On-board generation of HHO gas with dry cell electrolyser and its applications: a review

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Abstract: In this era of depleting fossil fuels, alternative fuels and their study has gained much importance. One of the methods of using alternative fuels is operating the IC engines in dual fuel mode. This review is an attempt to highlight the investigations on the HHO gas supplemented combustion in the internal combustion engines, particularly the diesel operated ones. HHO gas has better burning characteristics than pure hydrogen since, hydrogen and oxygen does not attain the diatomic state. Hence, ideally HHO gas is having higher energy releasing capability. HHO inducted systems show better performance than that of the ordinary diesel engines in terms of brake thermal efficiency, specific fuel consumption and engine torque. However, the volumetric efficiency of these systems are relatively lesser. HHO inducted systems also show better emission characteristics. The emission of CO and unburned hydrocarbons are almost reduced by 30–40%. One of the major disadvantages of using HHO gas is the possible increase in NOx emission.

Keywords: dry cell electrolyser; HHO gas; dual fuel.

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1 Introduction

Fossil fuels are getting depleted day-by-day, since they are excavated from the limited known reserves available in the earth. In this context, the studies of alternative fuels that can be used without drastic changes in vehicle design is assuming importance. The ultimate alternative fuel of the present era is considered to be hydrogen. Hydrogen gas, as pure chemical, finds wide range of practical applications. When used for energy requirements, it has the added advantage (over the fossil fuels) due to its clean nature. In addition, hydrogen is found to be having good burning characteristics. The simple reaction of hydrogen with oxygen gives water and this remains as a clean method for the energy conversion. Even if hydrogen is not used as the sole fuel, it can be supplemented for combustion in engines, which can be easily operated in the dual fuel mode. In order to overcome the difficulties of storing the hydrogen gas, it is better if the hydrogen is generated on-board itself. One of the age old methods used for production of hydrogen is water electrolysis (application of Faraday's law). In a typical electrolyser, two electrodes (namely, anode and cathode) kept in an electrolyte solution (usually, NaOH or KOH). When a potential difference applied across the electrode, water molecules get splitted into hydroxyl gas, also known as the Brown's gas. Albeit the fact that, only a small quantities of hydroxyl gas can be produced, it shows a better performance and emission characteristics when used in the IC engines.

Compared to some of the earlier review works (Chauhan et al., 2015; Thanga and Lalnunthari, 2016; Kerkal et al., 2017), this paper tries to present some fabrication details of dry cell electrolyzers, production methods of oxy-hydrogen gas and its optimisation. They are included as separate sections. Thermodynamics of water electrolysis is also discussed in detail. Use of water electrolysis gas in IC engines is the major focus of this review paper, and it is elaborately summarised. Additional to the performance and emission characteristics, vibration studies, and modelling studies in the field of oxy-hydrogen dual fuel operation is included in the present review paper. The main objective of this review paper is to summarise the various studies in the field of HHO gas generation and its use in internal combustion engines. The paper also discusses how the dual fuel operation is beneficial in terms of performance and emission characteristics of the engine.

The content of this review paper is presented in eight sections, which is mentioned below.

The first section is the introduction section, which includes the general background work in this area and objectives of the present study. The second section is about HHO gas generation, which includes the water electrolysis process and different types of electrolyzers, such as wet cell, dry cell electrolyzers, their components, and fabrication. Types of cell configuration, such as mono-polar, bi-polar, and PEM electrolysis is also discussed in this section. Third section deals with investigations related to pure hydrogen induction in IC engines. The fourth section includes the studies on HHO induction in CI engines, which discusses the usage of HHO gas with bio-diesel, optimisation of HHO generation and its use in CI engines, combustion characteristics with HHO admission, vibration studies, and effect of magnetic field and compression ratio related to CI engines. The fifth section is about HHO induction in SI engines and their results. The sixth and seventh section explains about the economic and environmental benefits of using HHO gas in IC engines. Eighth section is conclusion, which includes the overall conclusion based on the findings related to the usage of HHO gas in the IC engines.

2 HHO gas generation

The HHO gas generation process from water using the dry cell electrolyser is similar to any other electrolysis process and requires anode, cathode, DC power source and the electrolyte solution. When the electric current flows, it causes the hydrogen and oxygen ions to be separated from the water molecule. Hydrogen is generated at the cathode and oxygen at anode. Since pure water is a bad conductor of electricity, electrolyser solution such as KOH (or NaOH) is added for increasing the number of ions and thus improves its electrical conductivity.

Table 1 Methods of HHO gas generation

Sl. no.	*Technology*	*Resources*
1	Bio-photolysis	Algae
2	Steam reforming	Natural gas or biogas
3	Partial oxidation	
4	Plasma reforming	
5	Gasification	Coal
6	Pyrolysis	Biomass
7	Water electrolysis	Water
8	Radiolysis	
9	Photo-electrolysis	
10	Alkaline electrolysis	
11	Proton-exchange membrane	

The hydrogen and oxygen ions are produced as bubbles and they grow in size and rise upwards due to the force of buoyancy. They accumulate at the top, where it can be stored or extracted. The generated hydrogen gas has very high level of purity (more than 99%). One mole of water gives one mole of hydrogen and half a mole of oxygen during the process of electrolysis. Various methods used for the generation of HHO gas in summarised and given in the Table 1.

2.1 Water electrolysis

The water electrolysis is a well-established, simple and efficient method for the generation of oxy-hydrogen. This method is cost effective and the HHO generation is possible on demand, which eliminates the need for storage requirements. Study of the energy interactions and the thermodynamics of water electrolysis are critical for the research and further development in this area.

Table 2 Properties of hydrogen

Properties	*Hydrogen*
Molecular weight (kg/kmol)	2.016
Density (kg/m^3)	0.082
Calorific value (MJ/kg)	119.81
Octane number	130
Flame velocity (m/s)	2.70
Auto ignition temperature (°C)	585
Carbon residue (%)	0.0
Minimum ignition energy (mJ)	0.018
Diffusivity in air (cm^2/s)	0.63
Boiling point (K)	20.27
Flame temperature (K)	2,300

The change in free energy in a reaction equals to the total reversible work obtainable from the reaction diminished by flow work, $P \Delta V$.

$$-\Delta G = W_{rev} - P\Delta V \tag{1}$$

where W_{rev} is the sum of all work obtainable from the reaction, exclusive of any work, which can be obtained from a possible volume change in the system. Equation (1) can be simplified, in the absence of flow work, as,

$$-\Delta G = W_{rev} \tag{2}$$

Equilibrium cell voltage (E^0) or electromotive force is the minimum voltage value which has to be overcome for the reaction to take place. It is the potential difference between the anode and cathode, with established reversibility, in the absence of cell current between the two different electrode reactions. E^0 is represented as the difference between anode and cathode potentials.

$$E^0 = E^0_{anode} - E^0_{cathode} \tag{3}$$

To transport the electrical charge through a potential difference E^0, work needs to be done. The electrical work for the charge transfer can be calculated by multiplying the number of charge transfer (n), the potential difference across which the charge moves and the Faraday's constant, F. Hence, the expression for work done in transporting of 'n' charge is obtained as nFE^0. Accordingly the, electrical work carried out in the reaction and total work obtainable from the reaction, excluding the volume change is given by,

$$W_{rev} = nFE^0 \tag{4}$$

Substituting for W_{rev} in equation (1), the expression for ΔG becomes,

$$-\Delta G = nFE^0 \tag{5}$$

The potential of individual half reactions at anode and cathode needs to be summed up in order to get the overall standard potential E^0.

$$\text{Cathode reaction}: \quad 2H_2 0 + 2e^- \rightarrow H_2 + 2OH^- \quad (-0.83\text{ V}) \tag{6}$$

$$\text{Anode reaction}: \quad 2OH^- \rightarrow 0.5O_2 + H_2 0 + 2e^- \quad (-0.4\text{ V}) \tag{7}$$

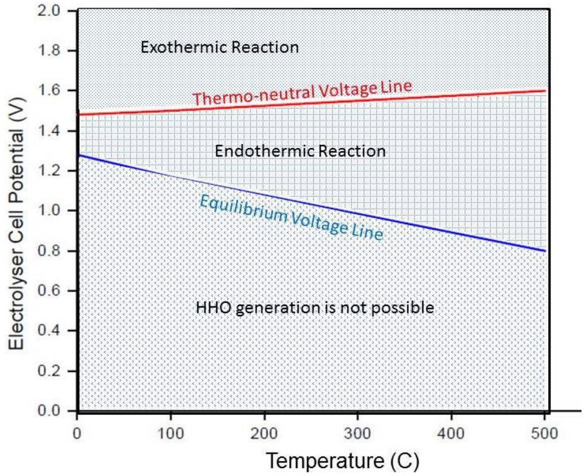
$$\text{Overall reaction}: \quad H_2 0 \rightarrow H_2 + 0.5O_2 \quad (-1.23\text{ V}) \tag{8}$$

These equations are applicable for the standard conditions of 1 bar and 298 K (STP). The equilibrium potential of the half reactions is given in equations (6) and (7) indicated by the corresponding voltage values. Equation (8) gives the overall standard potential for the full reaction. Here, the negative sign implies that, the energy needs is to be supplied for the reaction to take place. This shows that, under standard conditions, if a potential difference of 1.23 V is applied between anode and cathode, water molecule can be split into hydrogen and oxygen.

In standard conditions, a theoretical potential difference of 1.23 V is needed to perform electrolysis to split the water molecule to produce HHO gas. This voltage is according to the Gibbs free energy requirement for the process at the standard condition of 298 K and 1 bar. Equation (5) shows that, when the potential difference is negative, the value of Gibbs free energy is positive which implies that the reaction is not spontaneous. Accordingly, for a closed system, the heat supplied by environment will balance this and the water will retain its original temperature. Hence, it can be concluded that, heat is needed to be supplied from the environment to the system for an electrolysis process and similarly heat will be released to environment in the case of fuel cell reactions.

The potential difference corresponding to standard enthalpy ΔH^0 (285.5 kJ/mol) is called thermos-neutral voltage. At this particular voltage, the reaction to split water takes place without any need of heat from the environment. It is the potential difference at which the Gibbs free energy of reaction and the energy to maintain constant temperature of the water is getting matched. Figure 1 shows the plot of thermo-neutral and equilibrium potential difference lines with electrolyser cell potential on the y-axis and temperature on x-axis. These lines divide the plot into three distinct areas. The area below the equilibrium potential has no HHO generation at any temperature since equilibrium potential difference is the minimum cell potential for the reaction to be carried out. In the region above the thermo-neutral potential, the reaction is exothermic. In the region between the thermo-neutral and equilibrium potential, the reaction is endothermic (Ferrero et al., 2013; Petipas et al., 2014; Wang et al., 2014).

Figure 1 Electrolytic cell potential (V) variation with respect to temperature (C) (see online version for colours)



Source: Viswanath (2004)

2.2 *Wet cell electrolyser*

Wet cell electrolyser is the basic form of electrolytic cell, with electrodes generating hydrogen and oxygen at cathode and anode, respectively. The cell does not have any electrolyte circulation, since the electrodes are immersed in the electrolyte and are placed sufficiently apart. One of the major advantages of the wet cell electrolyser is its easiness in manufacture. As the setup is not very compact it faces problems in mobile applications. There occur losses and corrosion on the electrodes at the points which are immersed in electrolyte. Further, wet cell electrolyser tends to get overheated during its operation, which is considered to be a major limitation of these type of electrolytic cells for its practical usage.

2.3 *Dry cell electrolyser*

Dry cell electrolyser also uses water and the principle of operation is similar to that of the normal wet cell electrolyser. It is a design improvement over the normal cell where the electrolyte and the electrodes are in the same chamber. In a dry cell system, the reservoir and cell are apart. Only a small volume of water is exposed to the electrode plates. Hence, current requirement is less for dry cell than a normal cell. Normal cells need higher current for the generation of gas, since the current has to run through the water-filled chamber. Dry cell is able to produce more amount of HHO gas owing to the reservoir facility and higher surface area available for the reaction. Dry cell has a continuous circulation of electrolyte through the cell. For this purpose, the electrode plates are to be made with two passages for the entry of the electrolyte and for the exit of HHO gas from the cell. The entry of the electrolyte takes place from the bottom and fills the gaps of the plate. An insulating material such as the rubber gasket maintains the gaps between the electrodes. The splitting up of water to HHO gas takes place in this small gap between the electrolytic plates. The generated HHO gas move out through the holes provided at top of the plate. Electrolyte fills the voids caused by the evolution of HHO gas. The exiting fluid is a mixture of HHO gas as well as the electrolyte. This gets separated at the electrolyte tank provided outside the cell (Gollei et al., 2016). The major advantage of the dry cell electrolyser is that, it is very compact and hence can be used for the on board generation of HHO gas. Dry cell is devoid of many disadvantages of the wet cell. There is no corrosion problem and more surface area is available for the reaction to take place. Further, there is no overheating occurs, as in the case of wet cells.

2.4 Fabrication of dry cells

An electrolyser usually consists of electrodes, connected to a power source, dipped in electrolyte. Dry cell electrolyser essentially consists of electrode plates, electrolyte, insulation and a DC power source. The electrolyte fills the gap between two electrode plates that is provided by the insulation, and is continuously circulated through the dry cell and the electrolytic tank during the operation. Sufficient thickness of insulation has to be used so that the electric sparks between the electrode plates are avoided. The thickness should not be too large, as it contributes to an additional resistance in the electrolyser, which affects the volume of gas generated. Therefore, a careful selection of insulation material and its thickness has to be done so that the HHO gas generation is optimum.

2.4.1 Material selection

Electrode plate: Electrodes are chosen based on the electrolyte used in the cell. When alkaline electrolyte is used in the cell, electrode material normally selected is stainless steel 316 since it is highly resistant to corrosion in the presence of alkaline solutions. In the case of acidic electrolyte, noble metals need to be avoided in order to prevent corrosion of the electrodes.

- Electrolyte: electrolyte is used in an electrolyser cell in order to increase the conductivity of water. Alkaline electrolyte is preferred in the cell to avoid corrosion related issues. Many studies indicate higher production of oxyhydrogen gas while using potassium hydroxide as the electrolyte.
- Insulation: neoprene rubber gaskets are used as insulation between the two adjacent electrode plates. This not only serves as an insulation but also provides a gap for the electrolyte to be in contact with the electrode plates.
- Power source: a DC regulated power supply or battery normally serves the purpose of power source.

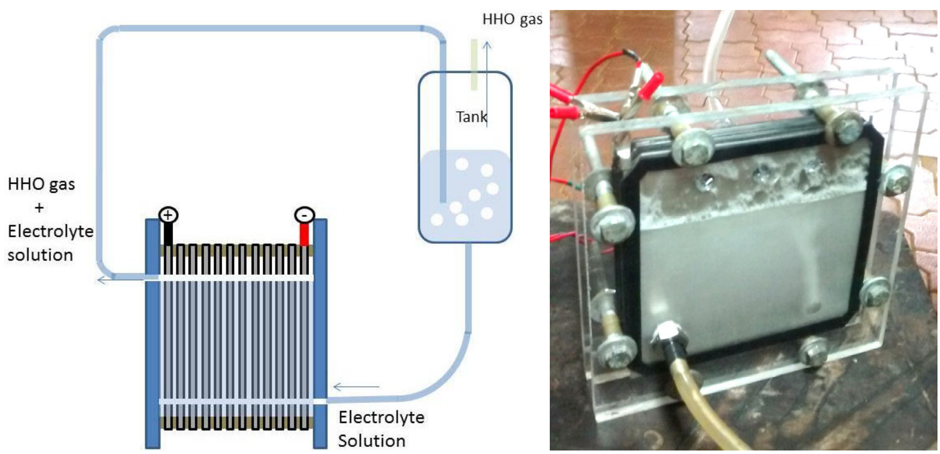
2.4.2 Electrode plate

Holes are drilled at the top and bottom of the electrode plates. Holes at the bottom facilitate the flow of electrolyte between the plates. For any of the selected configurations, the electrolyte allows conduction of ions in the cell. Continuous supply of electrolyte in the cell is necessary for the cell to function properly. This continuous flow of electrolyte also carries away the heat generated due to electrolysis. The bottom holes allow the flow of electrolyte to all individual cells in the dry cell. The oxy-hydrogen gas generated in the cell moves to the top owing to its lower density. Holes at the top of the cell allow the easy flow of oxy-hydrogen gas to the outlet pipe of the cell.

2.4.3 Assembly

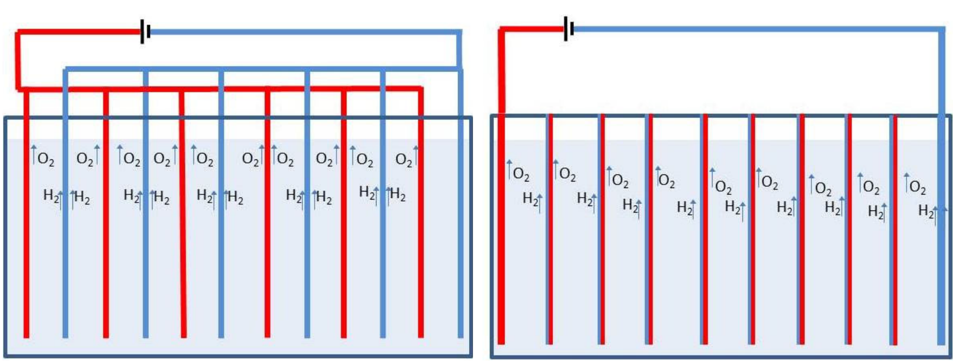
Two plates are overlapped with a gasket placed in between. These plates are sandwiched between acrylic plates and bolted to form a compact leak proof dry cell. Tubes are connected to bottom and top holes drilled in the acrylic plate. The bottom pipe from the electrolyser tank is connected to the bottom hole for the electrolyte flow into the dry cell electrolyser. The connection from the top hole of the plate gets connected to the electrolyte tank, inserted into the electrolyte to facilitate bubbling of the HHO gas. This is done to separate the electrolyte content from the oxy-hydrogen gas evolved from the cell. The electrolyte tank serves an additional purpose of preventing backfire from the engine into the cell.

Figure 2 Typical dry cell system configuration, (a) schematic diagram (b) actual cell (see online version for colours)



(a) (b)

Figure 3 Monopolar and bipolar configurations, (a) monopolar (b) bipolar (see online version for colours)



(a) (b)

Source: Carmo et al. (2013)

2.5 Types of cell configurations

There are two alkaline electrolysis cell configurations, namely, the mono-polar and the bi-polar. Schematic diagrams of these two configurations are shown in Figure 3.

2.5.1 Mono-polar configuration

In monopolar configuration, alternate electrodes are parallely connected to the opposite terminals of the DC power source as shown in Figure 3(a). This creates a number of individual cells inside the electrolyte solution. Since the connection is parallel, the voltage applied in each cell is equal, which is the same as the voltage of the DC power source. The current gets distributed through the plates. The gas generated on both sides of the electrode is the same; it can be either oxygen or hydrogen as shown in Figure 3(a). The conductivity is provided by the electrolyte available between the electrode plates. Generally, voltage applied in mono-polar configuration is 2.2V. The advantage of mono-polar configuration is in its easiness to manufacture, but this configuration suffers from high electrical currents at low voltages, causing large ohmic losses (Zeng and Zhang, 2010).

2.5.2 Bi-polar configuration

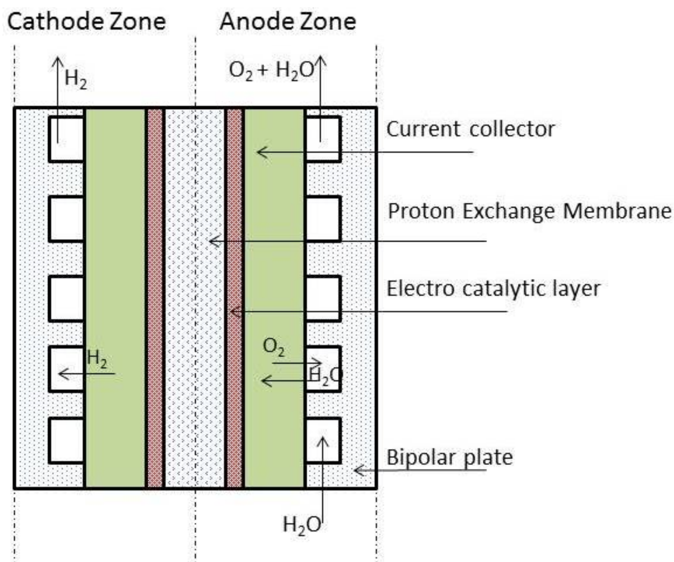
In the case of bi-polar configuration, only electrodes at the two ends are connected to the DC power supply as shown in Figure 3(b). All the other electrodes are connected by the electrolyte solution and all the adjacent electrodes form individual cells. These cells are forming a series connection and hence same current flows through each individual cell. In this configuration, each electrode undergoes two different reactions on either side (generating hydrogen on one side and oxygen on the other) as shown in Figure 3(b). In the same electrode, one side acts as anode and the other side acts as cathode (for all electrodes except the two end electrodes connected to power source). Here, the total voltage applied is the sum of all voltages applied in individual cells.

In bi-polar configuration, the electrical potential difference applied to cell is 2.2V multiplied by the number of cells. The bi-polar configuration requires careful design and manufacturing in order to prevent leakages between cells. They have the advantage of reduced ohmic losses. Providing small gap between electrodes reduces resistance for ionic transportation, but it may cause electric sparks if the cell is not carefully fabricated. Optimum gap between electrodes is essential to avoid the electric sparks in this dry cell (Santos and Sequeira, 2013).

2.6 PEM electrolysis

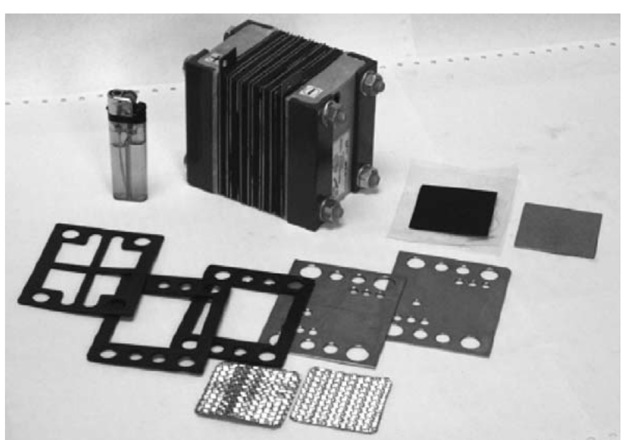
Proton exchange membrane (PEM) provides many advantages like higher efficiency, higher gas generation rate and compactness in the design of water electrolyser. The working principle of PEM electrolyser cell is the reverse of that of the fuel cell. PEM electrolyser cell can be seen as an extension of the dry cell. The PEM cells have an electro-catalytic layer/membrane, the anode and cathode is bonded to this membrane. The PEM helps to split the water into hydrogen and oxygen. When supplied with water at anode, it gets split into oxygen, electron and hydrogen ions. These ions are transferred to the cathode side through the proton conductive membrane. The electrons exit through the external circuit, which forms the cell potential for the reaction. In cathode, the electron and hydrogen ions combine to form the hydrogen gas. The use of PEM is restricted to a smaller scale because of many limiting factors. The initial cost of the PEM electrolyser cell is higher, similar to that of the PEM fuel cells. Considering that, platinum or platinum alloys are being used as electrodes and due to higher cost of membrane and catalyst. Figure 5 shows a schematic diagram of the arrangement of various parts of a PEM electrolyser cell. The electrodes are usually made of electro-catalytic particles or electrolyte polymers. Usually electro-catalytic material such as iron oxide (FeO_2) is used as anode and platinum (Pt) is a popular material for cathode (Carmo et al., 2013).

Figure 4 Schematic of PEM electrolyser cell (see online version for colours)



Source: Grigoriev et al. (2006)

Figure 5 Photo of PEM electrolyser cell



Source: Barbir (2005)

3 Pure hydrogen induction

Pure hydrogen can be used in the internal combustion engines as a dual fuel, without much alteration in the existing design of the engine. This is due to the fact that, hydrogen has very good combustion properties (much superior to diesel). Introduction of hydrogen creates a better flammable mixture and the higher diffusivity of hydrogen is helpful in increasing the flame propagation velocity (Koten, 2018). Experimental investigations of the hydrogen enriched induction system in a diesel engine showed that, the brake thermal efficiency can be increased by the enhancing the fraction of hydrogen and maximum efficiency was found around one third replacement by hydrogen fuel. The knocking tendency of the engine throughout the load range can also be reduced by the supplementation of hydrogen through the inlet port. The knocking tendency was minimum corresponding to one third hydrogen supplementation in the fuel. Since hydrogen has good burning characteristics, it aids in the combustion of the fuel in the engine cylinder. Hydrogen helps in the complete combustion of fuel and along with its own calorific value, more energy is produced in the combustion process. This leads to reduced fuel consumption and thus reduction in the specific fuel consumption throughout the working range of the engine (Saravanan et al., 2008).

Hydrogen can be used (as dual fuel) in a gasoline engine (as well) without any serious engine modification with an on-board generation facility. Whereas, pure hydrogen cylinder in which hydrogen is compressed to 20 MPa used in IC engines require major engine modifications and safety measures. Pressure regulators are used to reduce the pressure to operating conditions and then injected through the inlet manifold of the engine. At higher speeds, this setup increases the thermal efficiency and thus reducing the specific fuel consumption. The major advantage of using hydrogen in gasoline engines is that, it reduces the exhaust emissions (Kahraman et al., 2007).

Theoretical engine performance and emission characteristics are usually obtained by the application of modelling and simulations methodologies. An artificial neural network (ANN) modelling is developed by Syed et al. (2017) to investigate the hydrogen dual fuel diesel engine. In any ANN methodology, a set of input signal is received at a neuron; each input signal is weighted, summed together and subjected to an activation (transfer) function. The neuron gets fired when the resulted signal exceeds the threshold limit (bias) of the neuron. This configuration is known as a perceptron. The outcome of the perceptron is judged based upon the performance function, such as mean squared error (MSE). New weights and activation levels are redefined, feeding the error. In the hydrogen fuelled engine analysis, load and hydrogen flow rate are considered as inputs to the network whereas, BTE, BSFC, CO, NOx, HC and EGT are kept as the targets. Seven different training algorithms and eight transfer function combinations are used to arrive upon proper ANN model. Carefully generated experiment data was used to train the model in MATLAB® using the ANN module.

Commercial software packages such as AVL-FIRE package can be used to calculate the flow field, combustion and the engine parameters. A model is developed by Taghavifar et al. (2017) to investigate the effect of water injection in a hydrogen dual fuel diesel engine in its emission and performance characteristics. Water injection of 5% at 27°C was found to have the least emissions, while water injection of 15% at 60°C was found to improve the performance characteristics of the engine. Vibration produced by the engine is also a factor that needs to be addressed. Vibration not only causes structural and mechanical damage but also affects the comfort of the user. Çalık (2018) conducted a study on the vibration produced by diesel engines with hydrogen in dual fuel mode. Vibration produced by engine with neat diesel was selected as reference and compared against the cases when the engine operated with biodiesel and hydrogen injection in the duel fuel mode. Hydrogen injection is found to reduce the vibrations in the engine because of the shorter ignition delay period.

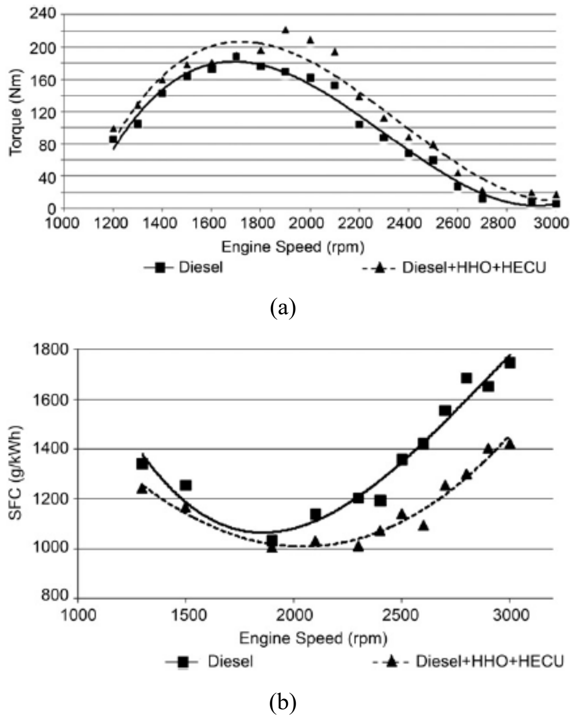
4 HHO induction in CI engines

The splitting of water molecule by electrolysis dates back to the nineteenth century. This splitting up of water results in a combustible gas, namely HHO, in which, the hydrogen and oxygen atoms exist as dimers in it and is not fully converted into its molecules (Santilli, 2006). This means that, additional binding energy is also available while burning the HHO gas. Yilmaz et al. (2010) used this HHO gas in compression ignition engine for the first time to determine its performance and emission characteristics (Figure 6). They studied the effect of HHO gas on the performance and emission characteristics in a diesel engine (Figure 6). Induction of HHO gas improved the engine torque in the middle and higher engine speed ranges. The volumetric efficiency reduced when HHO is inducted through the intake manifold. Exhaust emissions was found to decrease with induction of HHO gas (except for NO_x). Potassium hydroxide gives better generation of HHO gas in the electrolysis process and this aspect is also confirmed by another study by Abhilash et al. (2015). Liu et al. (2016) studied the emissions from a diesel engine, at various loads, having premixed HHO gas admitted with air. HHO gas is generated by means of a dry cell using NaOH and KOH electrolytes. It is found that, CO, HC and particulate matter emissions are decreased, whereas NO_x emissions increased. Gohar and Raza (2017) found out that, the performance parameters, like brake power, brake thermal efficiency, brake specific fuel consumption and mechanical efficiency, showed outstanding improvement upon the induction of HHO gas at 5 lpm to the CI engine. HHO gas induction always causes an increase in brake thermal efficiency and a corresponding reduction in brake specific fuel consumption (Dhariwal et al., 2018; Manu et al., 2015; Shah et al., 2014; Shitole et al., 2017; Shah et al., 2014).

It is necessary to find out the optimum quantity of HHO gas, that needs to be supplied for the best results. Rajaram et al. (2014) did experiments on a DI diesel engine with two flow rates of HHO gas and studied the performance, combustion and emission characteristics at various loads. Flow rates for HHO gas, selected by them were 1 lpm and 3.3 lpm. Experimental data obtained with 1 lpm HHO gas was relatively lower than that of the diesel. But data with 3.3 lpm HHO gas showed lesser emissions for CO, HC and smoke. However, CO_2 and NO_x emissions were found to increase. In general, performance and combustion characteristics were improved with 3.3 lpm of HHO gas.

Pure hydrogen is suitable to be used with diesel or gasoline in the dual fuel mode in IC engines. Advantages of using HHO gas (over pure hydrogen) have to be ensured and then only it can be justified for its use in engines (instead of pure hydrogen). Baltacioglu et al. (2016) presented a comparison of performance and emission characteristics, when premixed with hydrogen and HHO gas. It is found in their studies that, when HHO gas is used with bio-diesel gives better results than that with pure hydrogen. In this study too, NO_x emissions were found to increase both with the use of HHO and pure hydrogen. Ozcanli et al. (2017) determined that, HHO enriched castor oil methyl ester had better performance and emission characteristics (than that of pure hydrogen enriched diesel).

Figure 6 Performance parameters, (a) torque variation with respect to engine speed (b) SFC variation with respect to engine speed



Source: Yilmaz et al. (2010)

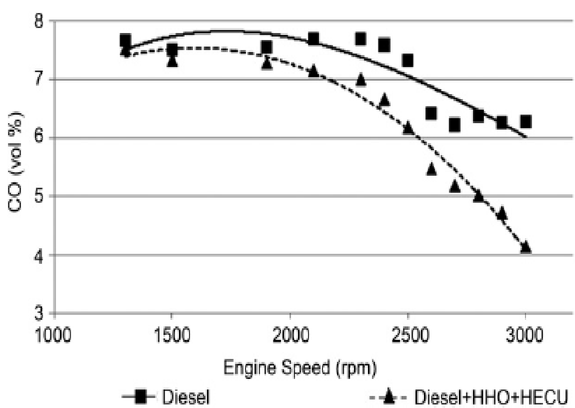
Elmaihy (2017) investigated the performance characteristics of diesel engine with the injection of HHO gas. Experiments were conducted with different input current to the dry cell, at various electrolyte concentration and loads. BSFC reduced and BP increased with the injection of HHO gas over the entire operating condition of the engine. Another finding is that the volumetric efficiency decreased with the injection of HHO gas, which concurs with the work of Yilmaz et al. (2010).

4.1 HHO gas with bio-diesel

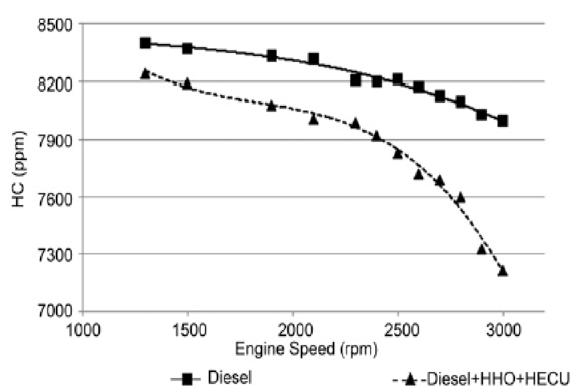
It is shown by many studies that, the use of biodiesel reduces emissions, but at a cost of major engine performance parameters. Inducing HHO gas with biodiesel improve both performance and emission characteristics and is a good substitute for the standard diesel. Jeffrey and Subramanian (2014) investigated performance and emission characteristics of biodiesel blends with and without HHO gas. Their results are quite interesting and B10 blend with supplemented HHO gas gave almost the same performance as that of straight diesel. Engine exhaust emissions were considerably reduced except for the NO_x compositions. Durairaj et al. (2012) experimented HHO gas, generated in wet cell electrolyzer using stainless steel electrode plates, supplemented with biodiesel obtained from Jatropha seeds. HHO gas was preheated using exhaust gas before supplying it to the inlet manifold. Preheating further increases the efficiency of the engine, even lowered the NOx emissions due to heat recovery, and thereby reducing the ignition delay. HHO gas at

0.5 lpm was used to enrich diesel as well as biodiesel obtained from soya bean, on a CI engine to compare the exhaust emissions. Biodiesel with HHO enrichment showed improved emission parameters compared to standard diesel with HHO gas (Koc et al., 2018). Thangaraj and Govindan (2018) evaluated the performance such as brake thermal efficiency, peak in-cylinder pressure, heat release rate and emission characteristics of diesel engine, using the Karanja oil methyl ester supplemented with 0.73 lpm of the HHO gas. HHO gas was produced by water electrolysis, using sodium bicarbonate electrolyte. They also tested EGR, so that the emission of NO_x gases got further reduced. It can be concluded from their work that, EGR with biodiesel blends supplemented by HHO gas has better performance. In addition, better emission characteristics were obtained compared to the engine using neat diesel. Baltacioglu et al. (2019) performed performance and emission analysis of a ternary fuel blend, that is, biodiesel, ethanol and diesel with HHO enrichment. They found out that the fossil fuel consumption can be considerably reduced, up to 15%, in ternary fuel combustion enriched with HHO gas. Almost 12% increase in brake thermal efficiency is also observed in their study.

Figure 7 Emission parameters, (a) CO variation with respect to engine speed (b) HC variation with respect to engine speed



(a)



(b)

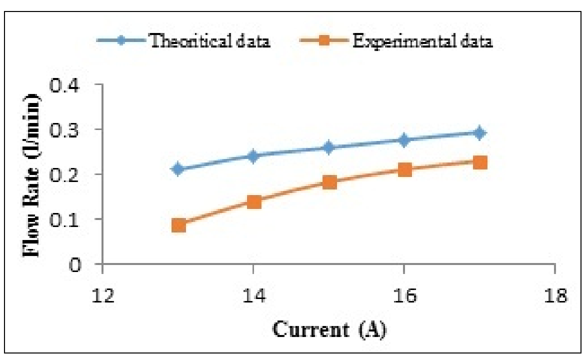
Source: Yilmaz et al. (2010).

4.2 Optimisation of HHO generation and its use in CI engines

While HHO gas can be generated by many methods, it is required to find out the best method for the on board generation of HHO gas. Two methods for generation of HHO gas and its implementation on an engine is discussed by Milind et al. (2011). One of the methods is by the application of Faraday's law and the other by creating resonance between the electrodes using DC pulses. They have compared HHO generation rate and the temperature rise during generation in both methods. HHO generation rate was higher for the cell, whereas the temperature rise was found to be lesser in the second method.

Since, only a smaller quantity of oxy-hydrogen gas can be generated by the dry cell electrolyzer, researchers are keen to maximum the production of HHO gas from a particular cell. Therefore, an optimisation method for the generation of HHO gas is a major thrust areafor the studies on this area of research. Abhilash et al. (2015) investigate the dependency of HHO gas generation on electrolyte and its concentration. They found that, the efficiency of the engine increases with concentration of electrolyte up to 10% w/w. In addition, the electrolyte solution of KOH gives better results than that of NaOH. They have suggested a modulated current source, so that, the generation of HHO gas can be varied with load. When using a modulator, it is needed to find the best duty cycle for its operation. Duty cycle is the length of time the signal is in the state of 'high' to the total period of the signal, and 100% duty cycle means that, there is no modulation. Sudarmanta et al. (2016) found out that, 40% duty cycle is the best for the generation of HHO gas and also it resulted in less specific energy input. Figure 8 shows the variation of HHO gas generated with respect to the current. It can be inferred from the graph that, a modulated current source can be used to change the volume of HHO gas generated and it can be admitted to the engine depending on the varying load conditions (Manu et al., 2018).

Figure 8 Variation of flow rate of HHO gas with respect to current (see online version for colours)



Source: Manu et al. (2018)

Number of electrodes, electrolyte concentration, type of electrolyte, current to the cell for the production of HHO gas and their optimised values, which gives the best rate of HHO generation, was presented by Masjuki et al. (2016). Optimum production of HHO gas was found to be with one anode for two cathodes in 1% KOH solution. Performance and emission characteristics were improved from that of ordinary diesel, except the emission of NO_x increased. Dhananjaya et al. (2015) arrived on a conclusion that, as the current consumption increases, the generation of HHO gas also increases. Their work also suggests that, ideal current consumption must be limited to 6A, for a three electrode electrolytic cell. El-Kassaby et al. (2016) discussed the rate of generation of HHO gas in response to the variation in number of electrodes and distance between them and the type of electrolyte. Maximum rate of generation was found with two neutral plates separated by 1 mm gap. They observed better performance of the engine, as well as the emission characteristics (even NO_x was found to reduce by 15%). Dweepson et al. (2014) identified KOH as the best electrolyte for the generation of HHO gas on board the vehicle using a dry cell electrolyzer (among NaOH, KOH and K_2CO_3). They conducted experiments on twin cylinder diesel engine with a steady induction of HHO at 0.45 lpm run at a constant speed of 1,500 rpm. Against the other studies, they found an increase in the volumetric efficiency and a significant decrease in the emission of NO_x. The work of El-Kassaby et al. (2016) can be considered as a validation for this study, which also found that, alkaline electrolyte (KOH solution) gives a higher generation of HHO gas for a given current flow. Experiments were done on a dry cell electrolyser, with different plate combinations by Işıktaş et al. (2016), and from their results it was concluded that, current consumed as well as the temperature rise in the electrolyser increases with the surface area, where the electrolytic reaction takes place. They had also developed a fuzzy logic modelling with Rule-Based Mamdani-Type Fuzzy technique for the current and temperature in the dry cell electrolyser. Ismail et al. (2018) carried out optimisation of the dry cell and study on the engine characteristics with more preference to emissions.

Owing to the good combustion characteristics of HHO gas, the combustion in the cylinder takes place more closer to the top dead centre. Therefore, useful energy that can be extracted increases. This fact is the reason for the higher brake power resulting from the engine when it is supplied with HHO gas. The higher rate of combustion and the presence of highly combustible hydrogen along with the presence of oxygen is favourable for ‘near complete combustion’. Hence, the major by-products of this combustion process are carbon dioxide and water only. If the power required for the electrolysis is supplied from the alternator of the vehicle, it amounts to an additional load on the engine. To avoid this, photovoltaic powered on board HHO generator can be used as elaborated by Ahmed et al. (2017) and Chennouf et al. (2012).

4.3 Combustion characteristics with HHO admission

Modelling may be regarded as the process of describing the physical phenomenon in terms of mathematical equations where some kind of assumptions is made. Solving these equations provides a deeper understanding of the nature of such phenomena. Engine modelling are more focussed on designing better performing engines with lower emissions. The various models developed till date include

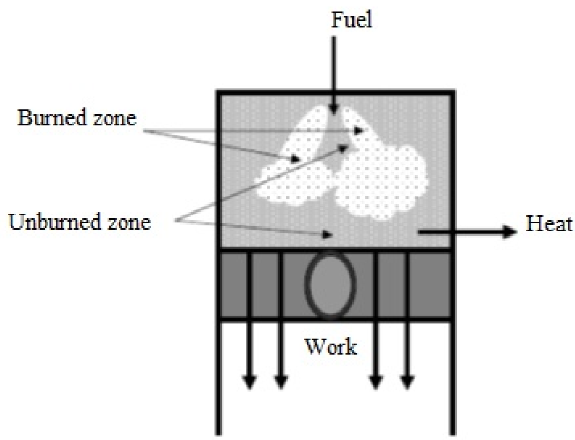
1 zero-dimensional models

2 quasi-dimensional models

3 multi-dimensional models, etc.

In the above list of classification, as we proceed downwards, the level of detail and proximity to physical reality increases, so does the complexity of creating and using these models. Zero dimensional models are the simplest and most suitable to observe the effects of empirical variations in the engine operating parameters on overall heat release rates and cylinder pressure schedules. Since the flow field dimensions are not considered in these models, they are called zero-dimensional models. Two-zone and four-zone combustion models are sub-divisions of zero-dimensional model. In two-zone combustion model, the working fluid is imagined to consist of two zones, namely, an unburned zone and a burned zone. These are actually two distinct thermodynamic systems with energy and mass interactions between themselves and their common surroundings, including the cylinder walls. By applying the laws of thermodynamics to the two zones and solving the resulting equations, the mass fraction burned can be obtained as a function of crank angle.

Figure 9 Two zone combustion



These models have been traditionally used in two different directions as given below:

1 to predict the in-cylinder pressure as a function of crank angle from an assumed energy release or mass burned profile

2 to determine the energy release/mass burning rate as a function of crank angle from experimentally obtained in-cylinder pressure data.

Modelling of the in-cylinder combustion process can be a fundamental tool in predicting the engine performance, as well as combustion characteristics. Ragupathy (2017) modelled a direct injection diesel engine with HHO gas induced. GT Power software was used and the single zone combustion model is analysed. Measured values of heat release rates and in-cylinder pressure were in good agreement with the predicted values by the model. Kenanoğlu et al. (2016) to compare HHO used AVL Boost simulation code and HHO-CNG injected engines with respect to their performance. Much reduced volumetric efficiency was found for the use of HHO-CNG, while that of HHO injected engine was very close to the standard diesel engine characteristics. The performance parameters such as brake power, torque and mean effective pressure were higher for HHO-CNG. A two-zone combustion model (which used the double Vieb function) is made use by Rimkus et al. (2018) to synthesise the combustion process. They have used the AVL Boost code for the modelling and selecting the fuel properties. It is found that mean cylinder pressure increases and ignition delays become shorter, upon the injection of HHO gas along with the main fuel.

4.4 Vibration studies and effect of magnetic field and compression ratio

While there are studies that deal with the vibration produced by diesel engines operated with hydrogen as a dual fuel, Uludamar et al. (2017) studied the same when HHO gas was injected. Effect of three different flow rates of HHO gas (2, 4 and 6 lpm) on the vibration characteristics was investigated. ANN implemented through MATLAB® software was used to predict the effect of HHO gas and the effect of fuel properties on the engine vibration level. With the use of HHO gas, reduction in the vibration was observed throughout the speed range of the engine. Tuccar (2018) also validates the result by Uludamar et al. (2017) that, the vibration reduced with the admission of HHO gas to the diesel engine. On board generation of HHO gas through the electrolysis of water was experimented by Bari and Esmaeil (2010). They evaluated the performance enhancement of the diesel engine with HHO gas as a co-fuel. Experiments were carried out for various loads and quantities of HHO gas admission. Induction of 6.1% of HHO gas resulted in an increase of brake thermal efficiency and reduction of specific fuel consumption. Emission of gases such as hydrocarbons, CO and CO_2were found to reduce, while the emission of NO_x was increased.

It is shown by Santilli (2006) that, the HHO gas is bonded by the opposing magnetic forces of the dimers, (hydrogen and oxygen atoms). The hydrogen isomer in its ortho-hydrogen state has a higher energy state. Strong magnetic fields applied on the oxy-hydrogen gas helps to convert the para-hydrogen into its ortho-hydrogen state, so that, while combustion, more energy is released and thus ensure more complete combustion. Barna and Lelea (2017) reported that the ionised HHO gas can reduce the opacity of the flue gases. Dahake et al. (2016) did experiments on a single cylinder diesel engine induced with 1 lpm of HHO gas maintaining a compression ratio of 18. They found an increase in the brake thermal efficiency, reduction in specific fuel consumption and reduction in emissions except for NO_x with increasing load. Chauhan et al. (2016) conducted experiments by varying compression ratio from 16 to 18. When HHO gas is inducted along with air in a single cylinder diesel engine, compression ratio of 18 gives better performance, validating the results of Dahake et al. (2016). HHO gas was generated by the use of a cell with electrolyte NaOH and electrode made of 316 L stainless steel. In the studies by Naresh et al. (2014), the emissions of NO_x were greatly reduced in a diesel engine supplemented with HHO gas generated on board in a dry cell electrolyser. Other results obtained by them, such as the performance characteristics and emission characteristics match with similar studies (except that for NO_x) reported earlier.

5 HHO induction in SI engines

As in the case of compression ignition engines, HHO gas can also be used in spark ignition engines. Chiriac et al. (2006) was the first to use oxy-hydrogen in gasoline engines. The hydroxyl gas was supplied at a pressure of 2 bar into the carburettor. Higher brake thermal efficiency and indicated mean effective pressure were observed when the combustion occurs with lean mixtures. Corresponding to lean mixtures, addition of HHO gas also results in the reduction of exhaust emissions such as CO and unburnt HC to a greater extent than in the case of rich mixtures. In gasoline engines, the use of HHO gas as a fuel additive reduces the NO_x emissions as presented by Musmar and Al-ARousan (2011). They used an inverse fuel cell which basically is an electrolyzer for decomposing water into HHO gas. Experimental results of Krishna (2018), Lakshmi et al. (2013), Al-Rababah and Bhuyan (2014), Rao et al. (2018) also report a reduction in NO_x emissions. However, there are other studies, where the emission of NO_x increased when HHO gas was used (Bhardwaj et al., 2014; Brayek et al., 2016; Patel, 2016).

Falahat et al. (2014) tested three flow rates of HHO gas (1, 1.5 and 2 lpm) to an SI engine and observed a reduction of NO_xin all the cases when HHO gas was admitted. In addition, maximum improvement in performance characteristics was observed for the case when HHO gas admission was 2 lpm. Brayek et al. (2017) also studied effect of three different flow rates of HHO gas to an SI engine. The highest flow rate that they tested (7.5 lpm) showed the highest performance and emission improvement. Admitting HHO gas to a gasoline engine increases its performance parameters like, brake power, brake thermal efficiency and correspondingly a reduction in the brake specific fuel consumption was observed (José and Rica, 2016; Sharma et al., 2015). Emission of CO and HC are always reduced upon the admission of HHO gas to a gasoline engine (Jain et al., 2016; Mughal et al., 2015; Patil et al., 2017). These results are attributed to the good combustion characteristics of HHO gas in combination with gasoline. The lower exhaust temperature in the studies also indicate better combustion leading to higher power output as well as cleaner combustion which means lower exhaust emissions.

Producer gas as well as HHO gas was inducted into a two stroke petrol engine and the performance characteristics and emission characteristics were studied by Kumar and Rao (2013). Producer gas was obtained by pyrolysis and HHO gas was generated by electrolysis. Both the alternative fuels have oxygen in them which means that, water vapour remains asa major combustion by-product. This results in the reduction of knocking and cylinder temperature, yielding lesser NO_x emissions. For a given speed and compression ratio, with the induction of HHO gas, brake power and mean effective pressure always increases irrespective of ignition advance as presented by Yadav and Sawant (2018). They also found that, for a given ignition advance, increase in compression ratio reduces the percentage improvement of the oxy-hydrogen blending.

Wang et al. (2011) gives a comparison hydrogen addition with HHO gas addition in a gasoline engine. Hydrogen and HHO gas were added in two concentrations (2% and 4% of the total intake by volume) and the engine was run at lean burn conditions. Results of HHO gas obtained, was better than that of the hydrogen mixed and standard neat gasoline. However, NO_x emissions were increased in this study when HHO gas was used. Compressed HHO gas was inducted to a gasoline engine at 1.95% by mass of total intake air and experiments were carried out by Le Anh et al. (2013). They studied as neat gasoline, gasoline with HHO gas in detail. Also they have analysed the effect of additional air intake. HHO gas with additional air intake showed higher performance and lesser emissions in terms of CO and HC. However, NO_x emissions increased in both cases, validating many other earlier studies. Dry cell is used by Nag and Shrivastava (2016) to generate HHO gas on-board a vehicle and induce it into the gasoline engine. Combustion efficiency and brake thermal efficiency increase considerably while using the HHO gas. Reduction of NO_x emissions by 54% is a good achievement reported in this study.

Addition of HHO gas in a three-cylinder gasoline engine reduces the cylinder temperature due to the presence of water vapour in the combustion products, as suggested by Narayan and Naveenchandran (2014). Their study also showed a reduction in the emission of carbon dioxide, which is different from other studies. Leelakrishnan et al. (2013) studied the effect of HHO gas enriched air intake in gasoline engine. They used wet cell to generate the HHO gas. During their studies, it was observed that, emission of NO_x and smoke increases with load and with the enrichment of HHO gas. Performance parameters showed some increase in their values (up to 10%). Further, emission of CO and unburned HC reduced by a staggering 80%. Aminy et al. (2014) used dry cell to produce HHO gas, and it was added to the inlet air of an SI engine. Their studies also record an increase in the performance parameters, like power and torque, (up to 5.5%) and reduction in emission of CO and HC (by 21% and 19%, respectively), when the HHO gas was admitted at a rate of 0.75 lpm. Along with gasoline, biogas, butane and HHO blends in different ratios can also be used to increase the performance parameters. Further it helps to reduce the vibrations of the engine, as well. Addition of HHO gas always reduces the engine vibrations, indicating smoother combustion with HHO gas admission (Sur, 2015). Polverino et al. (2019) found out from their studies that the gains in fuel savings mainly occur in small engines and for small flow rate of HHO. They used the engine battery as the power source for the electrolysis. Although a part of the engine work output is used for this, fuel savings are still observed. It is suggested in their work that, optimisation of pressure ratio and spark advance could guarantee fuel savings.

Al-Rousan (2010) have made an interesting finding that, the optimal area of the electrodes for the production of HHO gas is twenty times that of the piston surface area for a gasoline engine. Experiments were done with different electrolytic cells of varying dimensions, though the materials used for their construction remained the same (stainless steel 316 for electrodes and plexi-glass for casing). He found out that the major parameter for matching the engine and the inverse fuel cell is size. In addition, size is defined as the ratio of surface area of the cell to the surface area of the piston. Number of experiments was done with models and finally, two of the experimented cells showed significant improvement in the performance characteristics. One cell had electrodes of one square meter stainless steel plates and the other with half the area of the former. However, performance characteristics were found to be on the higher side for the use of HHO gas from the smaller electrolytic cell. In addition, the amount of water to be present in the cell was also empirically found out to be about1.5 times the engine capacity.

6 Economic benefits

The dry cell electrolyser used for the production of HHO gas requires a power source, electrolyte and other safety components. The cost of these components come to a rather moderate value and it is only an initial investment. In the case of electrolyte, only initial filling is necessary. After that, topping up with distilled water is sufficient. The electrolyte used is basic in nature and stainless steel is more stable towards basic electrolyte. So replacement of the electrodes also happens only once in a long while. Major design modifications of the engine is also not required for installing the HHO generator kit. It has already been established in the previous sections that the use of oxy-hydrogen gas reduce the fuel consumption by 4 to 9%. Therefore, when it is seen in a long duration (three to four years), running the engine is dual fuel mode is economically beneficial.

7 Environmental benefits

Engine exhaust is the primary source of carbon monoxide in the environment. CO has been reported to cause harmful effects on human beings such as, nausea, dizziness, vomiting etc. An exposure to a higher concentration of CO may even lead to death. It is observed from various studies that the emissions from the dual fuel combustion of diesel and HHO gas reduces the CO emission by 20–30%. Another pollutant from the IC engines is the unburned hydrocarbons. Some hydrocarbons are carcinogenic and hydrocarbons in general causes respiratory infections and they also act as ozone precursors. HHO gas and diesel dual fuel operation inhibits the emissions of hydrocarbons. The reduction in the HC emissions can be as high as 30%.

8 Conclusions

Pure hydrogen is a clean alternative fuel owing to its superior burning characteristics and the absence of carbon molecules. On-board production of hydrogen is an area, which seeks the interest of researchers due to the storage difficulties of hydrogen gas. Hence, water electrolysis have become one of the preferred choices for hydrogen generation. Dry cell electrolyser gives the best rate of oxy-hydrogen gas generation compared to that of the wet cell electrolyser. Owing to the compactness of the design, dry cells can be used for the on-board generation of HHO gas (on demand) with reasonable efficiency. The HHO generator is compact in size and can be easily retrofitted to the existing engine without major engine design modifications. The battery of the engine can be used as a power source for the electrolyzer. These merits have the potential to make the HHO generator usage commercially viable. The HHO gas generated by water electrolysis, when injected through the inlet manifold, is found to give better performance and emissions characteristics than a standard diesel engine. However, excess NO_x emission seems to be one of the major concerns with HHO gas usage in IC engines. Performance parameters such as brake thermal efficiency and specific energy consumption always improves in the case of both CI and SI engines when HHO gas was inducted. Most of the studies also report a reduction in exhaust emissions namely, HC and CO upon the admission of HHO gas. One of the main limitations of using HHO gas as a dual fuel is the reduction of volumetric efficiency and it is a problem that needs to be addressed in the near future for effective implementation of on-board HHO gas generators. Control methods for the production of HHO gas on demand according to the load variations is also a problem that needs to be tackled. This limitations open a research area in terms of increasing the HHO gas generations and methods for modulated supply of HHO gas with variation in load conditions while reducing the NO_x emissions.

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