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Feasibility of Supporting Diesel Engine Using Solar–Hydrogen Energy Cycle

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Abstract. This experimental study evaluates the feasibility of supporting compression ignition engine that primary run on diesel fuel with hydrogen gas that is produced by solar-hydrogen cycle. A photovoltaic panel is used to produce hydrogen through electrolysis from solar energy. Different mass ratio of hydrogen enrichment to liquid diesel fuel are tested on an engine operating under fixed torque of 14.7 N-m and engine rotational speed of 1100 rpm. Under same loading condition, the study shows that hydrogen can be used to reduce diesel fuel consumption and CO_2 emission however this comes on the cost of increasing of NOx emission. The results show that beyond a maximum mass ratio of hydrogen-to-diesel of 9.7%, the engine starts knocking. The experiment shows that adding hydrogen to the air intake of a diesel requires a simple pluming operation in which hydrogen is allowed to enter the engine from the air intake manifold and hence the cost of retrofitting of current diesel engine is considered marginal.

1 Introduction

Hydrogen is a good candidate fuel that can replace or reduce the dependence on petroleum fuel. The clean burning characteristics and high performance of hydrogen fuel has led many researchers to investigate the use of hydrogen as a fuel [1]. The high self-ignition temperature has prevented the used of hydrogen fuel as a sole fuel in a compression ignition (CI) engine. Therefore, hydrogen is used as dual fuel and combusted with the presence of diesel fuel. In a dual fuel engine the main fuel is either carbureted or injected into the air intake stream with combustion initiated by diesel. The major energy is obtained from diesel while the rest of the energy is supplied by hydrogen. Adding hydrogen to diesel engine that operate primary by combusting diesel fuel has showed a significant improvement in engine efficiency (around 20%) [2] when compared to pure diesel combustion and an increase of 13% in NOx emission. Masood et al. [3] reported a brake thermal efficiency of 30% when hydrogen is used in the dual fuel mode with diesel at a compression ratio of 24.5. Lee et al. [4] studied the performance of dual hydrogen-diesel fuel engine by using solenoid in-cylinder injection and external fuel injection technique. Lee et al. has reported an increase in thermal efficiency of 22% for dual injection at low loads and 5% at high loads compared to direct injection. Lee et al. [5] indicated that in dual injection, the stability and maximum power is accomplished by direct injection of hydrogen. Das et al. [6, 7] have carried out experiments on continuous carburation, continuous manifold injection, timed manifold injection and low pressure direct cylinder injection. Das et al. reported that the maximum brake thermal efficiency of 31.3% is obtained at 2200 rpm with 13 N-m torque. Recently, Hamdan et al. [8] showed that the use hydrogen could boost compression engine efficiency by more than 10% and reduce specific fuel consumption by more than 35% at the same load. Hamdan et al. [9] has reported an increase in thermal efficiency of more than 35% for dual injection at low speed (1080 rpm) and more than 8% at high speed (1800 rpm), where diesel is injected at 35 degree from btdc. Also that increasing amount of hydrogen boosts the thermal efficiency of the engine [9]. As shown in earlier literature, the use of hydrogen fuel has great potential to cut the demand on liquid diesel fuel however it comes with the expense of increasing NOx emission. Therefore, the needs for techniques to hinder NOx emissions become more significant for dual hydrogen-diesel engine operation when compared to pure diesel operation. The NOx emission can be hindered in diesel engine by injecting steam to the combustion [10] or by operating alean mixtures combustion. The lean mixture results in lower temperature that would slow the chemical reaction, which weakens the kinetics of NOx formation [11, 12].

There are many techniques to prepare hydrogen. This study only focus on producing hydrogen using solar energy combined with water electrolysis process. There is two major approaches in utilizing hydrogen in transportation which are (1) combusting the hydrogen inside internal combustion engine as dual fuel [12] and (2) using the hydrogen to run hydrogen fuel cell which operates an electrical vehicle [13]. The first approach integrate Solar-Water electrolysis system with diesel engine [9] which is referred in this study as System-A. The second approach integrates Solar-Water electrolysis

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system with hydrogen fuel cell [13] which is referred in this study as System-B. Both these systems produce hydrogen using water electrolysis which is directly combusted in presence of diesel in System-A as proposed by Hamdan et al. [12] or converted to electrical power use hydrogen-fuel cell in System-B as proposed by Kelly et al. [13]. Both systems give step forward in achieving energy sustainability and a step forward on using hydrogen as fuel. The use of System-A is more favorable than using System-B due to the following: (1) the need for hydrogen station is optional, (2) smaller hydrogen station is needed, (3) lower cost (installation and initial), and (4) safer to the public. The hydrogen use as supplement in diesel engine (System-A) makes the need for hydrogen station optional since the diesel can run on diesel in case hydrogen is not available while System-B will not operate unless hydrogen is available. The need for smaller hydrogen station in System-A is due to the fact that hydrogen is used as supplement and not as main fuel as in System-B. The cost of System-A is much less than System-B since diesel engine can operate with hydrogen supplement just by introducing hydrogen through the air intake manifold for the diesel engine while System-B will need huge investment to replace automobile with electric fuel cell one. System-A is safer than System-B since System-A operates with hydrogen at standard condition and it does not require high pressure tank storage in the vehicle which exactly the opposite of what is needed in System-B.

Earlier works by Hamdan [9, 10] and his team showed that hydrogen enrichment has great potential in reducing the need of liquid diesel, while in this work the authors is testing the effect of hydrogen-oxygen mixture as a supplement to diesel engine. One way to produce hydrogen gas is by water electrolysis which also produces oxygen. In recent years different engineers tried to produce hydrogen and oxygen mixture using renewable solar energy [14]. This study is devoted to explore the feasibility of using such hydrogen-oxygen gas mixture that produced by water electrolysis in diesel engine [15]. The study is going to refer to hydrogen-oxygen gas mixture as gaseous fuel mixture which consists of 2 moles of hydrogen and one mole of oxygen (the ratio of hydrogen to oxygen is 2-to-1 based on volume). The reason that the study selected the volumetric ratio of 2-to-1 between hydrogen and oxygen is to emulate the gas mixture produced by water electrolysis. Using a dual engine configuration, the gaseous fuel is inhaled to the air intake manifold as a supplemental fuel which is combusted in the presence of diesel and thus replacing a portion of the diesel fuel needed to produce engine output power. The study reports the effects of hydrogen-oxygen mixture enrichment on the compression ignition engine operating with diesel liquid fuel as primary fuel, mainly by reporting engine efficiency, specific fuel consumption, and exhaust gas temperature and emissions.

2 Experimental setup

A schematic diagram of the engine with instrumentations is shown in Fig. 1. The test engine used is a single cylinder DI diesel engine, having a rated power of 5 kW that runs at a constant speed of 3600 rpm which is modified to work with gaseous fuel $(H_2 + \frac{1}{2}O_2)$ in the dual fuel mode where gaseous fuel is inhaled into the air intake manifold as shown in Fig. 2. No retrofit is done on the engine except the one related to introducing the gaseous fuel through the air-intake. For safety reasons a 3 meter copper tube is used to supply the gaseous fuel just to assure flame quenching in case of any back flame. To allow easier control of gaseous fuel flow rate, in this experiment gaseous fuel is produced by mixing hydrogen and oxygen from external tanks and is not produced by water electrolysis process. However the ratio of hydrogen to oxygen is kept 2 to 1 per volume to assure that results reflect engine performance while being supplied by gaseous fuel that is produced by water electrolysis. This point is crucial for the study since it demonstrates the benefits if integrating a solar photovoltaic and water-electrolysis system to current diesel engine.

The engine used in this study is Petter AC1 by Gussons type P8163 which is a four strokes compression ignition air-cooled engine. The engine size is 304 cc with 76.2 mm pore diameter and 66.7 mm stroke length. The engine has compression ratio of 17, a maximum power of 5 kW at 3600 rpm and a maximum torque of 15.6 N-m at 2650 rpm.

As shown in Fig. 1, gaseous fuel is introduced into the air intake manifold at atmospheric pressure. A pressure regulator as well as a volumetric rotameter are installed to control the hydrogen and oxygen flow rate and to keep fixed volumetric ratio of 2:1 between hydrogen and oxygen. The flow rate of air is measured using a calibrated orifice air-drum manometer arraignment as shown in Fig. 1. The diesel flow rate is measured by recording required time to consume fixed volume of diesel. The torque of the engine is measured through force transducer that is connected to an electrical dynamometer. The force transducer is calibrated before testing using fixed weight loading calibration test. The electrical dynamometer is used to load the engine.

In this study, four cases have been identified to understand the effect of gaseous fuel on diesel engine which are as follow:

1) Case (1): Combustion of pure diesel is used as baseline case.
2) Case (2): Combustion of liquid diesel as main fuel with 2.4% hydrogen enrichment to diesel calculated based on mass ratio.
3) Case (3): Combustion of liquid diesel as main fuel with 6.4% hydrogen enrichment to diesel calculated based on mass ratio.
4) Case (4): Combustion of liquid diesel as main fuel with 9.7% hydrogen enrichment to diesel calculated based on mass ratio.

For cases 2, 3 and 4 hydrogen is added with oxygen with ration of 2 mole ($2\ m^3$) of hydrogen to 1 mole of oxygen ($1\ m^3$) to make sure that the gaseous mixture represent the gas produced by the water electrolyzer. The exhaust emission are measured using VARIO plus SE

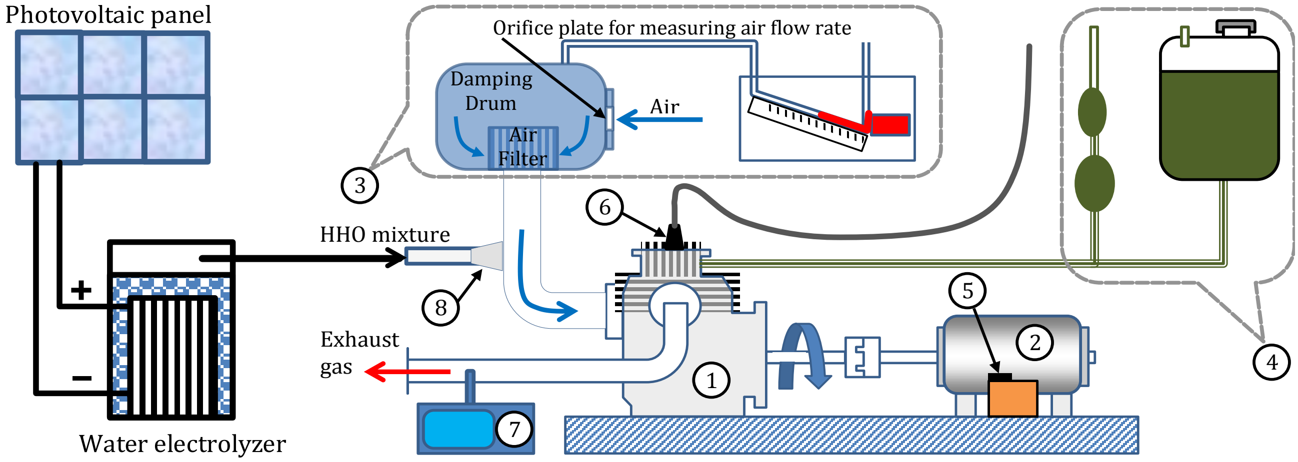

Figure 1. Schematic diagram for the engine test bed

instrumentation manufactured by MRU Instruments, Inc. The analyzer uses electrochemical sensors to measure the gas component concentrations in flue gases with accuracy of ±5 ppm for NOx. The unit is calibrated with regular air at standard conditions before start recording any measurements.

3 Mathematical analysis

The engine efficiency, specific fuel consumption and air-fuel ratio are calculated using equation (1) to (3) as shown below:

$$\eta = \frac{W_{out}}{Q_{in}} = \frac{T\cdot\omega}{(\dot{m}\times LHV)_{Diesel} + (\dot{m}\times LHV)_{H_2}} \quad (1)$$

$$sfc = \frac{(\dot{m})_{Diesel} + [(\dot{m})_{H_2} + (\dot{m})_{O_2}]_{gaseous}}{W_{out}} \quad (2)$$

$$AF = \frac{\dot{m}_{air}}{(\dot{m})_{Diesel} + [(\dot{m})_{H_2} + (\dot{m})_{O_2}]_{gaseous}} \quad (3)$$

The air-fuel ratio (AF) is calculated by dividing the amount of air consumed through the air-intake over the amount of added fuel which includes liquid diesel fuel and gas gaseous fuel. The lower heating value is used in the calculation since no vapor is condensed during the experiment. The density of hydrogen is calculated at atmosphere pressure and room temperature.

4 Results and discussion

4.1 Engine performance under different hydrogen to diesel mass ratios:

The study presents the effect of gaseous fuel enrichments on diesel engine under constant partial load of 1.69 kW (torque of 14.7 N-m and engine speed of 1100 rpm). The gaseous fuel consists of mixture of hydrogen and oxygen gases with volumetric ratio of 2:1 of hydrogen to oxygen. During the experiment, as the amount of gaseous fuel flow rate increases, the amount of diesel flow rate is reduced to maintain a fixed engine output power condition.

The effect of hydrogen content on the air-fuel ratio is shown in Fig.2. The pure diesel case is operated under air-fuel ratio of 17. It is necessary to mention that oxygen added with gaseous fuel mixture is considered as part of the fuel mass as shown in equation (3). The air-fuel ratio has non-monotonic relation with flow rates of gaseous fuel. For the case of 2.4% enrichment based on mass of hydrogen to diesel, adding gaseous fuel through the air intake has reduced the amount of air drawn to the engine however the amount of total fuel (diesel and H2) has dropped more since the energy added in the form of gaseous fuel has reduced the amount of diesel fuel needed to keep the engine at fixed load. Therefore from case 1 (no gaseous fuel) to case 2 (2.4% hydrogen enrichment), the amount of air has dropped but the amount of total fuel (diesel and gaseous fuel) has dropped even more causing the overall air-fuel ratio to increase. After that, for case 3 and case 4, as more gaseous fuel is added, the amount of inhaled air drops (since gaseous fuel is occupying the place of air) and that dominates the effect on air-fuel ratio and hence causes the reduction in air-fuel ratio as shown in Fig. 2.

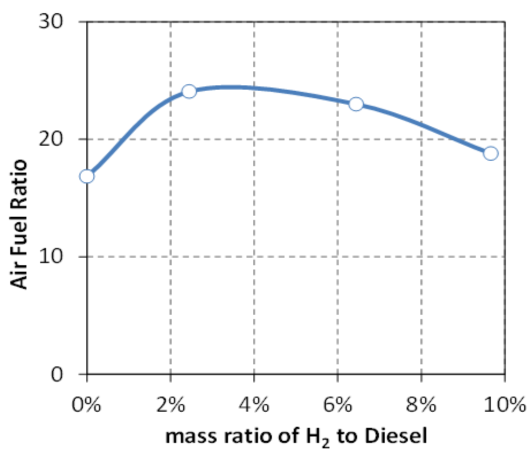

Figure 2. The effect of hydrogen enrichments on the air-fuel ratio at partial load of 1.69 kW.

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While adding gaseous fuel, the volumetric ratio of hydrogen to oxygen is kept fixed 2-to-1 which represent gaseous fuel produced by water electrolysis also it means that adding the hydrogen-oxygen mixture is not competing with diesel on available oxygen since every two mole of hydrogen will react with one mole of oxygen to form water vapor. Nevertheless, adding H_2 and $\frac{1}{2}O_2$ gas mixture reduces the demand of diesel hence the diesel will be combusted as leaner mixture and that explain the early rise in air fuel ratio shown in Fig.2 and the increase in efficiency as shown in Fig. 3. As amount of gaseous fuel enrichment is increased, Fig. 3 shows that engine efficiency is improving from 19% for pure diesel case up to 38% for gaseous fuel enrichment of 6.4%. The effect of amount of gaseous fuel enrichment when it is burned with diesel is shown in Fig. 3 where engine is operated at fixed load of 1.69 kW. The collected results show that the engine efficiency increases as gaseous fuel enrichment increases which is expected since the presence of hydrogen (1) rises the combustion temperature and (2) improves mixing. The rise in combustion temperature is due to the fact that hydrogen has high heating value compared to diesel (LHV of H2 is 120 MJ/kg while for diesel it is 42.5 MJ/kg) while the improvement in mixing is due to the fact that flame moves faster in hydrogen when compared to diesel.

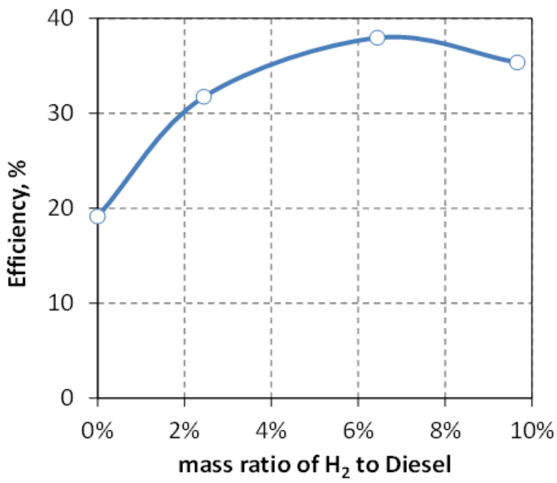


Figure 3. The effect of hydrogen enrichments on engine efficiency at partial load of 1.69 kW.

Another factor causes the increase in the engine efficiency is the high temperature that hydrogen can produce as shown in Fig. 4. This is expected since hydrogen will burn faster causing higher temperature and pressure rise when compared to pure diesel and hence it boosts engine efficiency. As shown in Fig. 4, the exhaust gas temperature keeps increasing with increase in the enrichment of the gaseous fuel. However this trend drops after the hydrogen to diesel mass ratio reach 6.4% and engine efficiency drops to from 38 to 36% at 9.7% mass ratio of gaseous fuel. It is noticed that any hydrogen to diesel mass ratio higher than 9.7% is causing unstable combustion since many time the engine backfired which also explains the drop in efficiency at 9.7% enrichment. The backfire has been observed when gaseous fuel enrichment reach 9.7% mass ratio or higher.

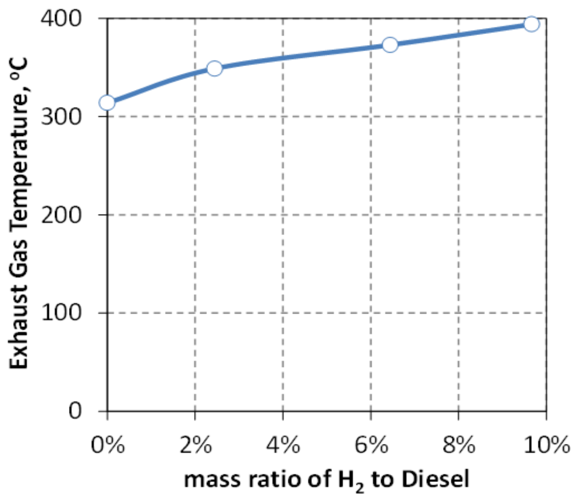


Figure 4. The effect of hydrogen enrichments on exhaust gas temperature at partial load of 1.69 kW.

Fig. 5 shows the specific fuel consumption for the engine under fixed partial load (engine torque at 14.7 N-and engine speed at 1100 rpm) for the four identified cases. At each case, the specific fuel consumption is calculate in three different ways which are demonstrated in the following equations:

$$sfc_{diesel} = \frac{\dot{m}_{diesel}}{W_{out}} \quad (4)$$

$$sfc_{gaseous\ \ fuel} = \frac{\dot{m}_{gaseous\ \ fuel}}{W_{out}} \quad (5)$$

$$sfc_{Total\ :\ diesel\ \ \&\ gaseous} = sfc_{diesel} + sfc_{gaseous} \quad (6)$$

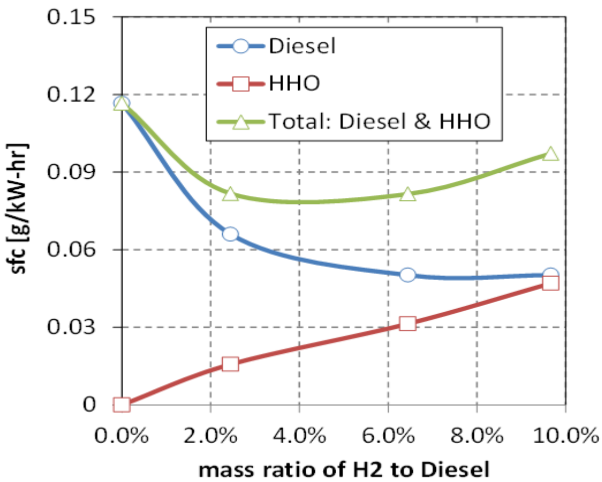
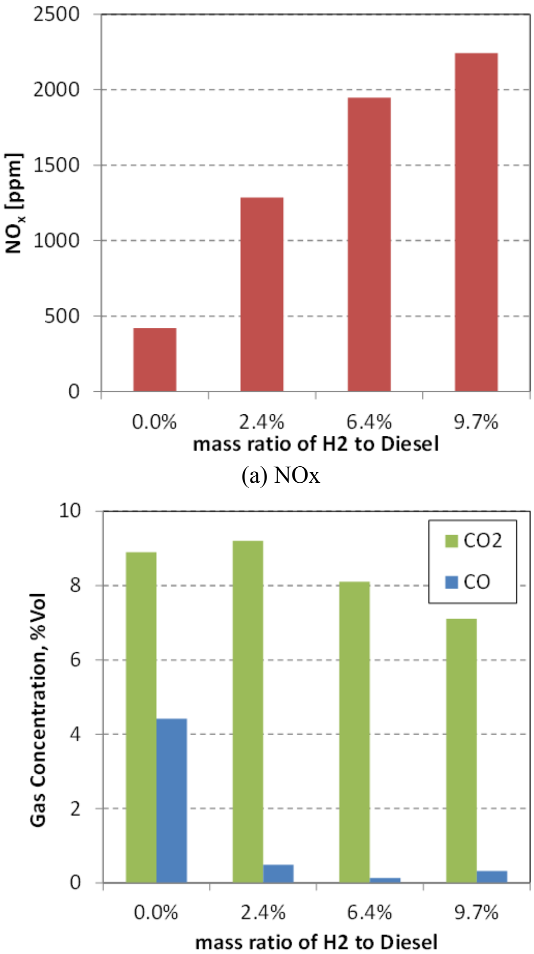


Figure 5. The effect of hydrogen enrichments on specific fuel consumption at partial load of 1.69 kW.

As expected, introducing gaseous fuel will reduce the diesel fuel consumption, hence it reduces specific fuel consumption (sfc) of diesel as shown in Fig. 6. The reduction in the diesel specific fuel consumption is more than the increase in the hydrogen specific fuel consumption since the LHV of hydrogen is 120 MJ/kg while for diesel it is 43.4 MJ/kg. While keeping power output fixed, Fig. 6 shows that the total specific fuel consumption decreases as gaseous fuel enrichment is introduced which is due to the enhancement in the engine efficiency and the higher LHV of hydrogen when compared to diesel. However at 9.7% gaseous fuel enrichment, the total specific fuel consumption starts to increase which means that we are running diesel as rich mixture since air flow rate has been partially replaced by gaseous flow rate which causes more fuel to escape the engine causing engine backfire which was observed during testing the engine at enrichment of 9.7% based on mass ratio or higher of the gaseous fuel.



(a) NOx

(b) CO_2

Figure 6. The effect of hydrogen enrichments on emissions at partial load of 1.69 kW

Also, Fig. 6 shows the engine emission and it is clear that as gaseous fuel enrichment increases NOx emission increases dramatically while the CO2 emission drop moderately. Also the amount of CO emission drop dramatically from pure diesel case when compared to the other cases which mean diesel is burned under rich mixture which is expected at part load. The NOx increases since hydrogen combust at high temperature when compared to diesel which stimulates NOx formation. The reduction in CO2 is expected since the amount of combusted diesel is decreased while the gaseous fuel enrichment increases. The combustion in the aid of gaseous fuel means more oxygen is available and at higher combustion temperature which increases engine break thermal efficiency however it increases NOx emission.

4.2 Case study: Sizing PV area needed for a 50 seats UAE University transportation bus

The fuel consumption of vehicle depends on many factors such as bus size, shape, engine technology, engine type, driving style, roads, number of stops, number of passengers, etc. These factor are not the target of this study hence they are not explored here. The author has selected a case study bus with fuel consumption of 0.6 mpg-US (39 L/100 km) [16]. The bus used in UAE university commute which is estimated to be around 300 km a day which put the fuel consumption to $= \frac{39}{100} * 300 = 117\, L = 97.34\, kg$ of diesel fuel. The total amount of energy produced by diesel is calculated based on lower heating value of diesel (43.4 MJ/kg) which will be 4224.6 MJ per day ($= 97.34\, kg * 43.4\, MJ/kg$).

For the case of 6% of diesel mass is being replaced with hydrogen, one can calculate the amount of hydrogen using the following equation:

$$4224.6 \frac{MJ}{day} = m_{H_2} * LHV_{H_2} + m_{Diesel} * LHV_{Diesel}$$

$$4224.6 \frac{MJ}{day} = 6\%\, m_{total} * LHV_{H_2} + 94\%\, m_{total} * LHV_{Diesel}$$

By substituting 120 MJ/kg and 43.4 MJ/kg for hydrogen and diesel respectively, the total fuel mass will be 88 kg (5.3 kg of hydrogen and 82.7 kg of diesel).

The size of the PV to produce this amount of hydrogen (5.3 kg) depends on the PV and water electrolysis efficiency and also depends on the expected solar radiation. The annual average solar radiation in Abu Dhabi is estimated to be 21.6 $MJ/m^2.day$ [17]. In this case study, the selected PV has an efficiency of 15% and the selected water electrolizer has an efficiency of 60%, hence one can calculate the size of the PV system as follow:

$$E_{Hydrogen} = E_s * \eta_{EG} * \eta_{PV} = 21.6 * 15\% * 60\% = 1.9\, MJ/m^2.day$$

$$E_{Hydrogen\ ,Combustion} = 5.3 * 120 = 636\, MJ/day$$

$$Area_{PV} = \frac{E_{Hydrogen\ ,Combustion}}{E_{Hydrogen}} = \frac{636}{1.9} = 335\, m^2$$

So the PV area needed to for each bus that consume 6% of total fuel mass of hydrogen is around 335 m^2. In case that hydrogen is used as sole fuel which is needed for electric bus with fuel cell, one can estimated the needed PV area for a single bus will be around 2224 m^2 which more than the need for 6 buses using System-A.

5 Conclusion

In this work, an experimental investigation has been conducted to examine the effect of combusting hydrogen which is produced through solar-electrolysis system. The produced gaseous fuel is testing in a dual fuel diesel engine at fixed output power of 1.69 kW (engine torque of 14.7 N-m and speed of 1100 rpm). For given engine specification, the data shows As gaseous fuel enrichment increases, the diesel specific fuel consumption decreases and engine thermal efficiency increases since hydrogen burn faster than diesel, has higher combustion temperature and has higher LHV. The engine backfire occurs when gaseous fuel enrichment reach 9.7% or higher. The addition of gaseous fuel increases NOx emission by more than 4 folds when compared to pure diesel case. The PV area required for a bus operating on dual hydrogen-diesel fuel is much smaller than the one needed for electrical bus that operate using fuel cell which mean smaller PV powering station is needed.

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