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Methods of on-board Hydrogen Generation in an IC Engine

M. Nikhil Mathew, Atul Dhar*

School of Engineering, Indian Institute of Technology Mandi, Mandi, Himachal Pradesh, India – 175001

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ABSTRACT

Hydrogen is considered to be the cleanest fuel for IC engines and also has a much higher calorific value than the other commonly used fossil fuels. The major problems inhibiting the commercialisation of hydrogen as a fuel is its extremely high cost of storage, production, and transport. The production of hydrogen on-board in an IC engine with simultaneous usage could solve most of the above-mentioned problems. In this paper we discuss the different methods commercially used for the production of hydrogen and the feasibility of them being used on-board on a vehicle propelled by an IC engine. The production of hydrogen using an alkali-based electrolyser with the electrical power produced from the energy extracted from the exhaust of the engine is considered as the most feasible option. Raney-Nickel is chosen as the most feasible electrocatalyst.

1. Introduction:

Hydrogen is the most abundant element in the universe, but its low density does not allow it to stay inside the earth's atmosphere, and high reactivity leads to it reacting with other elements and not being found in its native state. The most abundant sources of hydrogen are water (H_2O), and hydrocarbon fuels. There are four main sources for the commercial production of hydrogen: natural gas, oil, coal, and electrolysis (of water and in chlor alkali industry), which account for 48%, 30%, 18% and 4% of the world's hydrogen production respectively [Guido, 2010].

Table 1 compares the properties of diesel and hydrogen, it is observed that hydrogen as about 3 times higher calorific value, 9 times higher flame velocity and zero carbon residue, this makes it a preferred choice as a fuel in IC engines. The use of hydrogen in a mobile application requires it to be stored, and as can be seen in Table 1, it has much lower density (4 orders lower) in comparison to diesel which makes it very difficult, dangerous and expensive. The storage of hydrogen gas is generally classified into physical and material-based methods as shown in Figure 1. The physical methods require extremely high pressures or extremely low temperatures for meaningful density, both of which consume a lot of power and are not economically feasible now. The material-based method is less energy intensive but is still immature and not commercially viable.

Table 1 Properties of Hydrogen and Diesel [Senthil, 2003]

Properties	Diesel	Hydrogen
Density (kg/m3)	840	0.082
Calorific value (MJ/kg)	42.7	119.81
Flame velocity (m/s)	0.3	2.7
Auto ignition temperature (°C)	280	585
Carbon residue (%)	0.1	0

Hydrogen is widely used commercially and about 500 billion Nm^3/ year, is globally produced with the major contribution being from steam reforming of natural gas. Due to low efficiencies and high costs only 4% of hydrogen is produced byelectrolysis as shown in Figure 2. But as we need hydrogen for a mobile application, we will limit our focus to the methods of on-board hydrogen generation. As we can produce hydrogen from hydrocarbons (with diesel already stored in the vehicle)and water (easy to store and abundant) only methods using them is discussed, namely 1) hydrogen production from hydrocarbons, 2) hydrolysis and 3) electrolysis. The working principle, advantages and disadvantages of each method are briefly discussed.

* Corresponding Author: *add@iitmandi.ac.in*

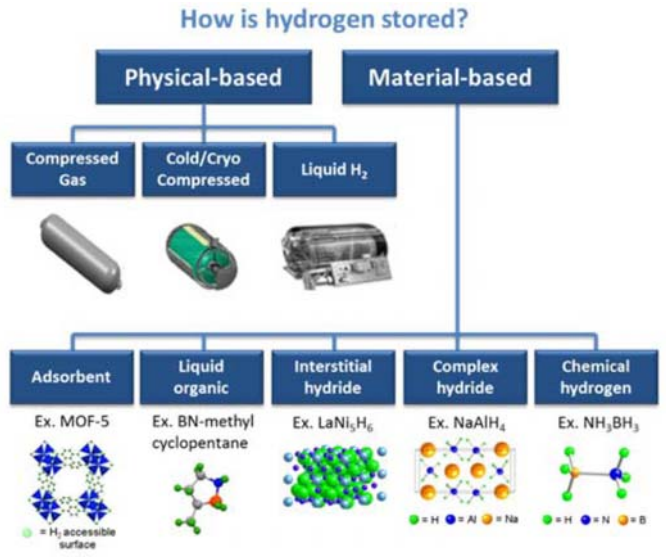

Figure 1 Methods of Hydrogen Storage

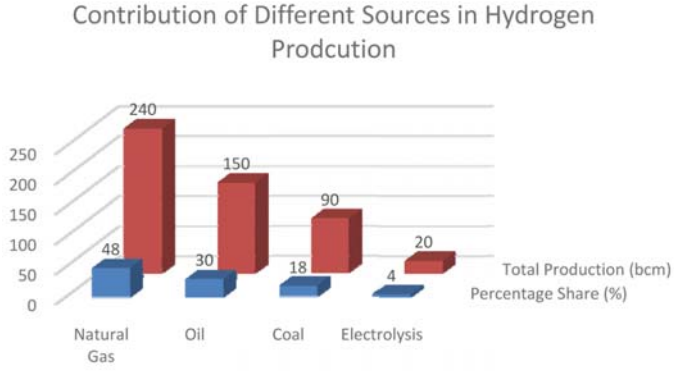

Figure2 Contribution of different sources in hydrogen production [Guido, 2010]

2 Methods of on-board hydrogen production in an IC engine

2.1 Hydrogen Production from Hydrocarbons

The most commonly used and commercially proven methods for production of hydrogen from hydrocarbons are discussed in this section.

2.1.1 Steam Methane Reforming

Steam methane reforming is globally the most widely used method for hydrogen generation. This method uses natural gas as its feedstock, generally methane is the preferred starting material as it has the best H/C (i.e., Hydrogen / Carbon) ratio among hydrocarbons. The process is not suitable for heavy hydrocarbons like diesel. The gas is heated to about 700-1100 °C in the presence of steam and nickel being used as the catalyst results in an endothermic reaction. The products of this reaction are carbon monoxide (CO) and Hydrogen (H_2) formed by breaking the methane molecule as shown in equation (1) [Guido, 2010].

$$CH_4 + H_2O \rightarrow CO + 3\ H_2 \quad (1)$$

The carbon monoxide is then passed with steam over iron oxide to undergo the water gas shift reaction to produce carbon dioxide (CO_2) and hydrogen.

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (2)$$

The advantages of steam reforming of natural gas are that it is the most economical hydrogen production method, it produces high yield from feed stock and is energy efficient. The major disadvantages are the pollution it causes due to the byproducts CO and CO_2 which are harmful greenhouse gases [Guido, 2010], depending on the quality of the raw material one ton of H_2 can produce 9 to 12 tons of CO_2 [Jaggi and Jayanti 2013]. The facility takes up a lot of space, and on-board generation is not technically feasible to produce pure hydrogen [Sanz et al., 2015]. Another drawback being the use of membrane reactors combines both chemical reaction and separation steps in a single device, but they operate with Pd or Pd-based alloys with high perm-selectivity nullifying the economic advantage [Holgado and Alique,2019]. The operation also requires high temperature and pressure, thereby reducing the life of the setup and increasing the chances of accidents. The temperature range of 700-1100 °C can't be achieved by transferring heat from the engine exhaust of most engines.

2.1.2 Partial Oxidation (POX)

The Partial oxidation process primarily uses heavy oil fractions (e.g., vacuum remnants, heating oil), whose further treatment and utilization are difficult as feedstock [Holmen, 2009]. This makes it a favourable method for the use of diesel as a feedstock for hydrogen production. The gasified raw material such as methane and biogas also can be used. Partial oxidation occurs when the oxygen is fed at a level below that which is needed for complete oxidation, and produces hydrogen and carbon monoxide as shown in equation (3).

$$C_nH_m + \frac{n}{2}O_2 \longrightarrow n\,CO + \frac{m}{2}\,H_2 \quad (3)$$

POX is generally a noncatalytic process, in which the raw material is gasified in the presence of oxygen and possibly steam, at temperatures ranging between 1300–1500 ^{0}C and pressures between 3–8 MPa. If a catalyst bed is used the partial oxidation can be achieved at a lower the operating temperature of 700–1000 ^{0}C, but this requires the feedstock to be free from sulphur in order to avoid catalyst poisoning. When compared to steam reforming (H_2:CO= 3:1), more CO is produced (H_2: CO= 1:1 or 2:1) in POX. [Krummenacher et al., 2003] had succeeded in using catalytic partial oxidation for decane, hexadecane, and diesel fuel. But as the operating temperatures are above 700 ^{0}C [Krummenacher et al., 2003] the heat for reaching the same cannot be sourced from the exhaust gases of most engines, it requires an additional heat source. The fact that the amount of oxygen used as a feedstock has to be regulated throughout the process for transient operation also makes implementation difficult. The safety concerns and complex after purification process also may make their use for practical and compact portable devices difficult [Holladay, 2004].

2.1.3 Steam Cracking

Steam cracking is the most sought after industrial method for producing lighter alkenes (olefins), including ethene (or ethylene) and propene (or propylene) and produce hydrogen as a by-product during the process. It is a petrochemical process wherein saturated hydrocarbons are broken down into smaller, often unsaturated, hydrocarbons, this method is more suitable for lighter hydrocarbon feeds like LPG (low pressure gas) or ethane (generally saturated hydrocarbons). The feedstock is diluted with steam and then briefly heated in a furnace to a temperature around 850 °C, in the absence of oxygen [Giovanni, 2013].

If heavier hydrocarbons such as full range and heavy naphthas as well as other refinery products as feed we still obtain hydrogen and similar products, but with other by-products rich in aromatic hydrocarbons and hydrocarbons suitable for inclusion in gasoline or fuel oil and may lead to secondary emissions for an onboard application. On the other hand if light hydrocarbon feeds (such as ethane, LPG, or light naphthas) are used the product streams are rich in the lighter alkenes, including ethylene, propylene, and butadiene [Posch, 2011].

In order to produce pure hydrogen, we need the quench, compressor, and separator units after the steam cracking furnace. This process has disadvantages similar to that of steam methane reforming i.e., even though it is more economical it produces secondary emissions in the form of unburnt hydrocarbons. The process is spatially inefficient for a mobile application, the use of lighter hydrocarbons requires an additional storage unit or the use of heavy hydrocarbons like diesel as the feedstock would incur a fuel penalty. The operating temperature of 850 °C is also not achievable from the exhaust of the engine used in the study as the maximum exhaust temperature is about 450 °C. Due to the above-mentioned reasons thermochemical processes like steam methane reforming, partial oxidation and steam cracking are not used in this study.

2.2 Aluminium-Water Reactions

At about ambient temperature, aluminum metal and water react to form aluminum hydroxide and hydrogen. This is illustrated in equation (4).

$$2Al + 6H_2O \rightarrow 2Al\,(OH)_3 + 3H_2 \quad (4)$$

Even though equation (4) is thermodynamically favorable, it does not occur spontaneously because of a thin layer of aluminum oxide on the surface of aluminum particles. This layer prevents water molecules from

reacting with the aluminum metal [Related, 2008].

The oxidation layer is very useful in preventing corrosion which is a very engineering friendly property but makes it unsuitable for hydrogen production. But as a solution the hydroxide ions (OH^-) present in strong aqueous alkaline solutions destroy the oxide layer. Therefore, aluminum is dipped in alkaline electrolytes for continuous production of hydrogen [Wang et al., 2009].

NaOH is the most widely used alkaline electrolyte and the reactions when using NaOH are as follows [Wang et al., 2009; John and George, 2008;Susana S., 2005].

$$2Al + 6H_2O + 2NaOH \rightarrow 2NaAl(OH)_4 + 3H_2 \quad (5)$$

$$NaAl(OH)_4 \rightarrow NaOH + Al(OH)_3 \quad (6)$$

$$2Al + 6H_2O \rightarrow 2Al(OH)_3 + 3H_2 \quad (7)$$

The use of an alkaline electrolyte only helps in obtaining continuous production, the production rate is still very low to be viable for any commercial application. To deal with this problem promoters are used along with aluminum to enhance the reaction and to reduce the oxide layer formation [Susana S., 2005]. The comparison of the effectiveness of the generally used promoters is done based on the production rate. Un treated aluminum produces 8 x 10^{-7} g H_2/sec/g of Al, when Al_2O_3 is used as a promoter the output obtained is 4 x 10^{-6} g H_2/sec/g of Al at 50ºC, whereas the use of KCl and NaCl increases the rate of reaction to augment the production rate to 2 x 10^{-4} g H_2/sec/g of Al at 55ºC [John and George, 2008].

The major advantage of this process is that it does not require any external energy source for operation. But aluminum hydrolysis has a fair share of disadvantages like the cost of producing hydrogen by this approach is dictated by the cost of aluminum metal. The wholesale cost of aluminum is about Rs.260 per kg in the Indian market. This makes the setup highly uneconomical. The continuous usage of aluminum as it oxidizes requires a huge storage of it onboard this makes it uneconomical and infeasible for this application.

2.1.1 Water Electrolysis

Based on literature survey, we have identified that non-thermal plasma electrolysis, polymer exchange membrane (PEM) electrolysis, traditional alkaline electrolysis and anionic exchange membrane (AEM) electrolysis are the only methods that can fit into our production rate and onboard requirement. But Plasma has a high energy input requirement (2000 watts for 1-2 mmol/min) [Nelson and Setijo, 2011].

In acid media, the first step in hydrogen evolution is always the Volmer reaction or electrochemical hydrogen adsorption [Quaino et al. 2014]:

$$H^+ + e^- \rightarrow H_{ad} \quad (8)$$

while for the second step there are two possibilities, namely Tafel reaction (9) and Heyrovsky reaction (10)

$$H_{ad} + H_{ad} \rightarrow H_2 \quad (9)$$

$$H^+ + H_{ad} + e^- \rightarrow H_2 \quad (10)$$

In alkaline solutions, the Volmer and Heyrovsky reactions are represented by equations (11) and (12) respectively.

$$H_2O + e^- \rightarrow H_{ad} + OH^- \quad (11)$$

$$H_2O + H_{ad} + e^- \rightarrow H_2 + OH^- \quad (12)$$

while the Tafel reaction stays the same.

The benefits of electrolysis are the size of the system can be changed according to the requirement, only water and electricity are required to produce the hydrogen therefore on-board production is not constrained by size and raw materials. The major drawbacks of this method are that mature and inexpensive methods are corrosive, inefficient, and bulky, the non-corrosive methods are immature.

The comparison between the three most promising methods have been taken from an extensive review [Immanuel and Dmitri, 2017].

2.1.1.1 Alkaline electrolysis

In alkaline electrolysis, the most used anode and cathode materials are nickel- and cobalt-based oxides, respectively, and the most used liquid electrolyte is 30–40 % KOH. The formation of K_2CO_3 reduces the performance of alkaline electrolysis. This is due to several factors such as the reaction reduces the number of hydroxyl ions present in the anolyte that are needed for the anodic reaction [Ahmed and Krumpelt, 2001;Akutsu et al., 2009;Artero et al., 2011], it also reduces the ionic conductivity of the electrolyte due to modification of the electrolyte composition [Singh et al. 2010]. The K_2CO_3 precipitates in the pores of the gas diffusion layer (GDL), blocking ion transfer. The alkaline electrolysis method is a very mature technology with demonstrated production rates of up to 760 Nm^3/h.

2.1.1.2 Proton Exchange Membrane (PEM) Electrolysis

In this method the anode and cathode are separated by a semi-permeable membrane rather than a physical separation as given in alkaline electrolysers. In PEM electrolysis, the anode and cathode catalysts are typically IrO_2 and Pt black, respectively [Butt et al., 2013; Ni et al., 2006]. Due to higher mobility of the H^+ ions and greater activity of Pt - IrO_2 the production per unit volume of PEM electrolysers is much higher than their alkaline counterparts. Titanium bipolar plates are used to resist the highly acidic nature which are not only costlier than Ni, Cu but also have lower electrical conductivity, Due to their inherently expensive rare earth nature only small-scale systems of the order of 30 Nm^3/min have been realized.

2.1.1.3 Anion exchange membranes (AEM) electrolysis

They offer benefits for both PEM and alkaline electrolysis. In Anion exchange membrane (AEM) water electrolysis the PEM membrane is substituted with an AEM [Immanuel andDmitri, 2017]. Due to the alkaline nature of the electrolyte transition metals such as Ni and Co are used as the catalysts reducing the overall costs. Unlike the alkaline electrolysers low concentration alkaline solutions can be used as electrolyte, the OH^- transfer is dealt by the highly activated AEM membrane. This also minimizes the adverse effects due to CO_2 poisoning. The quaternary ammonium ion-exchange-group-containing membrane that is used in AEM electrolysis is less expensive than the nafion-based membranes. The interaction between CO_2 and the AEM is low due to the absence of metal ions in AEMs. Furthermore, the absence of a corrosive liquid electrolyte offers added benefits of longer life, absence of leaking, volumetric stability, ease of handling, and a reduction in the size and weight of the electrolyser.

As the current densities achievable using alkaline electrolysis is low and being prone to stability issues due to high concentration of KOH it is not very feasible for on-board hydrogen generation. The PEM electrolysis method is very expensive for our target market segment; therefore, we intend to use the AEM electrolysis method to produce pure hydrogen and an alkaline electrolyser to produce HHO gas.We will be discussing the literature reviewed in order to select the appropriate HER electro catalyst for alkaline electrolysis.

2.1.1.4 Selecting the most appropriate Electrocatalyst

The hydrogen evolution reaction (HER) is a two-step catalysis reaction and involves the formation of an adsorbed intermediate. The Sabatier's principle [Sabatier, 1920] the oldest available rule states that the adsorption energy should neither be too high or too low. If the energy is too high (endothermic) the adsorption takes a lot of time and limits the overall rate of the reaction and if the energy is very low (exothermic) then the desorption rate is very low. An ideal catalyst should be able to make a temporary bond very fast, exchange electrons and then detach, forming the new compound almost instantaneously. Hence, a very strong or a very weak bond are both detrimental to the overall rate of reaction. In case of hydrogen electrocatalysis we can more precisely state that at the equilibrium potential the free energy of adsorption of hydrogen from the solution should be close to zero.

We can visualize a triangular plot when the metals under study are arranged by satisfying the criteria of optimum amount of adsorption energy being the reason for the highest catalytic activity. To conceptualise this Trasatti [Trasatti, 1972] was the first to collect experimental data and construct the first volcano curve for hydrogen evolution. Trasatti used the hydride bond formation energy as a measure of adsorption energy. His volcano plot was made for acidic solutions and is displayed in Figure 3.

If the Sabatier's principle is considered as the only criterion for the selection of the electrocatalyst we observe from Figure 3 (Where j_{00} is the exchange current density, and $E_{M\text{-}H}$ the energy of hydride formation) that platinum is the closest to the optimum energy of hydride of formation and also has the highest exchange current density. The platinum group of metals are well known for their catalytic activity, but they are extremely rare and expensive. We are targeting a market segment where the goods are both produced in large numbers and are required to be economical. The above-mentioned criterion prompts us to choose non noble metals for our task. As can be observed nickel is the most suitable non noble metal [Quaino et al., 2014] available which is both abundantly available and appropriately priced.

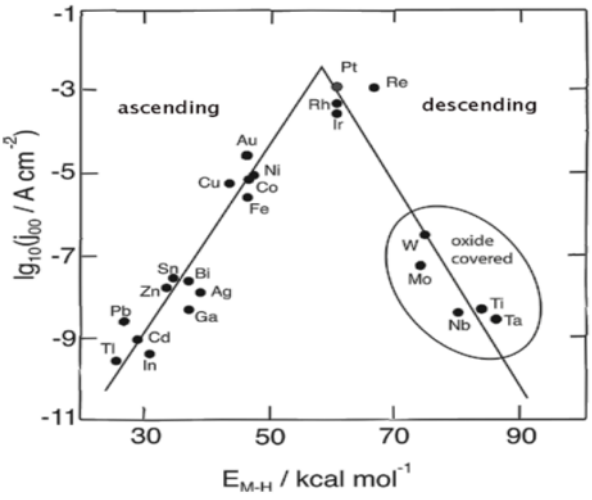

Figure 3 Trassati's volcano plot for the hydrogen evolution reaction in acidic solutions [Quaino et al., 2014]

In alkali-based water electrolysis potassium hydroxide is added as an additive to increase the electrical conductivity, the most important properties for the electrode surface are large active surface area, electrochemical stability, good electrical conductivity, low hydrogen over-potential, good electrocatalytic activity and high corrosion resistance [Lupi, 2009]. The first criterion implies to having higher surface area for a compact geometric volume of the system, this can be achieved by using mesh like structures and increasing the roughness of the electrodes. Copper has the highest electrical conductivity for a non-noble metal, but it is found to be electrochemically unstable in alkaline media [Othman, 2012]. The volcano plot suggests that nickel has low hydrogen overpotential and best electrocatalytic activity among non-noble metals, both of these properties can be enhanced using the law of synergism i.e., mixing two or more metals to form the electrocatalyst.

Low-price stainless steel and lead were pointed out as cheap electrode materials for good corrosion resistance and have relatively low overpotentials however their inability to tolerate highly alkaline environments puts them out of the fray. Ni is the best electrocatalyst among transition metals as per Figure3 and displays good corrosion resistance in an alkaline. Investigations of several co-deposits on nickel substrate have shown that the electrocatalytic, as well as stability sequence is Ni-Mo > Co-W > Co-Mo > Ni-W > Ni-Co > Ni-Fe > Ni-Cr [Gvozden et al., 2011].

We can logically use the volcano plot to select appropriate metals to increase the electrocatalytic activity. The use of Nickel being fixed we can use metals from the descending part of the volcano curve such as Molybdenum or Tungsten in order to reach closer to Platinum. We could also use cobalt, viz. closest to Nickel in the ascending part to enhance the electrochemical properties by means of synergism.

Ni–Mo alloys indicate that they could be suitable cathode materials for hydrogen production through water electrolysis [Lupi, 2009].[Elisa et al., 2005] reported that NiMo-1 (Ni7.3Mo) was found to yield the highest overall electrocatalytic activity among the investigated materials. On the other hand, NiW-1 (Ni3.4W) was found to yield the highest intrinsic electrocatalytic activity, which was postulated to be due to the modification of the electron density in the d-shell upon alloying Ni with W in a way that favours the HER kinetics. As engineers we are interested in the overall performance i.e., the production of hydrogen more than the intrinsic activity, therefore we prefer Ni-Mo over Ni-W. Because of the high catalytic activity for the HER, Ni-Mo alloys of various compositions have been the subject of numerous studies. The high electrochemical activity of Ni-Mo alloys encouraged researchers to conduct a number of studies on it, but none of these research works solved the issue instability of the electrode in strongly alkaline solutions at elevated temperatures [Tasic et al., 2006]. All published data in regard with the use of Ni-Mo catalyst for the HER in an alkaline medium have reported permanent destruction of electrodes over long term usage [Damian et al., 2006, Roriguez, 2004, Krstajic et al., 2008].

Hence even though Ni-Mo offers good electrolytic activity it is not stable in alkaline solutions and therefore cannot be used. We turn our focus to Ni-Co going by the order provided in [Gvozden et al., 2011] to find the most suitable electrocatalyst for our application. C. G. Buch et al. [52] reported that electrodeposited macroporous Ni, Co, and Ni-Co at high current density on stainless steel (AISI 304) substrates. They observed that as the Co content increases in the electrode position bath the obtained structures show lower surface roughness. An optimum Co content of 43% displayed highest intrinsic activity for HER.

[Lupi, 2009] have reported similar observations that the hydrogen over-potential appears to be lower in the case of Ni concentrations ranging between 35 and 59 weight percent. Therefore, in order to improve the intrinsic electrochemical activity, we arrive at the conclusion that Ni-Co with the above-mentioned ratio is the best non noble metal combination keeping in mind the cost and ease of production. We also looked only on literature where in electrode position was the method used for the catalyst coating due to the simplicity in the process. As per [Buch et al., 2013] the surface roughness is reduced when Co is co-deposited with Ni, we need to know if we have any method of increasing the surface roughness which can increase the rate of reaction for a unit external volume when compared to the increase due to synergism.

One very interesting catalyst in this pursuit is the Raney-Ni electrocatalyst, they display a porous character, and the surface porosity is generally characterised using the electrochemical impedance spectroscopy technique. The Porous electrodes decrease the reaction overpotential by enhancing the real surface area and: or by increasing the intrinsic electrocatalytic activity [Hitz and Lasia, 2001]. The porous electrodes are prepared by the method of co-deposition, i.e., Nickel and Zinc salts (other salts e.g., Co or Mo can be added if required) are electrodeposited together on the suitable substrate, then after preparing, the alloys were leached of to remove part of the zinc and generate a porous layer (type Raney electrodes) [Herraiz et al. 2011 a].

[Herraiz et al., 2013] studied the influence of the addition of Co to raney nickel to compare the effect of synergism and effect of real surface area due to cracks by gradually increasing the percentage of Co was from 5-22%. With the increasing percentage of Co, a change in surface morphology was noted from cracked to "cauliflower like". The kinetic parameters suggest that the presence of Co increases the intrinsic activity per unit of true surface area due to increased synergism. But the "cauliflower like" structure reduced the true surface area in comparison to the cracked morphology, and the improvement due to synergism does not compensate for the loss in surface area. Resulting in lower catalytic activities.

[Herraiz et al., 2011 b] reported that when the zinc is gradually added to the electrodeposition bath the number of cracks in the Ni/Zn and Ni–Co/Zn deposits substantially increase. As per the apparent activation energies obtained by EIS, the presence of Co decreases the catalytic activity of the Ra-Ni electrodes.Ni/Zn and Ni–Co/Zn (after leaching) show an improvement in their catalytic activity with time due to continuous improvement in area unlike smooth nickel electrodes even though the initial results may seem otherwise.

[Solmaz et al.,2009] also suggested that the zinc co-deposited electrodes show an improvement in their activity with time due to changes in the microstructure. The long-term operation of Cu/NiCo-Zn at 100 mAcm^{-2} showed that the Tafel slope improved from 96 mV dec^{-1} (after 24 h) to 112 mV dec^{-1} (after 120 h) and the overpotential decreased from -0.187 V to -0.169 V during the same period.The reason suggested is that due to similar conditions of operation and leaching the electrode gets activated in due course of time. Which means any existing corrosion products and accumulated impurities are removed with newer cracks being formed.

[Alejandro et al.,2019] reported that the combination of Raney Nickel as the cathode and SS316L as the anode resulted in a stable cell with good performance after observing it for a period of one month at 75° C and 300 mA cm^{-2}. The paper also reports that the addition Co or/and Cu to Ni results in increased intrinsic activity but reduced apparent catalytic activity.

[Applebyet al., 1978] The irreversibility of the oxygen electrode reaction is a major reason for the low efficiency of operation of electrolysers. Due to the bigger bubble sizes of O_2 evolution they are unable to benefit from porous high surface area electrodes. Hence the use of smooth electrodes is preferred. Even though Co, Ni and Fe based oxides are the most preferred electrocatalysts for OER we have used smooth SS316 for simplicity.

Based on the available literature [Herraiz et al., 2011 b, Herraiz et al., 2011 b, Herraiz et al., 2013] the Ra-Ni catalyst was electrodeposited on a stainless-steel mesh, to get good adherence a thin layer of Ni was coated before the main deposition, [Solmaz et al., 2009, Alejandro et al., 2019] used copper mesh where in no such precoating was required. But [Hartmut Wendt and Gerhard, 1999] suggests that as Ra-Ni coatings are porous in nature the substrate over which they are coated must be stable as well, most studies recommend a thin layer of nickel coating on stainless steel substrate to reduce cost. But the pre-treatment of stainless steel is more rigorous, and the thin layer of coating may also be porous and deteriorate soon.

Therefore, we have decided to coat Ra-Ni over a nickel mesh as the substrate for the hydrogen or cathode side. Based on Othman et al. [Othman, 2012] copper is unstable in alkaline medium hence smooth SS316 stainless steel mesh was used for the oxygen side.

As per Wang et al. [Mingyong et al., 2014] due to a magneto hydro dynamic (MHD) convection induced by Lorenz force there is enhancement effect of magnetic field on an electrochemical reaction with better bubble disengagement being described as the primary reason. Ferromagnetic materials such as nickel are better cathode material than paramagnetic (platinum) and diamagnetic (graphite) and improves further with shorter inter electrode distance. An increase of 14.6 % at 2mm interelectrode distance and 4V cell voltage was reported.

Conclusions

1. The three most commercially used hydrogen production methods were discussed in brief, with the working principle, advantages and disadvantages being the criteria of comparison.
2. The methods using hydrocarbons as a feedstock needs higher temperature for operation, they are not concise and also suffer from secondary emissions. They are also generally used when the feedstock is a lighter hydrocarbon and not the likes of gasoline and diesel. Therefore this method is omitted.
3. The use of hydrolysis involves Aluminum as a feedstock and to gain enough hydrogen flowrate we would need a large amount of it. This would lead to storage and cost associated problems. Due to these reasons we do not consider this method.
4. The use of on-board electrolysis with the electrical energy being provided by the engine exhaust is considered a feasible option for most enigne sizes.
5. The electric turbogenerator can be used for larger engines with good pressure in the exhaust and Thermoelectric Generators (TEGs) can be used when a significant amount of temperature difference is available at relatively low pressures.
6. A comparison of the most commonly used electrolyser technologies was done. Alkaline and anionic exchange membrane-based electrolysers were chosen to be feasible.
7. The electrocatalyst used on the cathode was chosen to be Raney-Nickel due to its larger real surface area and better catalytic activity of Ni amongst all the other transition metals.

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