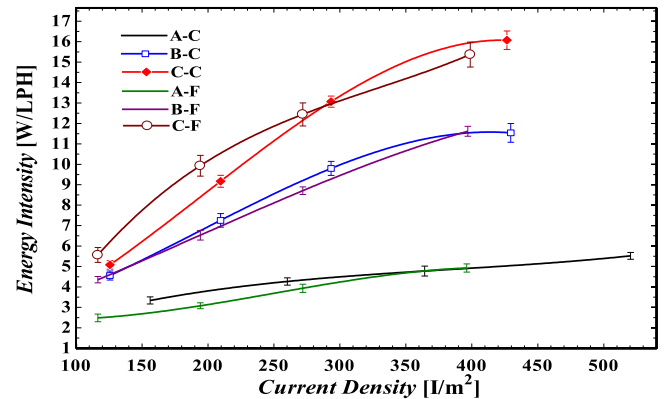


Fig. 9. Energy intensity of each cell in various current densities.

### 5.2. Evaluation of external parameters (retrofitting technologies)

As mentioned, the effect of other parameters such as ultrasonic waves, magnitude field and pulsed current are evaluated. First, the effects of ultrasonic waves on electrolysis efficiency was investigated. Fig. 10 indicates the rate of HHO gas production in ultrasonic assisted electrolysis in various power densities. Employment of ultrasonic waves in electrolysis process, increases bubble pumping efficiency of cell by pushing produced bubbles upward which results in decrement of cell resistance and electrolysis efficiency. Additionally, employment of ultrasonic waves in electrolysis process has increased the cell's rate of HHO production from nearly 6.4% to 52.4% compared to DC electrolysis in different power densities. Also, the effect of external magnetic field on HHO gas generation rate was presented in Fig. 11. It can be inferred from Fig. 11 that usage of magnetic field in electrolysis process has risen HHO gas production rate up to nearly 8 percent. The main cause of this efficiency increment is Lorentz force which increases bubbles pumping speed to leave electrodes surfaces faster. As a result, ultrasonic waves have caused have more positive impacts on gas production of the cell than external magnetic field.

Fig. 12 shows HHO production rate by applying DC pulsed power to the cell in different power densities. The impacts of pulsed power in various frequencies on HHO production rate was investigated in Fig. 12. Furthermore, the pulses' duty cycle was set to 10% which is reported as the optimum value in references. Moreover, Fig. 12 indicates that increase of pulsed power frequency leads to increment of cells gas production. The main cause of this increments in comparison with DC electrolysis,

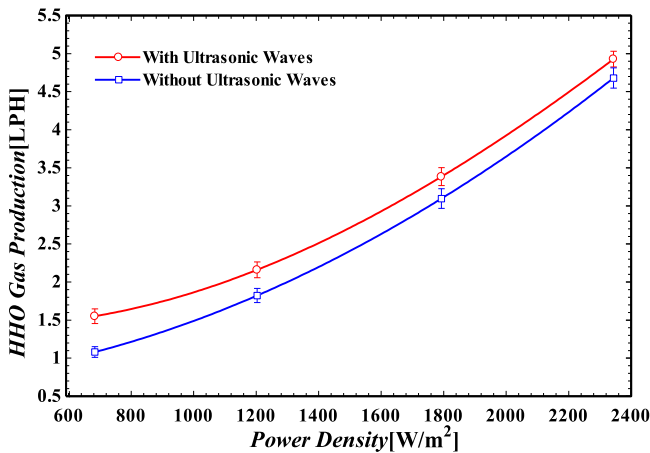


Fig. 10. HHO Gas production in various cell electrodes power densities with and without employment of ultrasonic waves.

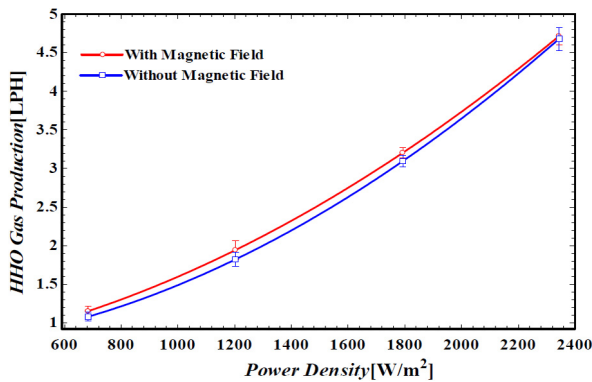


Fig. 11. HHO Gas production in various cell's power densities with and without Magnetic field assistant.

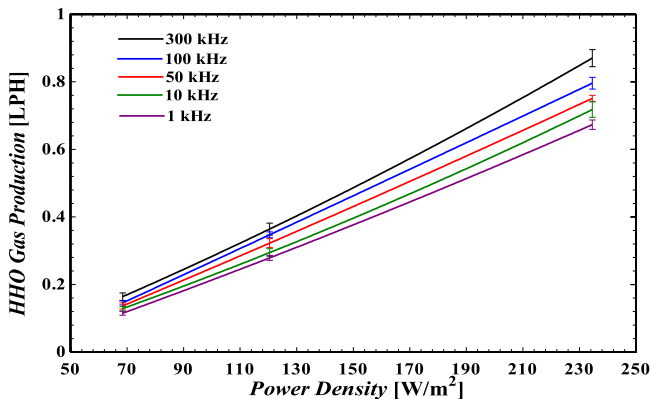


Fig. 12. HHO Gas production in various power pulsation frequencies in different power densities.

is that the bubble production rate on each electrodes is not continuously, therefore the electrodes surfaces are relaxed and cells' resistance would decrease. It can be demonstrated from Fig. 12 that pulsed power with frequency of 300 kHz has provided highest HHO production rate among other frequencies. However, due to employment of pulsed power, the cell's power density decreased dramatically. Therefore, it is the main disadvantage of DC pulsed power which required a battery in HHO electrical circuits.

The energy efficiency, energy intensity and surface intensity of the cell by employment of each retrofitting technologies in various current densities were calculated and shown in Figs. 13–15, consecutively. Moreover, DC pulsation power with 300 kHz frequency has allocated highest and the lowest energy efficiency and energy intensity among other retrofitting technologies, respectively, which has shown its superiority to other ones. However, the lowest surface intensity was owned by it which indicates that the usage of this technology has increased required cell's area leading to cause financial problems. Next to the DC power pulsations technology, the second place in highest energy efficiency was belonged to ultrasonic assisted dc electrolysis which has the lowest surface intensity among others, and has allocated a moderate energy intensity value between 12 W/LPH and 16 W/LPH. In addition, permanent magnets have increased cell's energy efficiency slightly while non-permanent ones have caused a reduction in it because of their auxiliary electrical power consumption. Consequently, it is not economical to employ electrical magnets in HHO generator. Also, non-permanent magnets have allocated highest energy intensity and the lowest surface intensity among other technologies except pulsed power.

As a result, ultrasonic assisted electrolysis provided better performance in surface intensity than other technologies. On the other hand, employing power pulsation technology in and HHO cell increased its efficiency dramatically and far higher than other retrofitting methods, however, its only disadvantage which is its poor energy density may cause some financial problems. Consequently, ultrasonic assisted electrolysis is preferred to DC pulsed power electrolysis when financial matter comes at first place.

Table 7 indicates the total required power and electrode surface area and their changes compared to DC by applying different retrofitting technologies for production of 1 LPH HHO gas at 390.6 l/m<sup>2</sup> of current density (highest amount of current density). Obviously, employment of electrical magnets increases demanded power and electrode area, so it is not recommended to use them for retrofitting of an HHO electrolyzer. In addition, a slight decrease is made by permanent magnets in mentioned parameters. Ultrasonic waves reduce cell's area and power demand by 4.32% and nearly 5%, respectively. Moreover, the lowest amount of required power belongs to pulsed power with 300 kHz frequency, however, it has the lowest surface area increment in comparison with other frequencies which makes it the best choice among other frequencies. Nevertheless, by the rise of pulsed power frequency, cell's power consumption increased and its required surface area decreased. As a result, an energy-economical trade-off should be done between the mentioned retrofitting technologies to choose the best one.

### 5.3. Determination of impacts of HHO generator energy efficiency improvement on engine

HHO generators are used in internal combustion engines to reduce their emission production and specific fuel consumption (SFC) and increase their thermal efficiency as mentioned in introduction section. Engine experiment data which was explained in Section 4, were employed to compare the DC and two superior retrofitting technologies such as Ultrasonic assisted and pulsed power electrolysis. Fig. 16 indicates how much power needed to be consumed by HHO generator to reduce 1 percent of engine SFC, CO, NOx and increase 1 percent of engine thermal efficiency. It can be figured out from Fig. 16 that amount of power used by HHO generator for reduction of engine pollutions and SFC by DC and ultrasonic assisted electrolysis are nearly the same, however, when the pulsed power applied to the generator, significant changes in generator's power consumption are



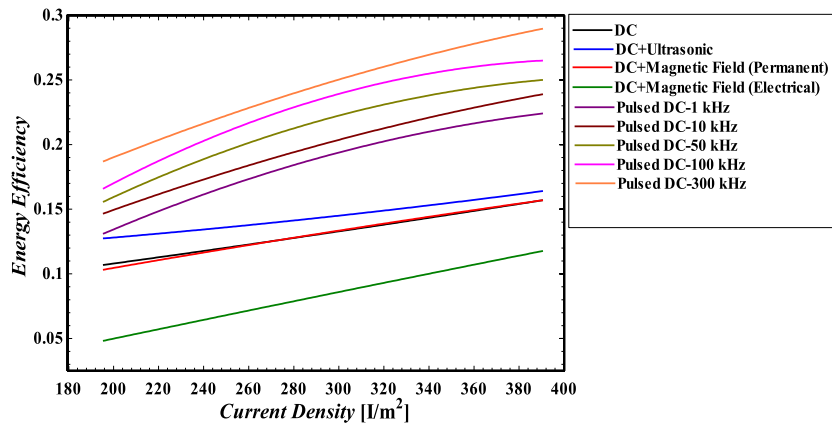


Fig. 13. Energy efficiency of HHO cell in various cell's power densities by employing different retrofitting methods.

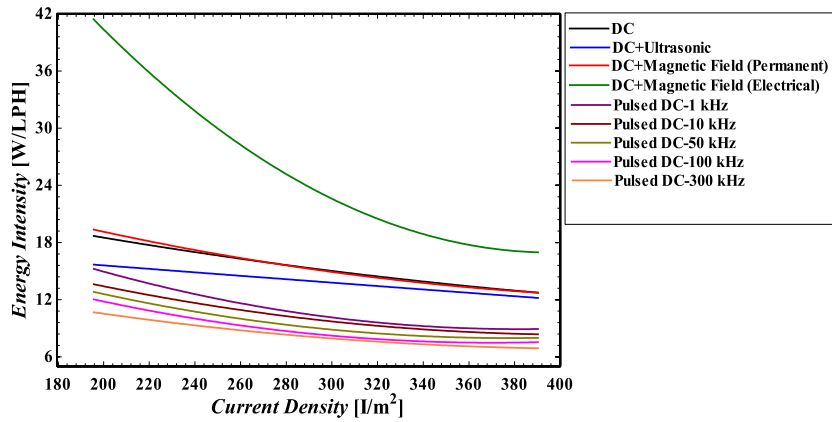


Fig. 14. Energy intensity of HHO cell in various cell's power densities by employing different retrofitting methods.

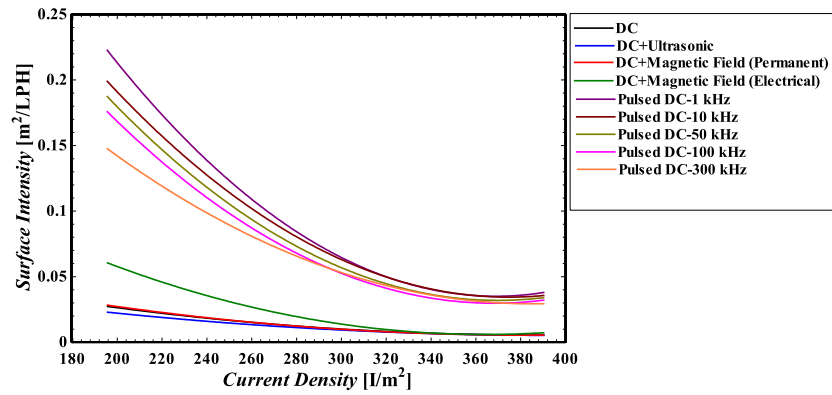


Fig. 15. Surface intensity of HHO cell in various cell's power densities by employing different retrofitting methods.

**Table 7**  
Amount of demand power and required surface area and their changes by employing various retrofitting technologies.

Applied technologies	Demanded power [W]	Demanded power change [%]	Required surface area [m <sup>2</sup> ]	Required surface area change [%]
DC	12.72	0	0.005428	0
Electrical magnets	16.96	33.33	0.007238	33.35
Permanent magnets	12.68	-0.31	0.00532	-1.989
Ultrasonic module	12.17	-4.32	0.005154	-5.047
Pulsed power (300 kHz)	6.894	-45.80	0.02942	442
Pulsed power (100 kHz)	7.537	-40.75	0.03216	492.48
Pulsed power (50 kHz)	7.989	-37.19	0.03409	528.039
Pulsed power (10 kHz)	8.357	-34.3	0.03566	556.96
Pulsed power (1 kHz)	8.913	-29.92	0.03803	600.63

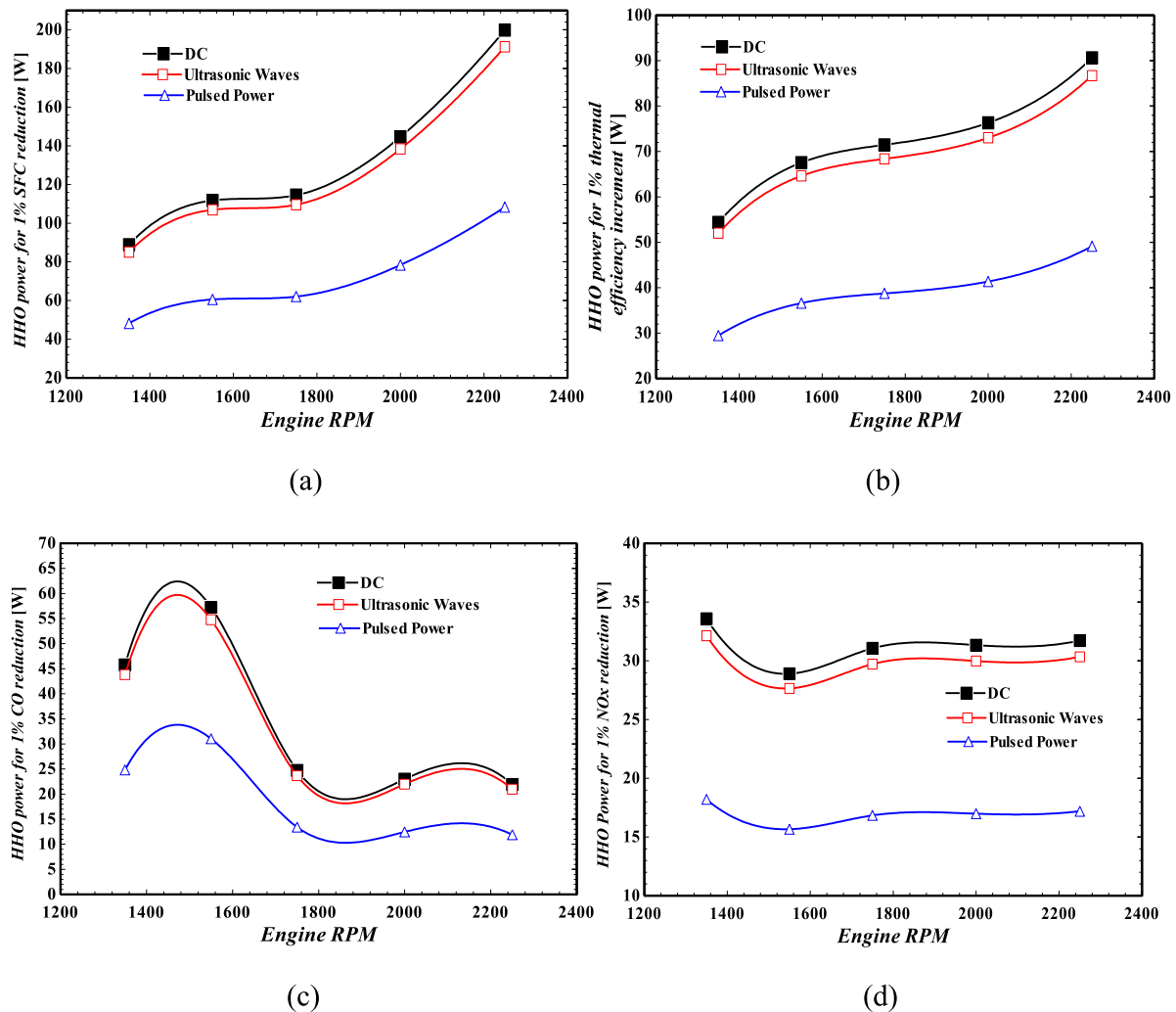


Fig. 16. Amount of HHO power consumption for one percent (a) engine SFC reduction, (b) engine thermal efficiency increment, (c) engine CO reduction and (d) engine NOx reduction in various engine RPMs.

made. Due to employment of pulsed power technology, amount of required power for reduction of 1 percent of engine SFC has decreased between 50 W and 100 W in various RPMs, however, ultrasonic assisted dc technology reduced it from 3 W to 10 W in various RPMs. In addition, Power to CO and NOx reduction ratio are changed between 40% and 60% by application of pulsed power in HHO generator compared to DC while it is improved by nearly 6 percent when ultrasonic waves are employed. However, Table 8 shows the extra cost and weight which will be added to the vehicle by employment of mentioned technologies. Additionally, employment of pulsed power increases HHO generator electrodes' weight from 5.211 to 28.246 and the cost of HHO generator will increase approximately 6 times higher than DC. On the other hand, Ultrasonic assisted electrolysis decreases HHO generator's cost and weight by 6\$ and approximately 0.25 kg, respectively.

## Conclusion

In this paper, the effects of many improvement parameters and retrofitting methods which increases HHO cell bubble pumping efficiency and production rate were investigated. For determination of superior geometry of the cell, two electrolysis chambers were designed to examine the effects of cylindrical and flat plate electrodes with different distances in HHO cell's gas

production rate and electrolysis efficiency. Then, the effects of such performance improvement methods as employing ultrasonic waves, external magnetic field and pulsed power in HHO cell were studied. Additionally, the performance of HHO cell by using mentioned methods was compared to each other by applying energy analysis. The results can be used as a reference for researchers who want to design an HHO electrolyzer for different purposes. The main conclusions which are drawn from paper can be listed as below:

- Flat plate cell which its electrodes have 2 mm distance provided highest HHO production rate and lowest energy intensity among other cells
- By applying DC pulsed power with 300 kHz frequency to the mentioned HHO cell, highest HHO gas production rate was achieved among other frequencies
- Ultrasonic waves and external magnetic field improved HHO production rate by from approximately 6.4% to 52.4% and up to nearly 8 percent, respectively
- The highest energy efficiency and lowest energy intensity were provided by applying DC pulsed power with frequency of 300 kHz to the HHO cell among other methods
- DC pulsed power electrolysis imposed the lowest surface intensity among other methods leading to requiring far higher electrode surface than other methods

**Table 8**

The changes in electrodes surface area and HHO generator costs made by applying retrofitting technologies.

Applied technologies	Electrodes total surface area [m <sup>2</sup> ]	HHO generator cost [\$]	HHO generator electrodes weight [kg]
DC	0.65136	119.17	5.211
Ultrasonic module	0.61848	113.16	4.948
Pulsed power (300 kHz)	3.5308	646	28.246

- Ultrasonic assisted electrolysis has a lower energy efficiency and intensity than DC pulsed power electrolysis, however, it is owned the highest surface intensity which result in requiring lowest electrode surface among other methods
- Due to the rise of pulsed power frequency, cell's power consumption increased and its required surface area decreased. As a result, an energy-economical trade-off should be carried out between the mentioned retrofitting technologies to choose the best one.
- Due to employment of pulsed power technology, amount of required power for reduction of 1 percentage of engine SFC has decreased between 50 W and 100 W in various RPMs, however, ultrasonic assisted dc technology reduced it from 3 W to 10 W in various RPMs.
- Power to CO and NOx reduction ratio are changed between 40% and 60% by application of pulsed power in HHO generator compared to DC while it is improved by nearly 6 percent when ultrasonic waves are employed.
- HHO generator electrodes' weight increases from 5.211 to 28.246 and the cost of HHO generator will increase approximately 6 times higher than DC. On the other hand, Ultrasonic assisted electrolysis decreases HHO generator's cost and weight by 6\$ and approximately 0.25 kg, respectively.

#### Nomenclature

SGM	Signal generator module
PWM	Pulse width modulator
LHV	Lower heating value [kJ/kg]
$\dot{V}$	Volume flow rate [LPH]
$\dot{m}$	Mass flow rate [kg/s]
V	Voltage [V]
I	Current [I]
DU	Duty cycle
SFC	Specific fuel consumption [gr/kWh]
PD	Power density [W/m <sup>2</sup> ]
EE	Energy efficiency
EI	Energy intensity [W/LPH]
SI	Surface intensity [m <sup>2</sup> /LPH]
A	Area [m <sup>2</sup> ]
Subscripts	
AUX	Auxiliary
H	Hydrogen

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### CRediT authorship contribution statement

**Farhad Salek:** Conceptualization, Methodology, Validation, Investigation, Resources, Writing – original draft, Writing – review, editing, Visualization. **Mohammad Zamen:** Conceptualization, Validation, Formal analysis, Writing – review, editing, Supervision, Project administration, Funding acquisition. **Sayed Vahid Hosseini:** Methodology, Writing – review, editing, Supervision.

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