People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research
Djillali Liabes University of Sidi Bel Abbès
Faculty of Technology
Department of Mechanical Engineering

الجمهورية الجزائرية الديمقراطية الشعبية
وزارة التعليم العالي و البحث العلمي
جامعةجيلالي ليابس – سيديلعباس
كلية التكنولوجيا
قسم الهندسة الميكانيكية

Teaching handout

Fuel cell and hydrogen production

Cours destiné aux étudiants :

Semestre : 3

Unité d'enseignement : UEF 2.1.2

Matière 2 : Pile à combustibles et production de l'hydrogène

VHS : 45h00 (Cours : 1h30, TD 1h30)

Crédits : 4

Coefficient : 2

Instructor
Dr. Kouider Bendine

Academic Year 2025/2026

Semestre : 3

Unité d'enseignement : UEF 2.1.2

Matière 2 : Pile à combustibles et production de l'hydrogène

VHS : 45h00 (Cours : 1h30, TD 1h30)

Crédits : 4

Coefficient : 2

Contenu de la matière :

Chapitre 1 : Introduction sur les piles à combustible (2 semaines)

- Historique
- Principe de fonctionnement

Chapitre 2 : Différents types de piles à combustibles (2 semaines)

- Les différents types de piles à combustibles et leur fonctionnement
- Les Piles à combustibles à basses températures
- Les Piles à combustibles à haute température

Chapitre 3 : Applications des Piles à combustible (2 semaines)

- Les avantages des piles à combustible
- Les inconvénients des piles à combustible
- Piles à combustible pour véhicule électrique

Chapitre 4 : Production d'hydrogène (4 semaines)

- Le vapeur formage
- L'électrolyse de l'eau
- Production à partir des énergies renouvelables
- Solaire thermique (haute température)
- Photovoltaïque (Photo-électrolyse)
- Production à partir de la biomasse

Chapitre 5 : Modélisation des piles à combustible (3 semaines)

Grandeurs standard de réaction

- Force électromotrice
- Tension
- Puissance
- Débit des réactifs
- Rendement
- Dimensionnement d'une installation à piles à combustible

Chapitre 6 : Risques liés à la production et le stockage de l'hydrogène (2 semaines)

- Risque : inflammation ou explosion
- Risque mécanique : grande température et haute pression
- Caractère toxique et corrosif
- Techniques de transport et de stockage d'hydrogène

1. Background

Fuel cells are one of the keys enabling technologies for future hydrogen economy. For the last 20 years, applications of the fuel cells are mostly replacing internal combustions engines, and providing power in stationary and portable power applications. But the history of the fuel cells is more than last 20 years; actually, it has covered almost two centuries. The purpose of this paper is to present the development of the fuel cells across the time, fuel cell types, its present state and some nowadays applications.

In 1800, **William Nicholson and Anthony Carlisle** described the process of using electricity to break water into hydrogen and oxygen. William Grove is credited with the first known demonstration of the fuel cell in 1839. Grove saw notes from Nicholson and Carlisle and thought he might "recompose water" by combining electrodes in a series circuit, and soon accomplished this with a device called a "gas battery." It operated with separate platinum electrodes in oxygen and hydrogen submerged in a dilute sulfuric acid electrolyte solution. The sealed containers contained water and gasses, and it he observed that the water level rose in both tubes as the current flowed. The device was nicknamed the "Grove cell," and it consisted of a platinum electrode immersed in nitric acid, and a zinc electrode immersed in zinc sulfate. It generated about 12 amps of current at approximately 1.8 volts.

Friedrich Wilhelm Ostwald (1853–1932), one of the founders of physical chemistry, provided a significant portion of the theoretical understanding of fuel cells. In 1893, Ostwald experimentally determined the roles of many fuel cell components.

Ludwig Mond (1839–1909) was a chemist that spent most of his career developing soda manufacturing and nickel refining. In 1889, Mond and his assistant Carl Langer performed numerous experiments using a coal-derived gas. They used electrodes made of thin, perforated platinum, and had many difficulties with liquid electrolytes. They achieved six amps per square foot (the area of the electrode) at 0.73 volts.

Charles R. Alder Wright (1844–1894) and C. Thompson developed a similar fuel cell around the same time. They had difficulties in preventing gasses from leaking from one chamber to another. The leaking and a few other design flaws prevented the battery from reaching voltages as high as 1 volt. Wright and Thompson felt that if they had more funding, they could create a more robust cell that would provide adequate electricity for many applications.

The French team of **Louis Paul Cailleteton** (1832–1913) and **Louis Joseph Colardeau** came to a similar conclusion, but thought the fuel cell electrochemical process was not practical due to needing "precious metals." Also, many papers published during that period said that coal was extremely inexpensive so that a new system with a higher efficiency would not decrease the prices of electricity drastically.

William W. Jacques (1855–1932), an electrical engineer and chemist, did not pay attention to these critiques and startled the scientific world by constructing a "carbon battery" in 1896. Air was injected into an alkali electrolyte to react with a carbon electrode. He thought he was achieving an efficiency of 82 percent but obtained only an 8-percent effici2ency.

Emil Baur (1873–1944) of Switzerland and several of his students conducted many experiments on different types of fuel cells during the early 1900s. He worked on high-temperature devices, and a unit that used a solid electrolyte of clay and metal oxides.

O. K. Davtyan of the Soviet Union did many experiments to increase the conductivity and mechanical strength of the electrolyte in the 1940s. Many of the designs did not yield his desired results, but Davtyan's and Baur's work contributed to the necessary preliminary research for today's current Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC) devices.

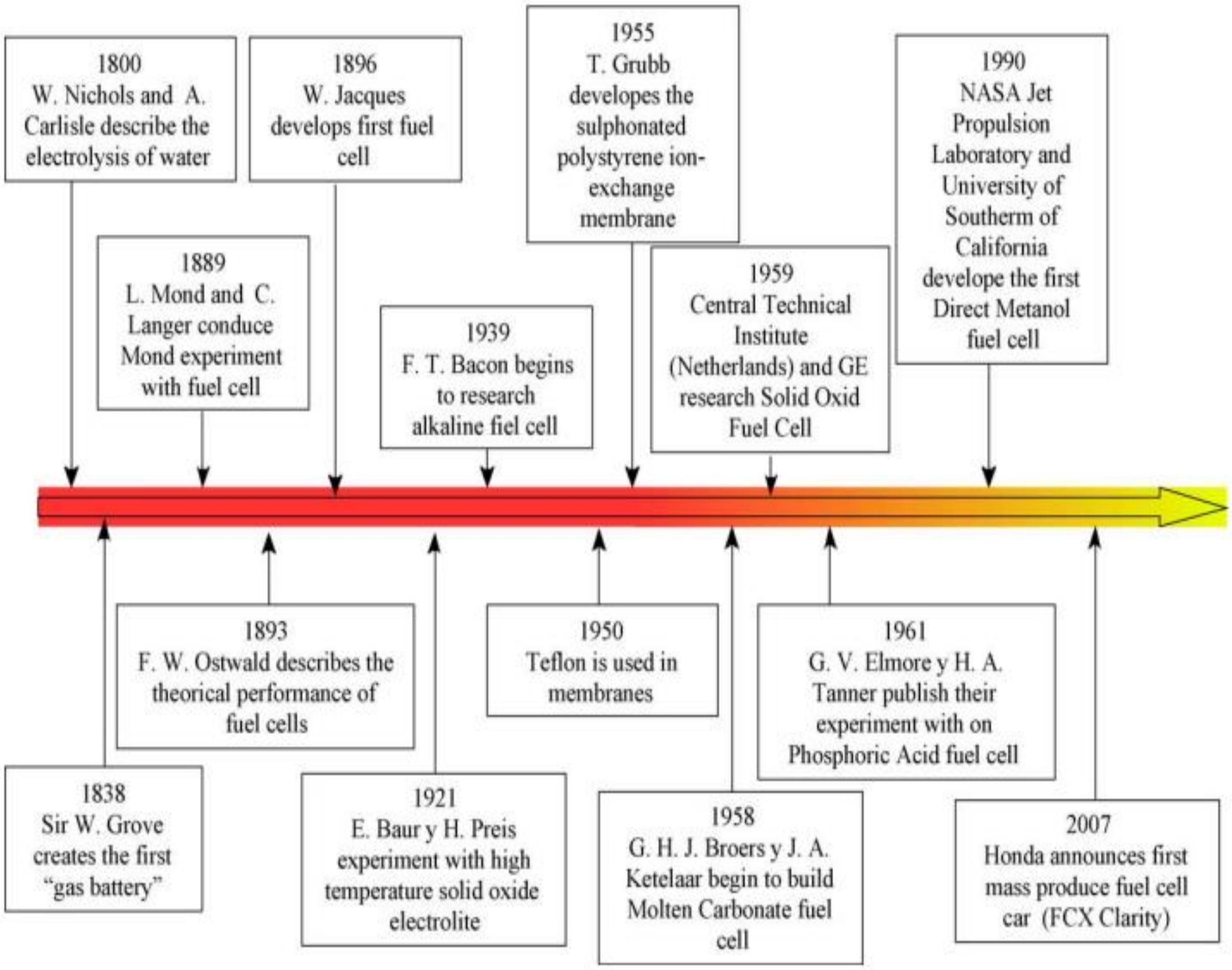


Figure 1. History of fuel cell

2. What is a fuel cell

A fuel cell is a device that generates electricity by a chemical reaction. Every fuel cell has two electrodes called, respectively, the anode and cathode. The reactions that produce electricity take place at the electrodes.

Every fuel cell also has an electrolyte, which carries electrically charged particles from one electrode to the other, and a catalyst, which speeds the reactions at the electrodes.

Hydrogen is the basic fuel, but fuel cells also require oxygen. One great appeal of fuel cells is that they generate electricity with very little pollution–much of the hydrogen and oxygen used in generating electricity ultimately combine to form a harmless byproduct, namely water.

One detail of terminology: a single fuel cell generates a tiny amount of direct current (DC) electricity. In practice, many fuel cells are usually assembled into a stack. Cell or stack, the principles are the same.

3. Working Principle

A fuel cell is a lot like a battery. It has two electrodes where the reactions take place and an electrolyte which carries the charged particles from one electrode to the other. In order for a fuel cell to work, it needs hydrogen (H_2) and oxygen (O_2). The hydrogen enters the fuel cell at the anode. A chemical reaction strips the hydrogen molecules of their electrons and the atoms become ionized to form H+. The electrons travel through wires to provide a current to do work. The oxygen enters at the cathode, usually from the air. The oxygen picks up the electrons that have completed their circuit. The oxygen then combines with the ionized hydrogen atoms (H^+), and water (H_2O) is formed as the waste product which exits the fuel cell. The electrolyte plays an essential role as well. It only allows the appropriate ions to pass between the anode and cathode. If other ions were allowed to flow between the anode and cathode, the chemical reactions within the cell would be disrupted.

The reaction in a single fuel cell typically produces only about 0.7 volts. Therefore, fuel cells are usually stacked or connected in some way to form a fuel cell system that can be used in cars, generators, or other products that require power.

The reactions involved in a fuel cell are as follows:

- Anode side (an oxidation reaction): $2H \Rightarrow 4H^+ + 4e^-$
- Cathode side (a reduction reaction): $O_2 + 4H^+ + 4e^- \Rightarrow 2H_2O$
- Net reaction (the "redox" reaction): $2H_2 + 2O_2 \Rightarrow 2H_2O$

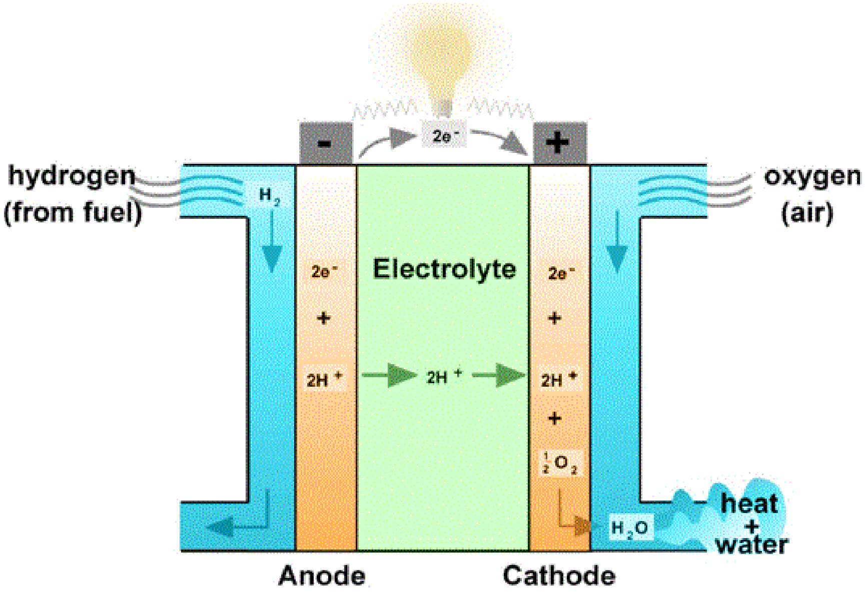


Figure 1.1 Schematic representation of an individual fuel cell

4. Types of fuel cells

Fuel cells are classified primarily by the kind of electrolyte they employ. This classification determines the kind of electro-chemical reactions that take place in the cell, the kind of catalysts required, the temperature range in which the cell operates, the fuel required, and other factors. Table 1 describes a brief summary of some types and, their characteristic features, operating temperatures and areas of application. Table 2 presents additional properties of the same fuel cells. Below more detailed descriptions are presented.

Table .1 Principal operation characteristics of some fuel cell types.

Fuel cell type	Mobile ion	Operating temperature ˚C	Application
Proton Exchange Membrane, PEMFC, PEFC	H^+	30-100	Vehicles, mobile equipment, low power CHP systems
Direct Methanol, DMFC	H^+	20-90	Portable electronic systems with low power, long operating times
Phosforic Acid (PAFC)	H^+	~200	Large numbers of 200 kW CHP systems
Alkaline, AFC	OH^-	50-200	Space vehicles
Molten Carbonate, MCFC	CO_3^{-2}	~650	Medium to large scale CHP systems
Solid Oxide, SOFC	O^{-2}	500-1000	All sizes of CHP systems

Polymer Electrolyte Membrane Fuel Cells

Polymer electrolyte membrane (PEM) fuel cells—also called proton exchange membrane fuel cells—deliver high power density and offer the advantages of low weight and volume compared with other fuel cells. PEM fuel cells use a solid polymer as an electrolyte and porous carbon electrodes containing a platinum or platinum alloy catalyst. They need only hydrogen, oxygen from the air, and water to operate. They are typically fueled with pure hydrogen supplied from storage tanks or reformers.

PEM fuel cells operate at relatively low temperatures, around 80°C (176°F). Low-temperature operation allows them to start quickly (less warm-up time) and results in less wear on system components, resulting in better durability. However, it requires that a noble-metal catalyst (typically platinum) be used to separate the hydrogen's electrons and protons, adding to system cost. The platinum catalyst is also extremely sensitive to carbon monoxide poisoning, making it necessary to employ an additional reactor to reduce carbon monoxide in the fuel gas if the hydrogen is derived from a hydrocarbon fuel. This reactor also adds cost.

PEM fuel cells are used primarily for transportation applications and some stationary applications. PEM fuel cells are particularly suitable for use in vehicle applications, such as cars, buses, and heavy-duty trucks.

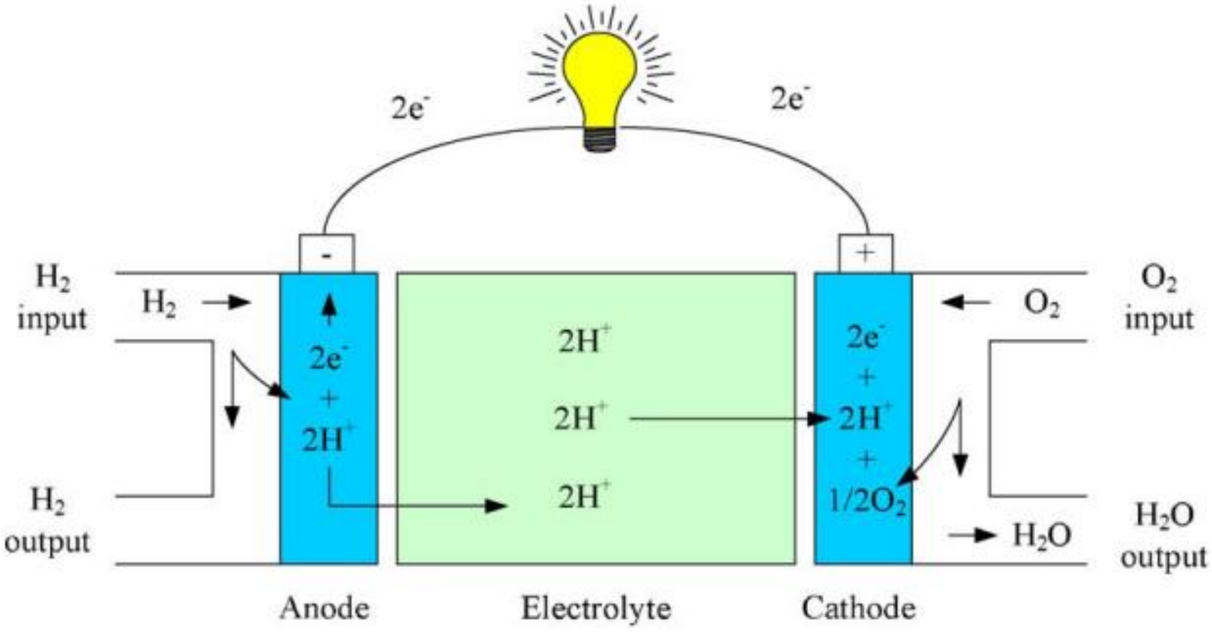


Figure. 1.2 Proton exchange membrane fuel cell principles of operation

Direct Methanol Fuel Cells

Most fuel cells are powered by hydrogen, which can be fed to the fuel cell system directly or can be generated within the fuel cell system by reforming hydrogen-rich fuels such as methanol, ethanol, and hydrocarbon fuels. Direct methanol fuel cells (DMFCs), however, are powered by pure methanol, which is usually mixed with water and fed directly to the fuel cell anode.

Direct methanol fuel cells do not have many of the fuel storage problems typical of some fuel cell systems because methanol has a higher energy density than hydrogen—though less than gasoline or diesel fuel. Methanol is also easier to transport and supply to the public using our current infrastructure because it is a liquid, like gasoline. DMFCs are often used to provide power for portable fuel cell applications such as cell phones or laptop computers.

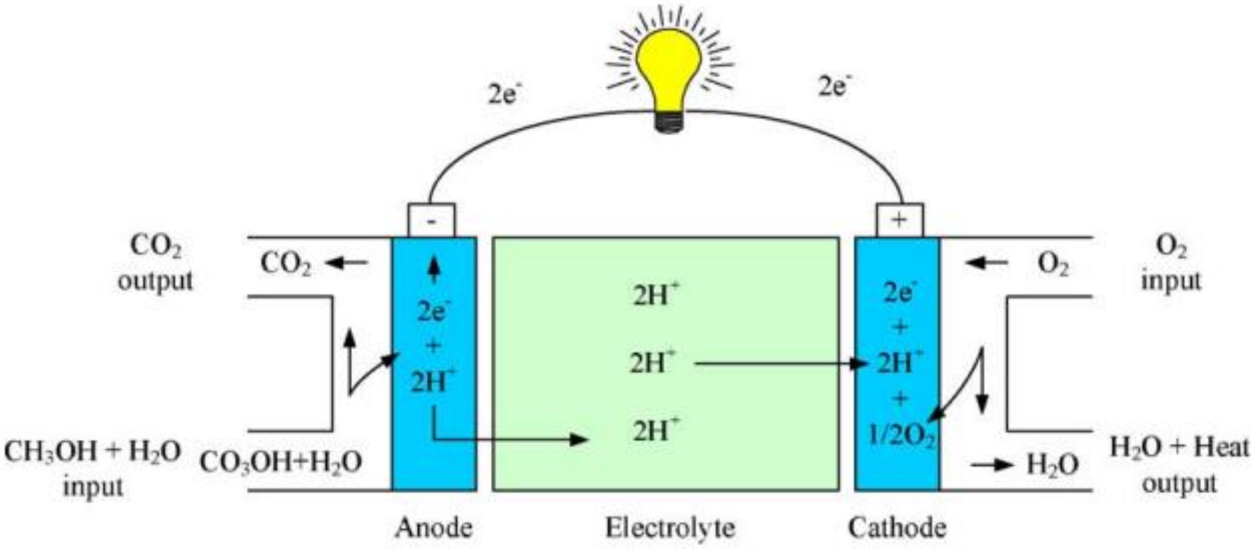


Figure. 1.3. Direct methanol fuel cell principles of operation.

Alkaline Fuel Cells

Alkaline fuel cells (AFCs) were one of the first fuel cell technologies developed, and they were the first type widely used in the U.S. space program to produce electrical energy and water on-board spacecraft. These fuel cells use a solution of potassium hydroxide in water as the electrolyte and can use a variety of non-precious metals as a catalyst at the anode and cathode. In recent years, novel AFCs that use a polymer membrane as the electrolyte have been developed. These fuel cells are closely related to conventional PEM fuel cells, except that they use an alkaline membrane instead of an acid membrane. The high performance of AFCs is due to the rate at which electro-chemical reactions take place in the cell. They have also demonstrated efficiencies above 60% in space applications.

A key challenge for this fuel cell type is that it is susceptible to poisoning by carbon dioxide (CO2). In fact, even the small amount of CO2 in the air can dramatically affect cell performance and durability due to carbonate formation. Alkaline cells with liquid electrolytes can be run in a recirculating mode, which allows for electrolyte regeneration to help reduce the effects of carbonate formation in the electrolyte, but the recirculating mode introduces issues with shunt currents. The liquid electrolyte systems also suffer from additional concerns including wettability, increased corrosion, and difficulties handling differential pressures. Alkaline membrane fuel cells (AMFCs) address these concerns and have lower susceptibility to CO2 poisoning than liquid-electrolyte AFCs do. However, CO2 still affects performance, and performance and durability of the AMFCs still lag that of PEMFCs. AMFCs are being considered for applications in the W to kW scale. Challenges for AMFCs include tolerance to carbon dioxide, membrane conductivity and durability, higher temperature operation, water management, power density, and anode electrocatalysis.

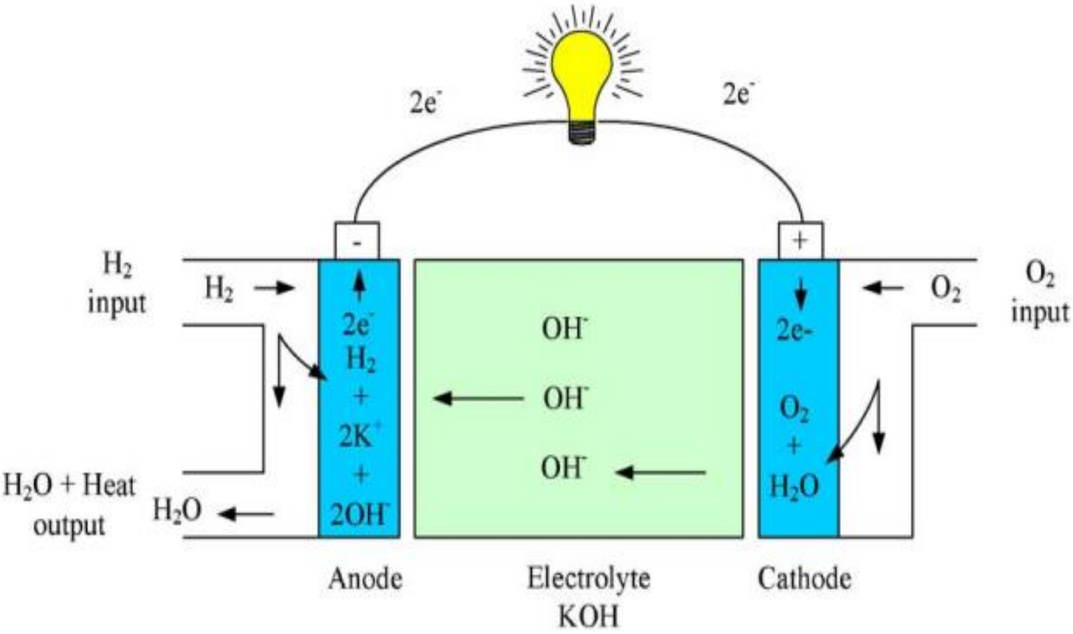


Figure. 1.4. Alkaline fuel cell principles of operation

Phosphoric Acid Fuel Cells

Phosphoric acid fuel cells (PAFCs) use liquid phosphoric acid as an electrolyte—the acid is contained in a Teflon-bonded silicon carbide matrix—and porous carbon electrodes containing a platinum catalyst. The electro-chemical reactions that take place in the cell are shown in the diagram to the right.

The PAFC is considered the "first generation" of modern fuel cells. It is one of the most mature cell types and the first to be used commercially. This type of fuel cell is typically used for stationary power generation, but some PAFCs have been used to power large vehicles such as city buses.

PAFCs are more tolerant of impurities in fossil fuels that have been reformed into hydrogen than PEM cells, which are easily "poisoned" by carbon monoxide because carbon monoxide binds to the platinum catalyst at the anode, decreasing the fuel cell's efficiency. PAFCs are more than 85% efficient when used for the co-generation of electricity and heat but they are less efficient at generating electricity alone (37%–42%). PAFC efficiency is only slightly more than that of combustion-based power plants, which typically operate at around 33% efficiency. PAFCs are also less powerful than other fuel cells, given the same weight and volume. As a result, these fuel cells are typically large and heavy. PAFCs are also expensive. They require much higher loadings of expensive platinum catalyst than other types of fuel cells do, which raises the cost.

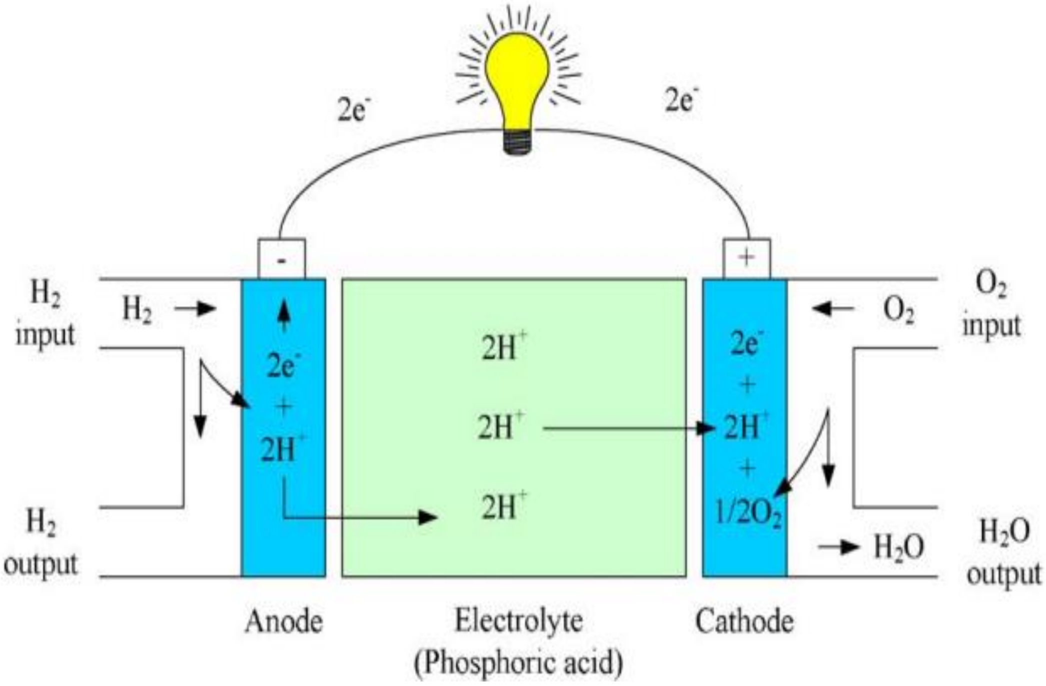


Figure. 1.5. Phosphoric acid fuel cell principles of operation

Molten Carbonate Fuel Cells

Molten carbonate fuel cells (MCFCs) are currently being developed for natural gas and coal-based power plants for electrical utility, industrial, and military applications. MCFCs are high-temperature fuel cells that use an electrolyte composed of a molten carbonate salt mixture suspended in a porous, chemically inert ceramic lithium aluminum oxide matrix. Because they operate at high temperatures of 650°C (roughly 1,200°F), non-precious metals can be used as catalysts at the anode and cathode, reducing costs.

Improved efficiency is another reason MCFCs offer significant cost reductions over phosphoric acid fuel cells. Molten carbonate fuel cells, when coupled with a turbine, can reach efficiencies approaching 65%, considerably higher than the 37%–42% efficiencies of a phosphoric acid fuel cell plant. When the waste heat is captured and used, overall fuel efficiencies can be over 85%.

Unlike alkaline, phosphoric acid, and PEM fuel cells, MCFCs do not require an external reformer to convert fuels such as natural gas and biogas to hydrogen. At the high temperatures at which MCFCs operate, methane and other light hydrocarbons in these fuels are converted to hydrogen within the fuel cell itself by a process called internal reforming, which also reduces cost.

The primary disadvantage of current MCFC technology is durability. The high temperatures at which these cells operate and the corrosive electrolyte used accelerate component breakdown and corrosion, decreasing cell life. Scientists are currently exploring corrosion-resistant materials for components as well as fuel cell designs that double cell life from the current 40,000 hours (~5 years) without decreasing performance.

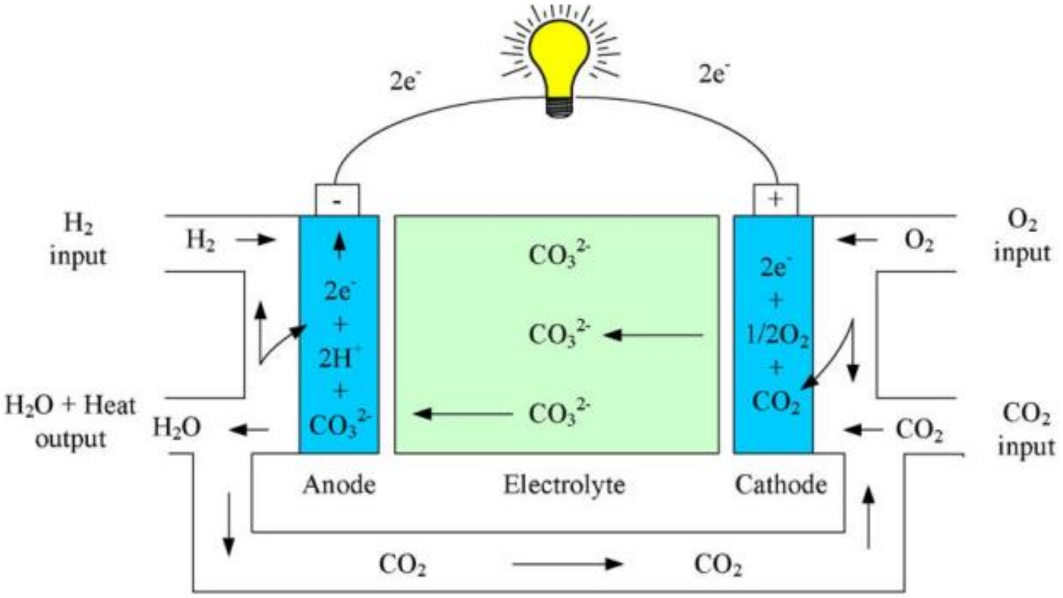


Figure. 1.6. Molten carbonate fuel cell principles of operation

Solid Oxide Fuel Cells

Solid oxide fuel cells (SOFCs) use a hard, non-porous ceramic compound as the electrolyte. SOFCs are around 60% efficient at converting fuel to electricity. In applications designed to capture and utilize the system's waste heat (co-generation), overall fuel use efficiencies could top 85%.

SOFCs operate at very high temperatures—as high as 1,000°C (1,830°F). High-temperature operation removes the need for precious-metal catalyst, thereby reducing cost. It also allows SOFCs to reform fuels internally, which enables the use of a variety of fuels and reduces the cost associated with adding a reformer to the system.

SOFCs are also the most sulfur-resistant fuel cell type; they can tolerate several orders of magnitude more sulfur than other cell types can. In addition, they are not poisoned by carbon monoxide, which can even be used as fuel. This property allows SOFCs to use natural gas, biogas, and gases made from coal. High-temperature operation has disadvantages. It results in a slow startup and requires significant thermal shielding to retain heat and protect personnel, which may be acceptable for utility applications but not for transportation. The high operating temperatures also place stringent durability requirements on materials. The development of low-cost materials with high durability at cell operating temperatures is the key technical challenge facing this technology.

Scientists are currently exploring the potential for developing lower-temperature SOFCs operating at or below 700°C that have fewer durability problems and cost less. Lower-temperature SOFCs have not yet matched the performance of the higher temperature systems, however, and stack materials that will function in this lower temperature range are still under development.

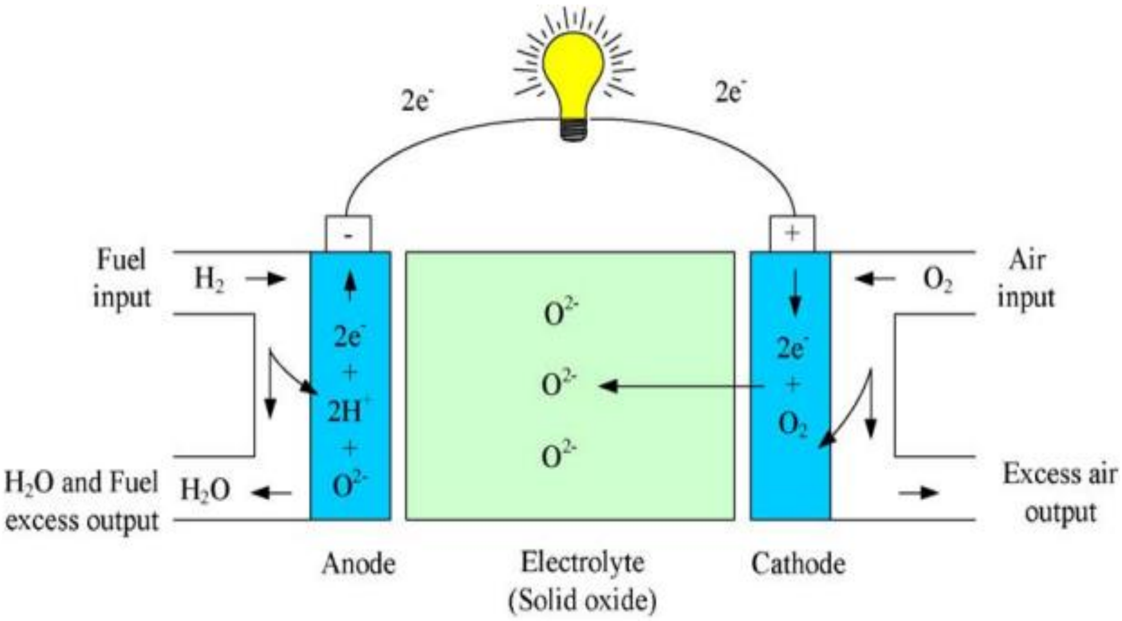


Figure. 1.7. Solid oxide fuel cell principles of operation.

5. Advantages of Fuel Cells

Hydrogen fuel cells have several benefits over the other sources of energy, such as the following:

Renewable and Easily Accessible

Hydrogen is by far the most abundant element on earth. Regardless of the difficulties in extracting it from water, it is a particularly sustainable and limitless form of energy, making it perfect for our prospective zero-carbon integrated heat and power needs.

Well Competent Compared to Other Energy Sources

Hydrogen fuel cells are more efficient in producing electricity than other conventional power sources, including many green power options. This fuel efficiency allows for a greater productive capacity per kilogram of fuel. A typical ignition power station, for example, generates energy at 33-35 percent efficiency, but a hydrogen fuel cell potentially creates electricity at approximately 65 percent efficiency.

Hydrogen is a Dependable and Adaptable Power Source that can Help with Zero-Carbon Energy Initiatives

Since the only by-products are water and heat, hydrogen fuel cells provide a pure energy form with no negative environmental impact throughout production. Hydrogen does not require considerable areas to create electricity, compared to hydropower and biofuel. NASA is already experimenting with hydrogen as a resource with liquid produced as a by-product of astronauts consuming water.

This demonstrates that hydrogen fuel cells are not a harmful source of energy. They should be favored over fossil fuels and nuclear energy, potentially dangerous and difficult to get. Generation, collection, and hydrogen usage; each will play a pivotal part in advancing sustainable power by aligning different supply methods with complex end-user demands, eliminating the need for significant initial payment in energy infrastructure

More durable and Energy Efficient in Comparison to Fossil Fuels

The hydrogen fuel cell technique delivers a robust, high-efficiency source of power. By weight, hydrogen has the highest primary energy output of any conventional fuel. The gravimetric power density of the high-pressure fluid and vapor hydrogen is nearly triple that of Liquefied natural gas and diesel. The volumetric power density is equivalent to natural gas.

Minimizes Carbon Residues

Hydrogen fuel cells emit almost no greenhouse gases, implying a negligible carbon footprint when in operation.

Minimal Sound Pollution

Hydrogen fuel cells do not generate excessive noise like some other alternative power sources, including wind energy. It also suggests that, rather like electric vehicles, hydrogen-powered automobiles make fewer sounds than those using conventional inside combustion engines.

Minimal Visual Pollution

Several reduced forms of energy, such as biofuel power generation and wind turbines, can produce some unappealing visual landscapes; but hydrogen fuel cells do not require the same area level, resulting in much fewer eyesores.

Emissions are Almost Non-existent

Unlike natural gases and coals, fuel cells do not emit carbon dioxide and other greenhouse gases to contribute to global warming, reducing pollution and improving air quality.

Charging takes Little Time

The charging rate for a hydrogen fuel cell’s battery pack is rapid, equivalent to that of classic internal combustion engines (ICE), and far quicker than those of rechargeable batterie used electric cars. Charge times for electric vehicles range from 30 minutes to a few hours, whereas hydrogen fuel cells may well be refilled in under 5 minutes. Because of the quick charging duration, hydrogen-powered automobiles appear to provide the same mobility as conventional cars.

Suitable for Use in Remote Locations

Due to local constraints, hydrogen generation and storage can substitute diesel-based electricity and heaters in remote regions. Providing non-polluting energy derived from a locally accessible resource would reduce the need to import fuels and raise the standard of living for individuals residing in remote locations.

Extensive Utilization Times

Higher efficiency in terms of utilization periods is possible with hydrogen fuel cells. A hydrogen car has the same mobility as an automobile that runs on fossil energy (about 500 Km). This is preferable to what electric vehicles are now proposing, usually enhanced with fuel cell energy cells as signal boosters. Unlike electric vehicles, hydrogen fuel cells are unaffected by the surrounding temperature and do not deteriorate in cooler temperatures. When combined with the rapid charging durations, this advantage is enhanced.

Ability to Adapt

Hydrogen fuel cells would be equipped to provide power for various stationery and consumer devices whenever technology advances. Hydrogen-powered cars are only one instance; they may also be used in smaller-scale systems like home and commercial heaters. The responsibilities of energy storage systems (i.e., the fuel tank) and engine capacity are separated, much like in ICE power stations. On the other hand, rechargeable batterie used energy (i.e., energy scales quadratically with mass) provides considerable design flexibility.

Decentralization of Power Supply

Hydrogen fuel cells can enable the democratization of electricity and energy supply globally by reducing a country’s reliance on non-renewable resources. Different nations that depend solely on fossil energy supplies are becoming increasingly interested in this increasing independence. Then again, when reserves decline, it should eliminate the issue of increasing fossil fuel costs.

6. Disadvantages of Fuel Cells

Despite the above-mentioned enticing benefits of fuel cells, we will now discuss a few of their drawbacks:

Hydrogen Removal

Hydrogen, while perhaps the most abundant element on earth, somehow doesn’t exist; it must be collected from the liquid by electrolysis or isolated from carbon-based natural gas. Each of these processes necessarily involves a considerable amount of power. This power may well be greater than that acquired from hydrogen alone while being extra expensive. Moreover, this removal usually necessitates fossil energy usage, undermining hydrogen’s environmental efficiency in the apparent lack of Carbon capture and storage.

Hydrogen Collection

Transporting and storing hydrogen is much more complex than transporting and storing natural gas and coal. As a result, there are additional expenses involved when using hydrogen fuel cells as a power source.

Hydrogen is Extremely Flammable

Hydrogen is a highly flammable fuel, which has apparent safety problems. At concentrations ranging from 4 to 75 percent, hydrogen gas ignites in the atmosphere.

Significant Developmental Investment

Hydrogen fuel cells need funding to get to the stage where they can be considered a sustainable form of energy. This will require a governmental incentive to pay cash and effort to improve and expand the innovation too. The biggest roadblock to generating long-term and universal hydrogen energy is figuring out how to establish a cost-effective price and quantity system.

Price of Raw Resources

Iridium and platinum are commonly used as catalysts in fuel cells and some forms of electrolysis of water, implying that the upfront cost of energy cells (and water electrolysis) might be high. Some people have been hesitant to spend on hydrogen fuel cell development because of the significant expense. For making hydrogen fuel cells a viable source of energy for everyone, these prices must be lowered.

Cumulative Cost

Hydrogen fuel cells currently cost more per unit of energy than other sources of power, including solar energy. This could change as technology develops, but at present, the expense of hydrogen remains an obstacle to its widespread usage, even though it is more efficient after being generated. This expenditure impacts future prices, like the pricing of hydrogen-powered cars, making widespread acceptance difficult at the time.

Administrative Difficulties

There are further constraints imposed by regulatory issues involved in the functioning that reflects industrial application scenarios. Commercial ventures may strive to maintain an economic investment strategy if there are no specific legal structures to allow them to achieve their cost and benefit objectives.

Foundation

As fossil fuels have been used for years, the framework for this energy source is already present. The widespread acceptance of hydrogen fuel cell innovation for vehicle industries will require a new resupply infrastructure. But, for long-distance operations like delivery vehicles and HGVs, start-to-end fueling could be used.

7. Fuel Cell Electric Vehicles

Fuel cell vehicles (FCV) use fuel cells to power the vehicle's electric motor. Many FCVs use a fuel cell combined with a battery and supercapacitor to efficiently start-up, power, and utilize the best energy source for constant and peak power. In FCVs, the fuel cell uses oxygen from the air and compressed hydrogen. These vehicles only emit water and heat as byproducts. The major reason for developing automotive fuel cell technology is their efficiency, low or zero emissions, and fuel production from local sources rather than imported sources.

Automotive fuel cells can have one or all of the following characteristics:

- A fuel cell is sized to provide all of the power to a vehicle. A battery may be present for startup.
- A fuel cell typically supplies a constant amount of power, so for vehicle acceleration and other power spikes, additional devices are typically switched on such as batteries, ultra or supercapacitors, and so on.
- A fuel cell can be used as the secondary power source. A system can be set up where batteries power the vehicle, and the fuel cell recharges the batteries when needed.
- A fuel cell can run part or all of the vehicle's electrical system. Sometimes another engine is used for propulsion.

The main components of a fuel cell system are shown in Figure 1.7. The operating temperature of the fuel cell stack for an automobile range from 60 to 80 ºC. Operating temperatures above 100 ºC would improve the heat transfer and simplify stack cooling, but most automotive fuel cells use PEMFCs or DMFCs, which have a polymer membrane, which limits the operation to temperatures below 100 ºC.

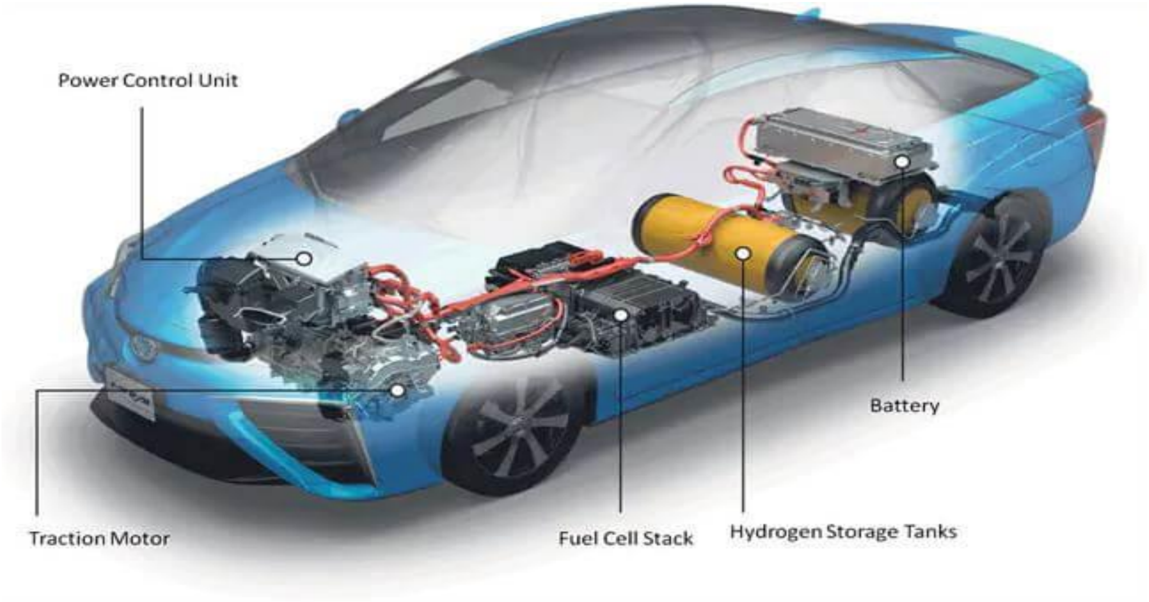


Figure. 1.7. fuel cell vehicle.

8. What is a fuel cell electric vehicle?

FCEVs use a propulsion system similar to that of electric vehicles, where energy stored as hydrogen is converted to electricity by the fuel cell. Unlike conventional internal combustion engine vehicles, these vehicles produce no harmful tailpipe emissions. Other benefits include increasing U.S. energy resiliency through diversity and strengthening the economy.

FCEVs are fueled with pure hydrogen gas stored in a tank on the vehicle. Similar to conventional internal combustion engine vehicles, they can fuel in about 5 minutes and have a driving range of more than 300 miles. FCEVs are equipped with other advanced technologies to increase efficiency, such as regenerative braking systems that capture the energy lost during braking and store it in a battery. Major automobile manufacturers are offering a limited but growing number of production FCEVs to the public in certain markets, in sync with what the developing infrastructure can support.

9. Hydrogen production

To produce hydrogen, it must be separated from the other elements in the molecules where it occurs. Hydrogen can be produced from many different sources in different ways to use as a fuel. The two most most common methods for producing hydrogen are steam-methane reforming and electrolysis (splitting water with electricity). Researchers are exploring other hydrogen production methods

Steam-methane reforming (SMR)

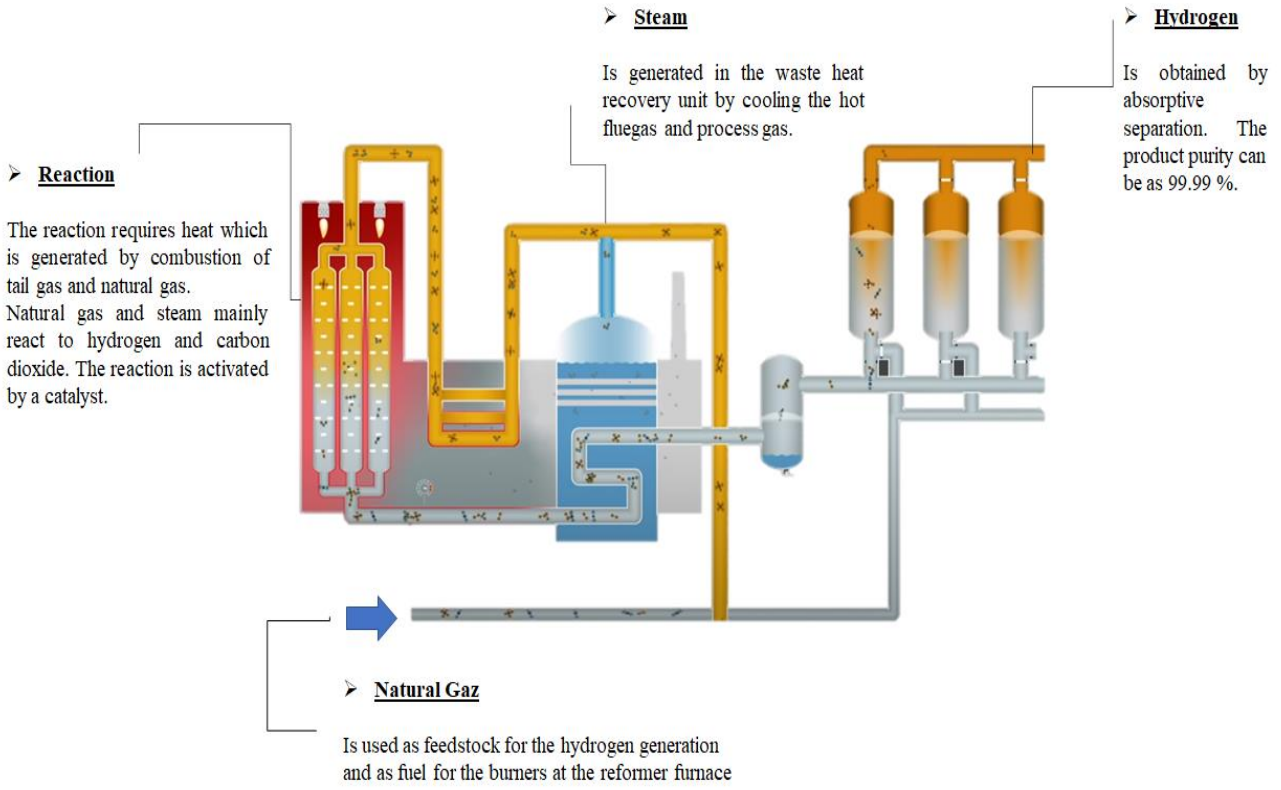
SMR Is a widely used method of commercial hydrogen production. Commercial hydrogen producers and petroleum refineries use steam-methane reforming to separate hydrogen atoms from carbon atoms in methane (CH_4). In steam-methane reforming, high-temperature steam (1,300°F to 1,800°F) under 3 bar–25 bar pressure (1 bar = 14.5 pounds per square inch) reacts with methane in the presence of a catalyst to produce hydrogen, carbon monoxide, and a relatively small amount of carbon dioxide (CO_2).

Steam-methane reforming reaction

$$CH_4 + H_2O\ (+\ heat) \rightarrow CO + 3H_2$$

Water-gas shift reaction

$$CO + H_2O \rightarrow CO_2 + H_2\ (+\ small\ amount\ of\ heat)$$



- **Steam**

Is generated in the waste heat recovery unit by cooling the hot fluegas and process gas.

- **Hydrogen**

Is obtained by absorptive separation. The product purity can be as 99.99 %.

- **Reaction**

The reaction requires heat which is generated by combustion of tail gas and natural gas. Natural gas and steam mainly react to hydrogen and carbon dioxide. The reaction is activated by a catalyst.

- **Natural Gaz**

Is used as feedstock for the hydrogen generation and as fuel for the burners at the reformer furnace

Figure. 1.8. Hydrogen generation by steam reforming.

Advantages

Steam reforming of natural gas offers an efficient, economical, and widely used process for hydrogen production, and provides near- and mid-term energy security and environmental benefits. The efficiency of the steam reforming process is about 65% to 75%, among the highest of current commercially available production methods. Natural gas is a convenient, easy to handle, hydrogen feedstock with a high hydrogen-to-carbon ratio. It is also widely available from sources in the U.S. and Canada. The cost of hydrogen produced by SMR is acutely dependent on natural gas prices and is currently the least expensive among all bulk hydrogen production technologies.

Challenges

During the production of hydrogen, CO2 is also produced. The SMR process in centralized plants emits more than twice the CO2 than hydrogen produced. To avoid emission of CO2 into the atmosphere, CO2 can be concentrated, captured, and sequestered; sequestration concepts and technologies are relatively new and there is no long-term test evidence to prove that these technologies will be successful. Sequestration in oceans is controversial because of the possible adverse impact on the aquatic environment by the reduction of ocean water PH. SMR is a mature technology, which makes it especially important to beginning the transition to a hydrogen energy economy. Yet, the problem with SMR is that it is operating at or near its theoretical limits; the hydrogen produced is still expensive.

Electrolysis uses electricity to produce hydrogen

Electrolysis is a promising option for carbon-free hydrogen production from renewable and nuclear resources. Electrolysis is the process of using electricity to split water into hydrogen and oxygen. This reaction takes place in a unit called an electrolyzer. Electrolyzers can range in size from small, appliance-size equipment that is well-suited for small-scale distributed hydrogen production to large-scale, central production facilities that could be tied directly to renewable or other non-greenhouse-gas-emitting forms of electricity production.

How Does it Work?

Like fuel cells, electrolyzers consist of an anode and a cathode separated by an electrolyte. Different electrolyzers function in different ways, mainly due to the different type of electrolyte material involved and the ionic species it conducts

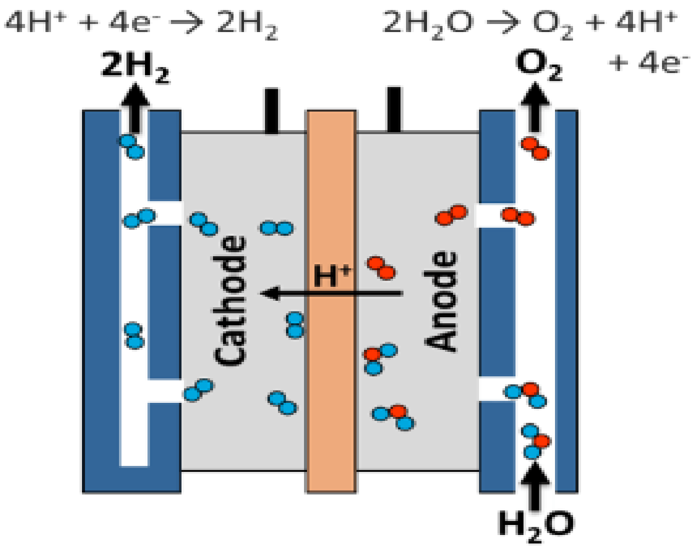


Figure. 1.9. Hydrogen generation by electrolyzers.

Advantages

- Clean and Green Technology
- High Purity Hydrogen
- Scalability
- Grid Balancing and Energy Storage.
- Decentralized Production.
- Versatility.
- Compatibility with Existing Infrastructure.
- Reduced Dependency on Fossil Fuels.
- Electrolysis Technologies.

Challenges

- Energy Intensive
- Cost
- Intermittent Nature of Renewable Energy
- Infrastructure and Scale-up Challenges
- Competing Technologies
- Durability and Maintenance
- Hydrogen Storage and Transportation

Other methods of hydrogen production

- Research is underway to develop other ways to produce hydrogen, including:
- Thermochemical processes to convert biomass into gas or liquids and to separate the hydrogen
- Photolytic processes that use solar energy to split water into hydrogen and oxygen
- Biological processes that use microbes, such as bacteria and microalgae, to produce hydrogen through biological reactions

10. Fuel Cell Formulation

In an H2/O2 electrochemical device hydrogen is oxidized by oxygen to water in an exothermic reaction:

$$H_2 + (1/2)O_2 \Rightarrow 2H_2O(g) \qquad \Delta_r H < 0 \tag{1}$$

The reaction enthalpy $\Delta_r H$ is equal to the enthalpy of water formation $\Delta_f H$. The (chemical) energy content of any fuel is called heating value. The heating value of hydrogen is equal to the absolute value of the reaction enthalpy. Because water is produced either as gaseous or liquid phase, we distinguish between the lower heating value (LHV) and the higher heating value (HHV) of hydrogen:

$$H_2 + \left(\frac{1}{2}\right) O_2 \Rightarrow 2H_2O(g) \qquad -\Delta_f H_{H_2O(g)} = \text{LHV} = 241.82\,.\frac{\text{KJ}}{\text{mol}}$$

$$H_2 + (1/2)O_2 \Rightarrow 2H_2O(l) \qquad -\Delta_f H_{H_2O(l)} = \text{HHV} = 285.83\frac{\text{KJ}}{\text{mol}} \tag{2}$$

Please note that LHV and HHV have positive signs whereas ΔH is negative. All thermodynamic potentials are dependent on temperature and pressure, but are defined at thermodynamic standard conditions (25°C and 100 kPa)

The electric power generated by a fuel cell is given by:

$$W_{el} = qE^0 \tag{3}$$

Where E [V] is the electromotive force (EMF) and q[col/mol] is the electric charge

The charge transferred by mole of H_2 can be calculated using the following formula:

$$q = nN_{avg}q_{el} \tag{4}$$

Hence, we get the following new electric work formula:

$$W_{el} = \left(nN_{avg}q_{el}\right)E^0 = nFE^0 \tag{5}$$

Where $F = 96485{,}3321233\ C/mol$ is Faraday's Constant, n is the number of exchanged electrons. For the hydrogen oxidation or water formation n = 2.

The electric work ca be expressed using the Gibs energy as follow:

$$W_{el} = -\Delta G$$

Thus,

$$E^0 = -\Delta G/nF \tag{6}$$

The free enthalpies ΔG of water formation is either:

$$\Delta_f G_{2H_2O(g)} = -228.57\,.\frac{\mathrm{KJ}}{\mathrm{mol}},\ \Delta_f G_{2H_2O(l)} = -237.17\,.\frac{\mathrm{KJ}}{\mathrm{mol}} \tag{7}$$

Therefore, the corresponding EMFs are

$$\begin{gathered} E_g^0 = \frac{\Delta_f G_{2H_2O(g)}}{2F} = 1.184V,\ E_l^0 = \frac{\Delta_f G_{2H_2O(l)}}{2F} = 1.229V \\ E_{LHV}^0 = \frac{LHV}{2F} = 1.253V,\ E_{HHV}^0 = \frac{HHV}{2F} = 1.481V \end{gathered} \tag{8}$$

Nernst equation

The theoretical cell potential or electromotive force (EMF) is not only depending on the temperature, but also depending on the pressure. This dependency is in general described by the Nernst equation. For the H_2O electrochemical reaction the Nernst equation is:

$$E = E^0 + \frac{RT}{2F} \ln \left(\frac{P_{H_2} {P_{O_2}}^{1/2}}{P_{H_2O}} \right) \tag{9}$$

Where P is the partial pressure of H_2, O_2 and H_2O.

Introducing a system pressure P_{sys} and defining $P_{H_2} = \alpha P_{sys}$, $P_{O_2} = \beta P_{sys}$, $P_{H_2O} = \gamma P_{sys}$, the Nernst equation simplifies to:

$$E = E^0 + \frac{RT}{2F} \ln \left(\frac{\alpha P_{sys} \beta P_{sys}{}^{1/2}}{\gamma P_{sys}} \right)$$

$$E = E^0 + \frac{RT}{2F} \ln \left(\frac{\alpha \beta^{\frac{1}{2}}}{\gamma} \right) + \frac{RT}{4F} \ln \left(P_{sys} \right)$$

(10)

If α, β and γ are constant, increasing the system pressure from P_1 to P_2 influences the cell potential as follows:

$$\Delta E = \frac{RT}{4F} \ln \left(\frac{P_2}{P_1} \right)$$

(11)

Reactant consumption and feed

The reactants H_2 and O_2 are consumed inside the fuel cell stack by the electrochemical reaction. Based on the Faraday's laws the molar flows $\dot{n}$ for reactant consumptions are defined as follows:

$$\dot{n}_{H_2} = \frac{I.N}{2F} \qquad \left[\frac{mol}{sec}\right]$$

$$\dot{n}_{O_2} = \frac{I.N}{4F} = \frac{1}{2} \dot{n}_{H_2} \qquad \left[\frac{mol}{sec}\right]$$

(12)

I is the stack load (electric current, $[I] = A$), and N is the number of single cells (cell count, $[N] = -$). 2 is again the number of exchanged electrons per mole H_2 for the hydrogen oxidation; respectively 4 eper mole O_2 for the oxygen reduction. F is the Faraday constant.

The stoichiometry λ defines the ratio between reactant feed (into the fuel cell) and reactant consumption (inside the fuel cell). Due to fuel cell design and water management issues etc., the stoichiometry must always be more than one:

$$\lambda = \frac{\dot{n}_{feed}}{\dot{n}_{consumed}} > 1 \qquad sign(\lambda) = -$$

(13)

The reactant feed for H_2 and air into the fuel cell stack are now defined by an anode and cathode stoichiometry λ:

$$\dot{n}_{H_2,feed} = \dot{n}_{H_2}.\lambda_{anode} = \frac{I.N}{2F}.\lambda_{anode}$$

$$\dot{n}_{air,feed} = \frac{\dot{n}_{H_2}}{x_{O_2}}.\lambda_{cathode} = \frac{I.N}{4F.x_{O_2}}.\lambda_{Cathode}$$

(14)

where x_{O_2} is the oxygen content in air. The molar flows of unconverted (dry) reactants at the stack exhaust are given as:

$$\dot{n}_{H_2,out} = \dot{n}_{H_2,feed} - \dot{n}_{H_2} = \frac{I.N}{2F}.\lambda_{anode}.M_{H_2}$$

$$\dot{n}_{air,out} = \dot{n}_{air,feed} - \dot{n}_{O_2} = \frac{I.N}{4F}(\frac{\lambda_{cathode}}{x_{O_2}} - 1)$$

(15)

It is very common to give the reactant feed either as a mass or volume flow. The mass flow $\dot{m}$ is the product of molar flow $\dot{n}$ and molar weight M:

$$\dot{m} = \dot{n}.M \quad [\frac{g}{sec}] \tag{16}$$

The mass flow for stack anode and cathode inlet are therefore:

$$\dot{m}_{H_2,feed} = \frac{I.N}{2F}\lambda_{anode}.M_{H_2}$$

$$\dot{m}_{air,feed} = \frac{I.N}{4Fx_{O_2}}.\lambda_{cathode}.M_{air_2} \tag{17}$$

The dry mass gas flow at stack cathode outlet contains less oxygen than air and is calculated as:

$$\dot{m}_{cathode,out} = \dot{m}_{air,feed} - \dot{m}_{O_2,consumed} = \frac{IN}{4F}.(\frac{\lambda_{cathode}}{x_{O_2}}.M_{air} - M_{O_2}) \tag{18}$$

The amount of product water is equal to hydrogen consumption and given by:

$$\dot{n}_{H_2O,prod} = \frac{I.N}{2F}.M_{H_2O} \qquad [\frac{mol}{sec}] \tag{19}$$

The product water mass flow is:

$$\dot{m}_{H_2O,prod} = \frac{I.N}{2F}.M_{H_2O} \qquad [\frac{g}{sec}] \tag{20}$$

Hydrogen energy and power

Hydrogen is a chemical energy carrier with a specific (chemical) energy density, which is defined by either HHV or LHV. The mass specific chemical energy is:

$$W_{H_2,HHV} = \frac{HHV}{M} = \frac{285.83\,\frac{KJ}{mol}}{2.02\,\frac{KJ}{g}} = 141.79\,\frac{KJ}{g} = 39.39\,\frac{Kwh}{kg}$$

$$W_{H_2,LHV} = \frac{HHV}{M} = \frac{241.82\,\frac{KJ}{mol}}{2.02\,\frac{KJ}{g}} = 119.96\,\frac{KJ}{g} = 33.32\,\frac{Kwh}{kg} \qquad (21)$$

The chemical power of an H_2 flow is:

$$P_{H_2,HHV} = HHV * \dot{n}_{H_2} \quad [\frac{J}{s} or\ w] \qquad (22)$$

Now the (chemical) power of H_2 consumed in a stack (with N cells at the stack load I) using equations 8 and 12 can easily be expressed as:

$$P_{H_2,HHV\ Consummed} = 1.481\ V.N.I \qquad (23)$$

The (chemical) power of H_2 feed

$$P_{H_{2,HHV}\,feed} = 1.481\,V.N.I.\lambda_{anode} \tag{24}$$

Fuel cell stack power

Electric stack power P_{el} is the product of stack voltage and stack load, also called gross power:

$$P_{el} = U_{Stack} * I = AveCell * N * I \tag{25}$$

where AveCell $= U_{Stack}/N$ is the average single cell voltage.

Thermal stack power P_{therm} is that part of the consumed chemical fuel power which is not converted into electric power:

$$P_{therm} = P_{H_2,HHV} - P_{el} \tag{26}$$

For the hydrogen fuel cell, it is defined based on HHV as:

$$P_{therm,HHV} = (1.481V - AveCell) * N * I = P_{el}(\frac{1.481V}{AveCell} - 1) \tag{27}$$

The voltage equivalent 1.481 V is defined by equation 8. To calculate the thermal power based on LHV this voltage equivalent needs to be replaced by 1.253 V.

Recovered heat The recovered heat is that part of the thermal stack power that is actually converted into usable heat. This is e.g. the heat transferred into the (liquid) coolant and can be calculated as follows:

$$P_{recover\ heat} = \dot{V}.c_p.\Delta T.\rho \tag{28}$$

Coolant parameters are: Volume flow $\dot{V}$, heat capacity cp, temperature increase ΔT and density ρ. Due to technical issues not, all thermal power can be transferred to coolant; therefore:

$$P_{recover\ heat} < P_{therm,HHV} \tag{29}$$

The unusable or waste heat:

$$P_{waste\ heat} = P_{therm,HHV} - P_{recover\ heat} \tag{30}$$

Fuel cell efficiencies

All efficiencies can be based on either LHV or HHV of the fuel. In general, the energy conversion efficiency is defined by:

$$\eta = \frac{Energy\ Output\ (useful)}{Energy\ input} = \frac{Power\ output}{Power\ input} \tag{31}$$

Thermodynamic efficiency: the thermodynamic or maximum or ideal efficiency is the ratio between enthalpy (or heating value) ΔH and Gibbs free enthalpy ΔG (reflecting the maximum extractible work) of any electrochemical device:

$$\eta_{el,max} = \frac{-\Delta G}{LHV}$$

$$\eta_{el,TD,LHV} = \frac{-\Delta G_{H_2O(g)}}{LHV} = \frac{E_g^0}{E_{LHV}^0} = \frac{1.184\ V}{1.253\ V} = 94.5\%$$ (32)

$$\eta_{el,TD,HHV} = \frac{-\Delta G_{H_2O(g)}}{LHV} = \frac{E_g^0}{E_{LHV}^0} = \frac{1.229\ V}{1.481\ V} = 83.1\%$$

Electric efficiency: the electric efficiency of a fuel cell (stack) is defined as:

$$\eta_{el} = \frac{P_{el}}{P_{fuel,consumed}}$$ (33)

P_{el} is the stack electric (gross) power and $P_{fuel,consumed}$ is the consumed fuel power.

The electric efficiency can easily express as

$$\eta_{el,LHV} = \frac{AveCell}{1.253\ V} \text{ or } \eta_{el,HHV} = \frac{AveCell}{1.481\ V}$$ (34)

Fuel electric efficiency the fuel efficiency considers the amount of hydrogen feed to the stack (and not only the amount of consumed hydrogen). It is defined as:

$$\eta_{el} = \frac{P_{el}}{P_{fuel,feed}}$$ (35)

P_{el} is the stack electric gross power and $P_{fuel,feed}$ is the fuel feed power

$$\eta_{fuel,el,LHV} = \frac{AveCell}{1.253\ V.\lambda_{anode}} \text{ or } \eta_{fuel,el,HHV} = \frac{AveCell}{1.481\ V.\lambda_{anode}} \tag{36}$$

Voltage efficiency is the ratio between average and reversible cell voltage E^0.

$$\eta_{voltage} = \frac{AveCell}{E^0} \tag{37}$$

Normally the voltage efficiency is based on $\Delta_f G_{H_2o(l)}$:

$$\eta_{voltage} = \frac{AveCell}{E^0{}_l} = \frac{AveCell}{1.229V} \tag{38}$$

$$\eta_{voltage} = \eta_{el,HHV} \cdot \eta_{el,TD,HHV} = \frac{AveCell}{1.481V} . 83.1\% \tag{38}$$

Risks and challenges of hydrogen productions and storage

the challenges and risks associated with hydrogen production and storage are crucial aspects in the development and adoption of hydrogen as an energy carrier. Let's explore these challenges in more detail:

Hydrogen Production:

1. **Costs and Economic Viability**:

High Initial Costs: The capital costs associated with building and operating hydrogen production facilities, especially those employing advanced technologies like electrolysis, can be significant.

Competitive Pricing: The economic viability of hydrogen as an energy carrier depends on its cost competitiveness with other energy sources. Achieving cost parity or superiority is crucial for widespread adoption.

2. **Energy Source and Efficiency:**

Energy Input: The source of energy for hydrogen production significantly influences its environmental impact. Using renewable energy sources is desirable but may face challenges related to intermittency and grid integration.

Process Efficiency: Improving the efficiency of hydrogen production methods, such as electrolysis and methane reforming, is essential to reduce energy consumption and overall costs.

3. **Environmental Impact:**

Carbon Emissions: If hydrogen is produced from fossil fuels without carbon capture and storage, it may not deliver the intended environmental benefits. The transition to "green hydrogen" produced using renewable energy sources is crucial for carbon reduction.

4. **Water Usage:**

Electrolysis Water Demand: Hydrogen production through electrolysis often requires significant water usage. Balancing water demand with sustainable sourcing and conservation practices is essential.

Hydrogen Storage:

1. **Infrastructure:**

Distribution and Storage: Developing a dedicated infrastructure for hydrogen storage and distribution is a complex and expensive task. Hydrogen's small molecule size poses challenges in terms of leakage and containment.

Transportation: Storing and transporting hydrogen involves addressing challenges related to compression, liquefaction, or other storage methods. Safe and efficient transportation infrastructure is crucial for the widespread adoption of hydrogen.

2. **Hydrogen Embrittlement:**

Material Compatibility: Hydrogen can cause embrittlement in certain materials, potentially compromising the structural integrity of pipelines and storage tanks. Research into materials that resist hydrogen embrittlement is ongoing.

Safety Concerns:

Flammability: Hydrogen is highly flammable, and safety measures must be implemented throughout the production, storage, and transportation processes. Detection systems, safety standards, and emergency response protocols are critical.

1. **Leakage and Permeation**:

Hydrogen Leakage: Hydrogen molecules are small and can permeate through materials. Ensuring the integrity of storage and distribution systems to prevent leaks is crucial for safety and environmental reasons.

2. **Energy Density:**

Low Energy Density: Hydrogen has a low energy density per unit volume, which requires efficient storage solutions. Research into advanced storage materials and technologies, such as solid-state storage, is ongoing to address this challenge.

3. **Scale-up Challenges:**

Large-Scale Storage: As the demand for hydrogen increases, developing large-scale storage solutions becomes more challenging. This includes both stationary storage for industrial use and mobile storage for transportation applications.

4. **Lack of Standards:**

Standardization: The lack of standardized protocols and regulations for hydrogen storage can hinder the development of a cohesive and interoperable infrastructure.

Addressing these challenges requires a multi-faceted approach involving technological innovation, research and development, regulatory frameworks, and collaboration among industry stakeholders. Overcoming these hurdles is crucial for realizing the full potential of hydrogen as a clean and sustainable energy carrier.