On the Efficiency of the Fuel Cell Vehicles with Onboard Hydrogen Generation

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Abstract:

The present paper explores the impact of an on-board hydrogen harvesting system (fuel reformer) on the overall efficiency of a fuel-cell powered vehicle. Various methods of hydrogen production for automotive applications have been discussed first. As the hydrogen production is one of the major challenges for application of proton exchange membrane (PEM) fuel cells, especially in vehicular industry, this paper aims to provide an overview on different methods of cold plasma generation and plasmatrons which can be used to improve hydrogen production problem. Experimental results from a laboratory prototype have been included as a point of reference.

Keywords: Fuel cell vehicle, Cold plasma, Hydrogen generation

Submission date: Jan. 14, 2009

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1. Introduction

Considering the rising price of petroleum fuel cells are now considered as an economical candidates for the vehicular applications. This is primarily due to the fact that fuel cells are efficient and relatively clean. In particular proton exchange membrane (PEMFC) type fuel cells have received considerable attention for vehicular applications. The major problem in application of PEMFC is related to generation and storage of hydrogen which forms one of the main reactants [1]. These problems can be classified as:

- Low efficiency in production of hydrogen.
- Safety issues related to onboard storage, transportation, and handling of hydrogen

Fig. 1 illustrates two architectures that can be considered for use of hydrogen in vehicular applications. Figure 1(a) shows a typical electric vehicle that incorporates a Fuel cell along with an onboard fuel reformer. Ethanol and water (H_2O) are fed into the fuel reformer as main ingredients. Similar arrangements have been investigated in which methane and other hydrogen-rich fuels have been used. In order to decompose the molecules of ethanol and water into hydrogen, there will be a need for additional energy. This has been illustrated by $P_{reformer}$. The hydrogen harvested from this process will be then stored and used as a reactant in the PEMFC to generate the necessary electric power for the adjustable speed motor drive (ASMD) which provides propulsion force. Although in reality there would be a need for separate energy storage such as battery in such configuration (especially during start-up), it is assumed that in steady state, fuel cell can generate the necessary power for the fuel reformer as shown in Fig. 1 (a). According to the architecture shown in Fig. 1(a) one can state:

$$\begin{aligned} P_{H2} &= \eta_r.(P_{Eth} + P_{reformer}) \\ &= \eta_r.(P_{Eth} + \eta_{PS}.P_{PS}) \end{aligned} \qquad (1)$$

In which $\eta_r, \eta_{PS}, P_{Eth}$, and $P_{reformer}$ represent efficiency of the reformer, efficiency of the power supply, chemical power of the incoming fuel (i.e. Ethanol), and input power to the power supply respectively. The power supply is necessary to condition the output of the fuel cell (usually an unregulated dc voltage) into the desired waveform. Furthermore, the output mechanical power can be expressed as:

$$\begin{aligned} P_{out} &= \eta_{ASMD}.(P_E - P_{PS}) \\ &= \eta_{ASMD}.(\eta_{FC}.P_{H2} - P_{PS}) \end{aligned} \qquad (2)$$

Where η_{ASMD}, η_{FC}, and P_{H2} denote the efficiency of the adjustable speed motor drive, efficiency of the fuel cell, and chemical power of the hydrogen respectively. As a result, the overall relationship between the input (chemical) and output (mechanical) powers can be expressed as:

$$P_{out} = \eta_{ASMD}.(\eta_{FC}.\eta_r(P_{Eth}) + (\eta_{FC}.\eta_r.\eta_{PS} - 1)P_{PS}) \qquad (3)$$

Assuming that the power consumed by the fuel reformer will ensemble the following expression:

$$P_{PS} = \gamma P_E \qquad (4)$$

In which P_E represents the output electric power of the fuel cell. The overall efficiency of the system can be approximated as follows:

$$\frac{P_{out}}{P_{Eth}} = \eta = \frac{\eta_r.\eta_{ASMD}.\eta_{FC}.(1-\gamma)}{1-\gamma.\eta_r.\eta_{PS}.\eta_{FC}} \qquad (5)$$

One can further investigate the sensitivity of the overall drive train efficiency to γ and η_r.

$$\begin{aligned} S_\eta^\gamma &= \frac{\partial\eta}{\partial\gamma}.\frac{\gamma}{\eta} = \frac{\gamma.(\eta_r.\eta_{PS}.\eta_{FC} - 1)}{(1-\gamma).(1-\eta_r.\eta_{PS}.\eta_{FC}.\gamma)} \\ S_\eta^{\eta_r} &= \frac{\partial\eta}{\partial\eta_r}.\frac{\eta_r}{\eta} = \frac{1}{(1-\gamma.\eta_{PS}.\eta_{FC})} \end{aligned} \qquad (6)$$

Similar computations can be done for an alternative use of hydrogen in automotive applications as shown in Fig. 1(b). In this configuration, hydrogen is used to enrich the fuel in the internal combustion engine (ICE). One can note that the power necessary for operation of the fuel reformer is extracted from the output of the ICE. As a result, one can expect to observe a profound impact by reformer efficiency on the overall efficiency of the system. It must be noted that in Fig 1(b) there is an added generator that will convert the mechanical energy into electric form for consumption in the fuel reformer.

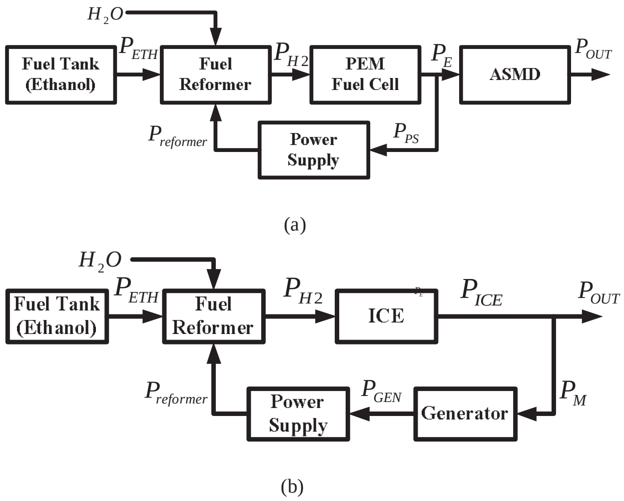

Fig. 1: Various topologies for use of hydrogen in vehicular applications, (a) conventional FC vehicle with onboard fuel reformer, (b) fuel enriched ICE

As can be noted the efficiency of the hydrogen generation plays a central role in overall efficiency of the vehicular power trains. It is also notable that introduction of hydrogen-fueled vehicles into the automotive market would only transfer the above problem to the utility grid. In other words, generation of hydrogen from hydrogen rich fuels (especially renewable fuels such as Ethanol) will remain a technical challenge in an overall optimal policy for energy consumption.

Over the years a wide variety of research has been done to invent efficient methods of hydrogen generation. The common denominator among all these methods has been to use a hydrogen rich fuel as the main ingredient and harvest its hydrogen by means of external electric/thermal energy. The energy required for this process can be provided from conventional thermal power plants, nuclear reactors, solar, and wind energy sources. Regardless of the primary source of the energy, development of a conservative energy policy demands maximum harvest of hydrogen for a minimum cost (i.e. maximize productivity (η_r) while minimizing the input electric energy to the chamber (γ) per unit of output energy from the reformer). This is a multifold problem in which selection of the most appropriate fuel, the optimal reformer architecture, and the optimal form of electric excitation will be the main design criterions.

Fig. 2 illustrates the major fuels and the related methods that are used for harvesting hydrogen. It must be noted that renewable fuels such as Ethanol have received considerable attention for generation of hydrogen

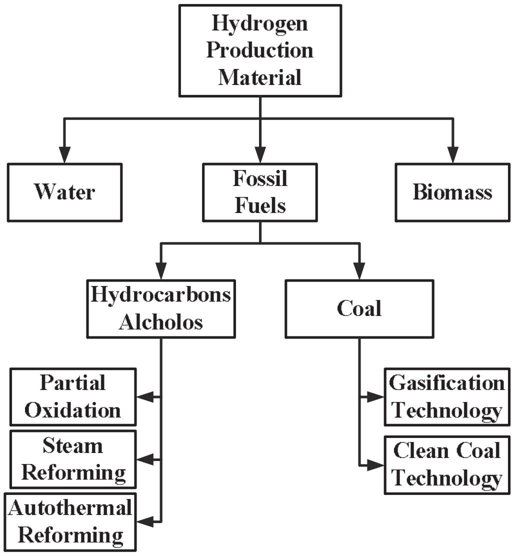

Fig. 2: Different materials used in hydrogen production and related processes

Using water and fossil fuels are among the older methods. Recently usage of bio-mass has attracted significant attention from the research communities. The chemical and physical properties of hydrogen, being energy dense in mass but energy poor in volume make the distribution and storage of hydrogen, a challenging task.

One of the most common methods of hydrogen production is through the electrolysis of the water. There are two types of electrolyzers for this process, namely alkaline electrolyte type and polymer electrolyte membrane (PEM) type. As mentioned earlier hydrogen harvesting process is energy demanding. Several studies have been made to minimize this energy demand by raising the operation temperature and replacing some electrical inputs with thermal energy [3]. This method can be combined with other forms of energy like renewable energies to become even greener.

It is expected that the wind energy would be one of the leading choices among renewable sources of energy in the future. Use of harvested wind energy for generation of hydrogen when the utility demand is low can be viewed as a reasonable combination for generation of hydrogen. However, one may keep in mind that existing power plants in the network operate less efficiently at lower levels of loads. Hence, harvesting and storage of hydrogen during slow hours of operation can have a positive impact on the overall efficiency of the network [4].

Harvesting of hydrogen can be realized using nuclear (large scale) or solar (small scale similar to those of wind energy) sources to split water by electrolysis or thermo-chemical processes without any carbon dioxide emission [2, 5]. Hydrogen is produced more efficiently by increasing water temperature significantly. Such approaches require temperatures in the range of 700 to 1000 °C so advanced light water reactors with special coolants should be used for this purpose.

In the case of solar energy, there are three ways of

hydrogen harvesting: electrochemical, photochemical and thermochemical. Concentrated solar radiation is used as the energy source for handling high temperature reactions [5]. These methods can be used for hydrogen production either in industrial applications or in fuel cells for automotive purposes.

2. Hydrogen Harvesting For Fuel Cells

The petrochemical industries have incorporated hydrogen harvesting schemes using different methods for decades. Methods that are used for automotive hydrogen production are different from those industrial counterparts in several aspects as addressed below [6]:

- Level of production is lower by several orders of magnitude.
- Compactness and light weightiness due to automotive constraints.
- Ability to handle daily start up and shut downs.
- Responsiveness to the change in demand which can vary from 5 to 100% of the rated processing rate.
- Strictly cost targeted (economical).
- Reliable in performance although the life time is shorter than the industrial units.

Different fuels may be used to harvest hydrogen depending on the application. For example in transportation it might be ethanol, methanol, gasoline or diesel. Stationary systems tend to use natural gas and propane but ethanol, butane and biomass driven materials are also used. Hydrogen can be harvested using a variety of hydrocarbon fuels like gasoline, diesel, oil biomass, natural gas and jet fuel with high conversion efficiencies. The conversion of fuels into hydrogen is carried out using the following 3 major methods [6]:

2.1. Steam Reforming (SR)

It is one of the common methods for harvesting hydrogen. In this process steam reacts with the fuel (for instance natural gas) in the presence of a catalyst to produce hydrogen, carbon dioxide and carbon monoxide according to the following formula:

$$(C_nH_mO_p) + steam \Rightarrow CO_x + Hydrogen, \quad \Delta H > 0 \tag{7}$$

This reaction is endothermic and reactor designs are limited by the extent of heat transfer. As a result they are designed to promote heat exchange and tend to be large and heavy. This indirect heat transfer makes conventional steam reformers less attractive for the rapid start and dynamic response needed in automotive applications.

2.2. Partial Oxidation Reforming (PO)

In this method fuel reacts with a sub stoichiometric amount of hydrogen. The initial oxidation generates heat and high temperatures. As follows:

$$C_nH_mO_p + air \Rightarrow CO_x + hydrogen + nitrogen, \quad \Delta H_r < 0 \tag{8}$$

The generated heat raises the gas temperature up to $1000^\circ C$. The oxidation step may be managed with or without a catalyst.

2.3. Autothermal Reforming (ART)

This method is a combination of the latter methods and leads to the following chemical reaction:

$$C_nH_mO_p + air + steam \Rightarrow CO_x + hydrogen + nitrogen, \Delta H_r < 0 \tag{9}$$

This process is carried out in the presence of the catalyst which controls the reaction pathways and determines the relative extent of the oxidation and steam reforming reactions. The SR reaction absorbs part of the heat generated by the oxidation reaction limiting the maximum temperature in the reactor. It is slightly exothermic and to get the best results an appropriate catalyst is needed.

So for the above mentioned processes two factors are important in hydrogen harvesting: heat and catalyst. An option that fulfills both of these requirements is the use of plasma. This method would be discussed in the following sections.

3. Hydrogen Harvesting Using Plasma

Plasma technology has potential advantages over conventional means of hydrogen harvesting. Plasma assisted techniques are widely used in various industrial processes like automotive, aerospace, biomedical industries and fabrication of microelectronics components.

The shortcomings of the conventional reformers include the need for large scale plants, cost and deterioration of catalyst, size and weight requirements, limitations on rapid response and limitations on hydrogen production from heavy carbohydrates. Disadvantages are the dependence on electrical energy and difficulty of high pressure operation that while achievable increases electrode erosion due to decreased arc mobility and thus decreased electrode lifetime [7].

Plasma generators referred to as Plasmatron can generate very high temperatures with a high degree of control using electricity. The heat generation is independent of reaction chemistry and optimal operating conditions. Furthermore, heat generation can be maintained over a wide range of feed rates and gas composition. Compactness is assured by high energy density associated with the plasma and by reduced reaction times resulting in short residence time.

The plasma conditions of high temperature and high degree of dissociation and substantial degree of ionization can be used to accelerate thermodynamically favorable chemical reactions without a catalyst or provide the energy required for endothermic reforming processes. Plasma reformers can provide number of advantages as follows:

- Compactness and lightness due to high power density
- High conversion efficiencies
- Minimal cost (simple metallic or carbon electrodes and simple power supplies)
- Fast response time (fraction of a second)
- Operation with a broad range of fuels including heavy hydrocarbons like crude oil and with dirty hydrocarbons like high sulfur diesel.

As an example one can consider methane reformation which consists of 2 stages. During the first stage complete combustion of part of methane occurs producing mainly CO_2 and H_2O and substantially increasing the temperature of the system. During the second stage, reactions of the remaining methane with CO_2 and H_2O occur producing H_2 and CO while decreasing the temperature of the system.

The use of plasma in the plasma catalysis reformation affects both stages. The plasma process accelerates the reactions (both by the increase in temperature as well by the presence of highly reactive radicals/ions preparing the hydrocarbon air mixture for the catalytic phase [7]. So the plasma acts as the catalyst and the source of heat required for the reforming.

As mentioned earlier, Hydrogen production is an energy demanding procedure. Plasma is a high density source of energy, which can cover process enthalpy and provide optimal temperature range to eliminate kinetic limitations [8]. Plasma media represents a high energetic state of matter characterized by a high electric conductivity. From energy point of view plasma is the 4th state of the matter besides gas, liquid and solid. Plasma contains a multitude of different neutral and charged particles and the following parameters characterize the plasma [9]:

- Density of neutral particles
- Density of electrons and ions
- Energy distribution of the neutral particles, ions and electrons.

The efficiency of the plasma reaction is directly dependent on the density of the charged particles. Electrons are the main agents to transfer energy from the external electric field to the discharge gas. Both electrons and ions which are electrically charged are accelerated by absorbing energy from applied external field. Because of their lightness the electrons absorb the major part of energy and accelerate much more than ions. The collision of energized electrons and gas molecules make them ionized. So the more energized electrons in the gas the higher the efficiency [9]. Plasma can be generated by a number of methods that based on generation mechanism, applied pressure and electrode geometry can be classified as follows:

- Combustion
- Flames
- Electrically heated furnaces
- Electric discharges (corona, spark, glow, arc, microwave discharges, plasma jets and radio frequency)
- Shocks (electrically, magnetically and chemically driven)

Based on the different parameters defined for plasma it can be classified into the following groups:

- Plasmas in complete thermodynamic equilibrium (CTE) - It only exists in stars or during short intervals of a strong explosion.
- Plasmas in local thermodynamic equilibrium (LTE) - That can exist under 2 circumstances: very energetic heavy particles at temperatures of the order of $10^6 - 10^8\ {}^\circ K$ and atmospheric pressure even at temperatures as low as, $6000^\circ K$. These plasmas at atmospheric temperature are also called *thermal* plasma.
- Non LTE plasmas which are also called *cold* plasmas. In this type the temperature of the electrons is much higher than that of the heavy particles. The electrons can reach temperatures of $10^4 - 10^5\ {}^\circ K$ while the temperature of the gas is as low as room temperature [9].

As an example, neon lamps use cold plasma while sun is a good example for thermal plasma [10]. It has been shown [11] that comparable amount of hydrogen can be produced with both kinds of plasma while the energy demand for cold plasma is significantly lower comparing to that of the thermal plasma. Plasma would replace catalysis and accelerates chemical reactions mainly because of high temperature effect. The advantages of using plasma are extremely high productivity of apparatus, low investment and operational costs [8].

4. Cold Plasma

Relatively high energy consumption applies certain restrictions on possible applications of thermal plasma approach. Also high current operation results in high electrode wear. Cold plasmas have been used for fuel gas treatment and are very promising for organic synthesis because of non equilibrium properties, low power requirements and its capacity to induce physical and chemical reactions within gases at relatively low temperatures [10]. The electrons in Cold plasma can reach temperatures in the range of $10^4 - 10^5 \ {}^\circ K$ so they would be very energetic while the gas temperature could remain at room temperature. High electron temperature and so high energy, determines the unusual chemistry of Cold plasmas [10]. This removes the necessity to preheat feed streams. As mentioned before different types of cold plasma arise from the generation mechanism, applied pressure and the electrode geometry. Different kinds of plasma can be classified as follows:

4.1. Production using Electric Field

The most widely used method for plasma generation uses electrical breakdown of natural gas in an external electric field. The electric discharges are classified as dc, ac and pulsed discharges on the basis of electric field behavior [12].

A. DC Discharges

In this method plasma is created in closed discharge vessels using internal electrodes. According to Fig. 3 [9] based on the applied voltage and the discharge current, different discharges could be created [12].

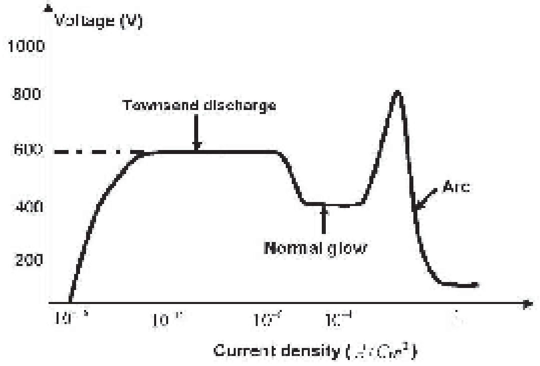

Fig. 3: Various kinds of DC discharges based on applied voltage and discharge current

Based on this figure following discharges can be considered [10]:

- Glow Discharge: It is a low pressure discharge (10 mbar) usually operating between flat electrodes. In this plasma the electrons are highly energetic. The excited neutral atoms and molecules generate a typical glow like in fluorescent tubes. Because of the low pressure characteristics it is not suitable for chemical synthesis.

- Corona discharge: It is an inhomogeneous discharge and can be initiated at atmospheric pressures using inhomogeneous electrode geometries like a pointed wire electrode as anode and a plate for cathode. The small radius of curvature at the top of the electrode results in high electric field required for ionizing the neutral molecules.

- Silent or Dielectric barrier discharge (DBD): In this type a dielectric layer covers at least one electrode. The entire electrode area will be effective for discharge reaction. The discharge is initiated at any location within the gap between electrodes and the charge accumulates on the dielectric to form an opposite electric filed and interrupts the current flow in a few nanoseconds to generate micro discharges. The duration of the current pulse relates to the pressure, properties of the gases and the dielectric material applied.

B. Pulsed Discharges

In this kind, dc pulsed discharges are used instead of continuous dc discharge. This method has advantages like higher operating power, additional performance control by a variable duty cycle of active plasma regime and overflow and minimization of the effect like inhomogeneous thin film decomposition compared to the DC discharge [12]. It must be noted that the main reaction occurs when high energy electrons are sprayed upon heavy molecules of hydrocarbons in the first portion of the breakdown (few tens to hundreds of nanosecond in length)

C. AC Discharges

Following methods are classified as AC discharges:

- Microwave discharge: It operates at very high frequencies such as 2.45 GHz in the range of microwaves in which only light electrons can follow the oscillations of the electric field. It can be implemented over a wide range of pressure. Various types of microwave reactors are: discharges produced in closed structure, in open structure and in resonance structure with a magnetic field [12].

- Radio frequency discharge: It operates at high frequencies of several MHz (1-100MHz) and very low pressures to achieve the non equilibrium condition. This type of plasma is not suitable for chemical synthesis [10].

- Gliding arc discharge: It is a transitional type of atmospheric pressure arc discharges, which can provide relatively high levels of electron density, current and power-typical for thermal plasmas, together with relatively low temperature and elevated electric field-typical for cold non-equilibrium plasmas. This phenomenon consists of periodic self-triggered

- transitions of atmospheric pressure thermal arc $(3000-5000^{\circ} K)$, moving in a gas flow between divergent electrodes, into non-thermal non-equilibrium discharge [14].

D. Production using Beams

This method is mainly used in material fabrication. It is frequently accomplished by the use of electron beams and laser beams. The plasma discharges generated using this method is sustainable by interaction of an electron beam with a gaseous medium. This interaction produces turbulent plasma oscillations with high amplitude. The heating of the electrons in this turbulent field is sufficient to sustain the beam produced discharged plasma. Up to 70% of the beam energy can be transferred to the plasma. In this method it is possible to generate plasmas with high degrees of ionization in low pressure environment [12].

5. Efficiency Analysis

In this section a comparative analysis has been done on the efficiency of plasma related methods and the water electrolysis which is one of the most important industrial processes for hydrogen generation.

5.1. Water Electrolysis System

As a case study, water electrolysis using heat has been considered. Water electrolysis involves the catalytic decomposition of water into hydrogen and oxygen using electricity based on the following formula [16]:

$$2H_2O \rightarrow 2H_2 + O_2 \qquad (10)$$

The electrolysis reaction as shown in Fig.4 is an endothermic and almost 242 KJ of energy per mole of hydrogen is needed.

This process, in a thermal power plant, includes the following steps [16]:

- Electricity generation: The heat in the power plant is transformed into the electric power. The efficiency of this process is around 39%.
- Electricity preparation: This process includes AC to DC conversion whose efficiency is 97%.
- Electrolysis
- Hydrogen cooling and compression

Fig. 5 depicts the above mentioned steps. Table 1 shows the amount of energies in the different sections of the plant depicted in Fig.5. Based on these figures for 3000 MW of energy fed into the electrical power plant 6.69Kg of hydrogen is generated per second [16]. So the energy out of the generated hydrogen is almost 800MW. Considering the 3000MW input energy the overall efficiency of the process is almost 30%. Considering the energy fed into the electrolysis section the efficiency is almost 70%. Now for a typical system like what was shown in Fig. 1, this hydrogen should be fed to the fuel cell and the adjustable speed motor drive as shown in Fig. 5. So, the overall efficiency of the system is given by:

$$\eta = \eta_{el} \times \eta_{FC} \times \eta_{ASMD} \qquad (11)$$

Table 1: Energy quota in the electrolysis system

Energy	MW
High temperature input	3000
Local consumption: pumps, …	60
Transformers and rectifiers input	1110
Electrolysis process	1054

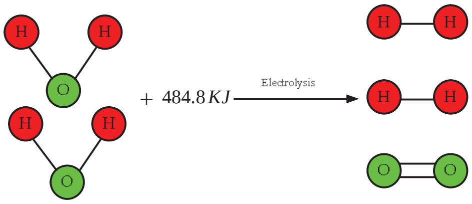

Fig. 4: Chemical reaction in water electrolysis

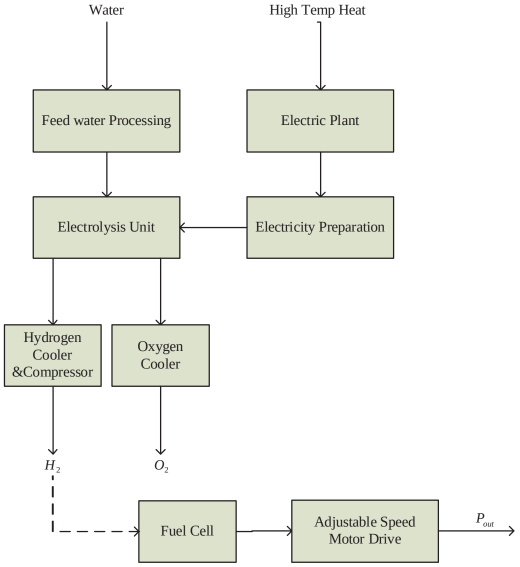

Fig. 5: Flowchart of hydrogen generation using Electrolysis of water

Assuming the typical values of 45% and 80% as fuel cell and ASMD efficiencies respectively, the efficiency of this system is almost 25.2%. It is clear that for small scale hydrogen generation systems which use electrolysis the efficiency is much lower than 70% (For laboratory scale 40-50% is expected). Also, hydrogen pumps should be maintained for fueling of the cars which uses this hydrogen while using plasma technique on board generation of the hydrogen is achievable. As hydrogen is highly explosive the storage of it in a vehicle tank where accidents are quite probable is a big challenge.

5.2. Plasma System

A typical hydrogen generation system that deploys plasma technique has been shown in Fig. 1(a). The following analyses consider the effect of fuel cell and reformer efficiencies and the energy consumed by the power supply on the overall efficiency of the system. As mentioned in (5) the overall efficiency of the system is dependant on the adjustable speed motor drive, reformer, fuel cell and power supply efficiencies. Fig. 6 depicts the overall efficiency of the system for typical values of efficiencies for the ASMD and fuel cell.

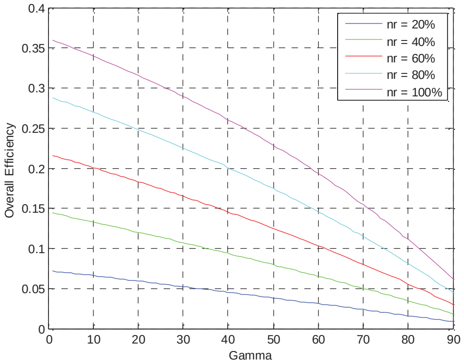

Fig. 6: Overall Efficiency versus γ curves for $(\eta_{ASMD} = 0.8\ ,\ \eta_{PS} = 0.9\ ,\ \eta_{FC} = 0.45)$ while η_r is variable

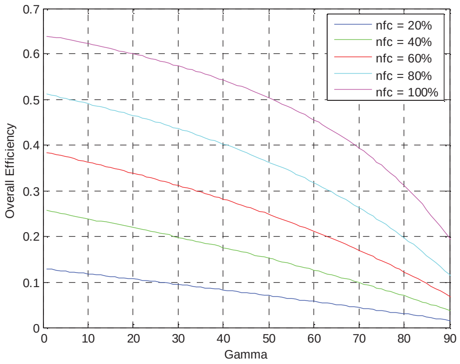

Fig. 7: Overall Efficiency versus γ curves for $(\eta_{ASMD} = 0.8\ ,\ \eta_{PS} = 0.9\ ,\ \eta_r = 0.8)$ while η_{fc} is variable

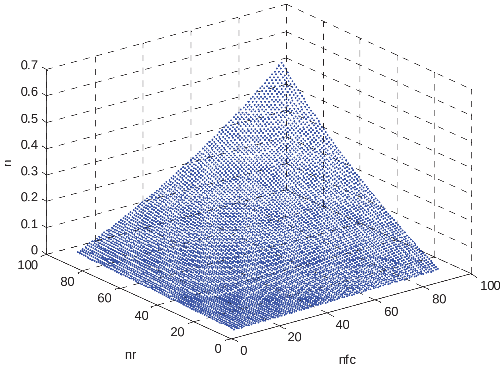

Fig. 8. Efficiency versus η_{fc} and η_r while $(\eta_{ASMD} = 0.8\ ,\ \eta_{PS} = 0.9\ ,\ \gamma = 0.4)$

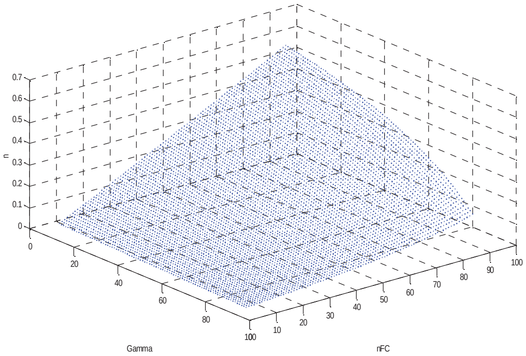

Fig. 9: Efficiency versus γ and η_{fc} while $(\eta_{ASMD} = 0.8\ ,\ \eta_{PS} = 0.9\ ,\ \eta_r = 0.8)$

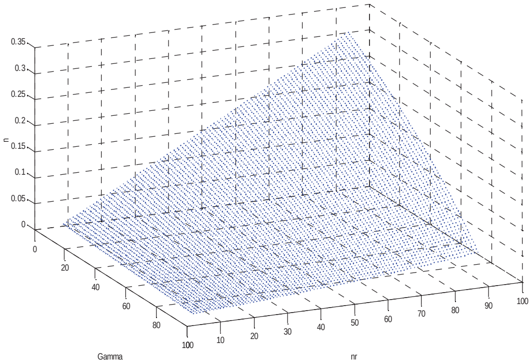

Fig. 10: Efficiency versus γ and η_r while $(\eta_{ASMD} = 0.8\ ,\ \eta_{PS} = 0.9\ ,\ \eta_{FC} = 0.45)$

According to this figures and based on the typical values of 80% for η_r and 40% for γ the overall efficiency would be almost 20% that is much better than what offered by the electrolysis. The efficiency can be increased to 30% by decreasing γ to 20% and increasing η_r to 90%. Figs. 7, 8, 9 and 10 depict the overall efficiency with respect to the parameters of the system.

Based on these figures by increasing the efficiency of the power supply, reformer and the fuel cell the overall efficiency can be theoretically improved to 40% which is quite acceptable even compared to the IEC.

6. Case Study

In this section, results of an experimental test incorporating a pulsed cold plasma chamber are reported. The chemical reaction within the chamber using ethanol as fuel can be summarized as:

$$C_2H_6O+3H_2O \rightarrow 2CO+4H_2+2H_2O \rightarrow 6H_2+2CO_2 \qquad (12)$$

Assuming this ideal conversion, one mole of ethanol and three moles of water produce 6 mole of hydrogen and one mole of carbon dioxide. Given the fact that the molar weight of ethanol and water are 46 (2*12+6*1+16) and 18(2*1+16) respectively, the weight proportion of the ethanol in the initial mixture is 46/(46+3*18)=46%. Furthermore, the burn energy of the alcohol (LHV) in air equals 18kJ/gram. Therefore the complete burn of one mole of ethanol creates 828(46*18) kJ of energy. The burn energy of hydrogen (LHV) is 120kJ/gram which corresponds to a total burn energy of 1440(6*2*120) kJ for a total of 6 moles. As a result the ideal, no energy consumption, fuel conversion process can increase the heat production of a unit volume of ethanol fuel by 75%. It must be noted that the choice of HHV or LHV does not alter this figure significantly. It is notable that the hydrogen harvested through this conversion process may be used directly in a PEM fuel cell or alternatively be used for partial enrichment of fuel in Diesel and gasoline engines to improve fuel economy. Fig. 11 illustrates the excitation to the cold plasma chamber from the experimental test bed (100W Hydrogen chamber). Ignoring the energy necessary for preheating (vaporizing) ethanol, (12) can be brocken down into two steps as shown in Fig. 12.

Fig. 11: Voltage and current waveforms obtained from a 100 W cold plasma Hydrogen chamber using ethanol as fuel

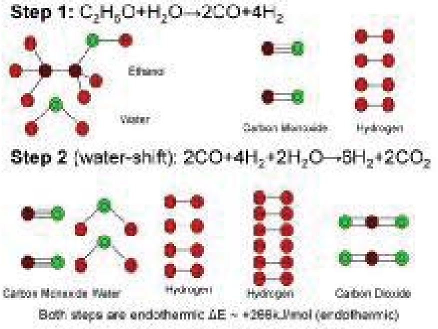

Fig. 12: Breakdown of the chemical reaction in the cold plasma chamber

As one can note by taking into account the balance between both sides of (12) and the respective bond energies at the end of the process there is need for 266 kJ of external energy per one mole of ethanol.

However, the ethanol and water must be heated from 20ºC to 80ºC (100ºC for water) to the evaporation temperature. The required power for conditioning of one mole of fuel is about **650W**. For low degree of ionization the plasma atoms move and collide, following the Maxwellian distribution of speeds. If the energy is lower than the activation energy, the collision is elastic, if higher the collision is inelastic and a quanta of activation energy is absorbed, however the excess of the collision energy is released in the mechanical motion. Therefore, for 0.21mole of ethanol per minute flow require approximately 800W to sustain plasma ((0.21mole/60) 6 10^{23} 1.6 * 10^{-19}*2). Therefore **800W** needs to be spent electrically to maintain the “chemically loaded” plasma. This crude stationary model serves the simple purpose of energy balance calculation and did not explain why the simple heating of the gas will not make the same effect as plasma. Also it did not include the inherent generation and recombination of photons in plasma which are the important part of energy balance. In simple words to produce **5kW** of hydrogen the ideal device have to spend **800W** of electrical power on plasma sustaining and **600W** on fuel conditioning which corresponds to a total external energy of **1400W**. The heat required for conditioning of the fuel can be retrieved from the fuel cell so the necessary power in generation of 5kW of hydrogen power is close to **800W** (i.e. $\eta_r \approx 0.8, \gamma \approx 0.40$ assuming efficiencies of 90% and 45% for the power supply and fuel cell respectively). Using (5), and (6) and assuming an efficiency of 80% for the ASMD variation of the overall efficiency to γ has been computed and plotted in the following figure. As can be seen from Fig. 13 assuming somewhat ideal figures for the efficiency of various blocks in a system including an onboard fuel reformer, the overall efficiency will be very close to those of internal combustion engine. In fact to make this technology competitive, a much higher efficiency in the main propulsion electric drive has to be sought.

Improvement of efficiency in the power supply used for arc generation can be another area in which better performance can be obtained.

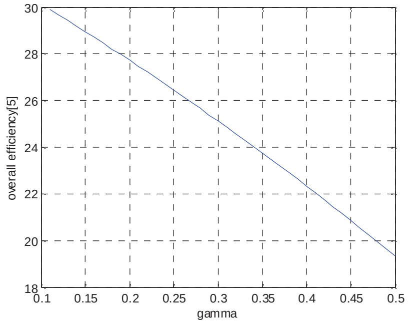

Fig. 13: Variation of the overall efficiency as a function of internal consumption in the reformer.

As can be seen 242KJ of energy is needed for the water electrolysis which in return generates 1 mole of hydrogen. In case of ethanol-water mixture 266KJ of energy is needed which results in 6 moles of hydrogen. Considering the energy required by the peripherals of each unit, the hydrogen generation using plasma is more efficient than electrolysis of the water.

7. Conclusion

As the storage of hydrogen is a safety concern onboard

generation of hydrogen is an active area of research. Different methods of hydrogen generation have been discussed in this paper. As the hydrogen generation process is endothermic a reliable source of energy is needed for the process. Besides the various methods of hydrogen generation using plasma as the energy source and catalyst has been considered as a potential and economical method. Among the different plasma status it is shown that cold plasma is more feasible and efficient to be used for hydrogen generation in plasmatrons. Also, a comparative study on the hydrogen generation using water electrolysis and plasma has been carried out. Finally, a case study considering cold plasma technique has been considered to show the effectiveness of this method.

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