Lecture Note

On

FUEL CELLS

By

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For

B.Sc Hons (6th Sem)

FUEL CELLS

A fuel cell is a device that converts chemical potential energy (energy stored in molecular bonds) into electrical energy.

Unlike a generator, a fuel cell directly “converts” an energy source into electricity through a chemical reaction. This involves one step rather than multiple steps. This allows a fuel cell to remain efficient, quiet and clean.

Difference between fuel cell and battery:

The biggest difference between the two is that a battery stores energy, while a fuel cell generates energy by converting available fuel. A fuel cell can have a battery as a system component to store the electricity it’s generating.

Types of Fuel Cells

Fuel cells are classified primarily by the kind of electrolyte they employ.

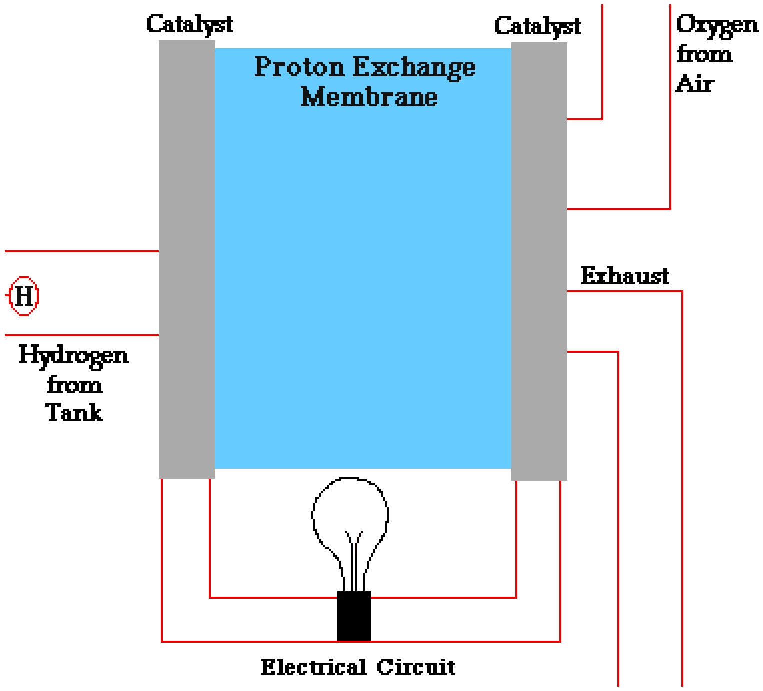
The electrolyte plays a key role. It must permit only the appropriate ions to pass between the anode and cathode. If free electrons or other substances could travel through the electrolyte, they would disrupt the chemical reaction.

Whether they combine at anode or cathode, together hydrogen and oxygen form water, which drains from the cell. As long as a fuel cell is supplied with hydrogen and oxygen, it will generate electricity.

- **Polymer electrolyte membrane fuel cells**. ...
- Direct methanol fuel cells. ...
- **Alkaline fuel cells**. ...
- **Phosphoric acid fuel cells**. ...
- **Molten carbonate fuel cells**. ...
- **Solid oxide fuel cells**. ...
- Reversible fuel cells.

How do fuel cells work?

There are several kinds of fuel cells, and each operates a bit differently. But in general terms, hydrogen atoms enter a fuel cell at the anode where a chemical reaction strips them of their electrons. The hydrogen atoms are now "ionized," and carry a positive electrical charge. The negatively charged electrons provide the current through wires to do work. If alternating current (AC) is needed, the DC output of the fuel cell must be routed through a conversion device called an inverter.



Graphic by Marc Marshall, Schatz Energy Research Center

Oxygen enters the fuel cell at the cathode and, in some cell types (like the one illustrated above), it there combines with electrons returning from the electrical circuit and hydrogen ions that have traveled through the electrolyte from the anode. In other cell types the oxygen picks up electrons and then travels through the electrolyte to the anode, where it combines with hydrogen ions.

The electrolyte plays a key role. It must permit only the appropriate ions to pass between the anode and cathode. If free electrons or other substances could travel through the electrolyte, they would disrupt the chemical reaction.

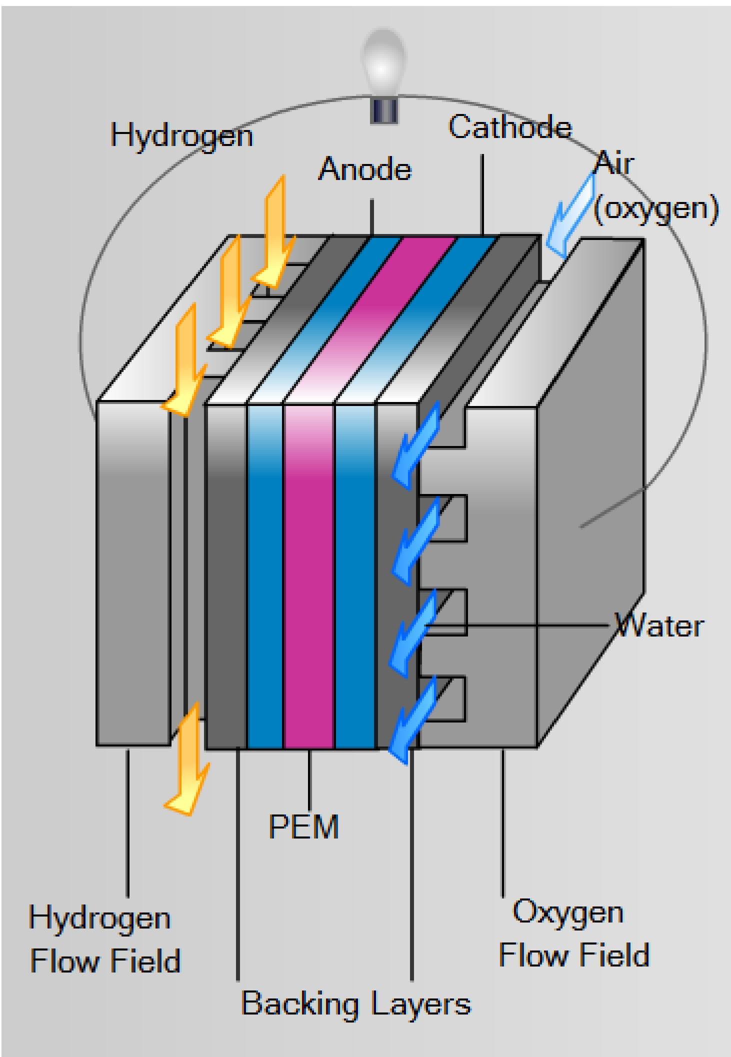
Whether they combine at anode or cathode, together hydrogen and oxygen form water, which drains from the cell. As long as a fuel cell is supplied with hydrogen and oxygen, it will generate electricity.

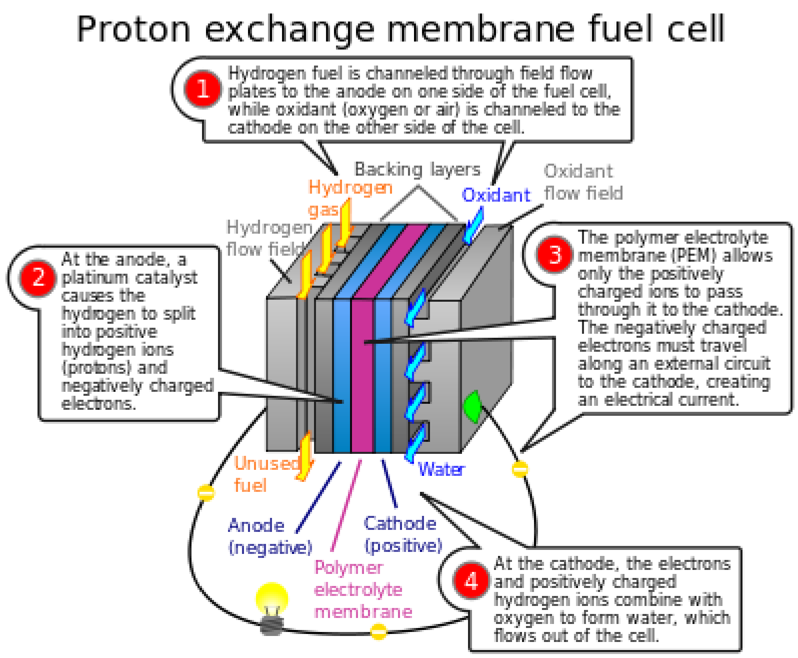
Hydrogen Fuel Cell

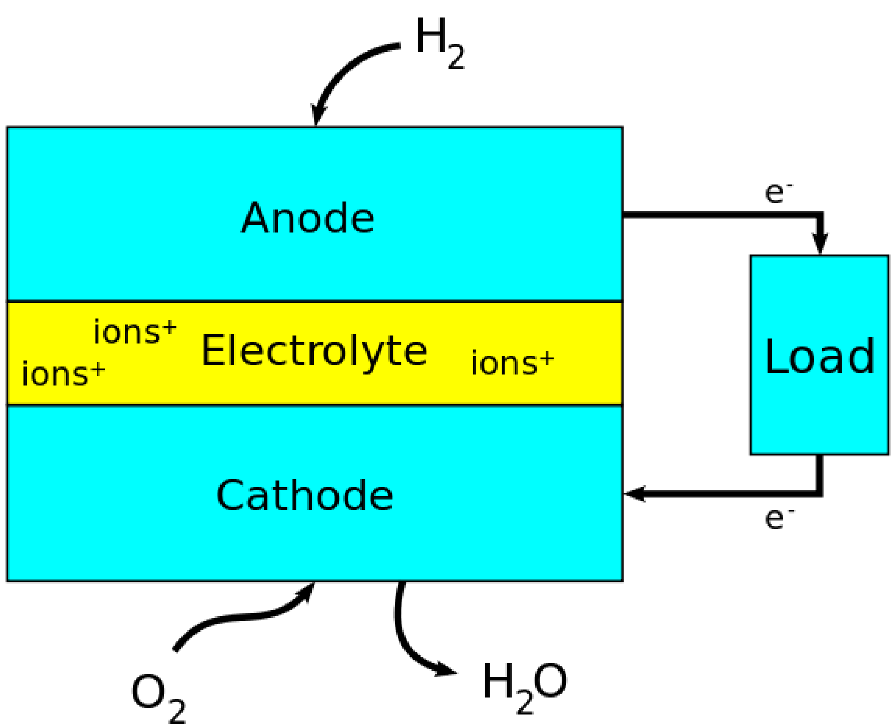
Hydrogen + Oxygen = Electricity + Water Vapor

A PEM (Proton Exchange Membrane) cell uses hydrogen gas (H_2) and oxygen gas (O_2) as fuel. The products of the reaction in the cell are water, electricity, and heat.

There are four basic elements of a PEM Fuel Cell:




Proton exchange membrane fuel cell
1 Hydrogen fuel is channeled through field flow plates to the anode on one side of the fuel cell, while oxidant (oxygen or air) is channeled to the cathode on the other side of the cell.
Backing layers
Hydrogen gas
Oxidant
Oxidant flow field
Hydrogen flow field
2 At the anode, a platinum catalyst causes the hydrogen to split into positive hydrogen ions (protons) and negatively charged electrons.
3 The polymer electrolyte membrane (PEM) allows only the positively charged ions to pass through it to the cathode. The negatively charged electrons must travel along an external circuit to the cathode, creating an electrical current.
Unused fuel
Water
Anode (negative)
Cathode (positive)
Polymer electrolyte membrane
4 At the cathode, the electrons and positively charged hydrogen ions combine with oxygen to form water, which flows out of the cell.


H2
Anode
e-
ions+
Electrolyte
ions+
ions+
Load
Cathode
e-
O2
H2O

How does it work?

Pressurized hydrogen gas (H_2) entering the fuel cell on the anode side. This gas is forced through the catalyst by the pressure. When an H_2 molecule comes in contact with the platinum on the catalyst, it splits into two H+ ions and two electrons (e-). The electrons are conducted through the anode, where they make their way through the external circuit (doing useful work such as turning a motor) and return to the cathode side of the fuel cell.

Meanwhile, on the cathode side of the fuel cell, oxygen gas (O_2) is being forced through the catalyst, where it forms two oxygen atoms. Each of these atoms has a strong negative charge. This negative charge attracts the two H+ ions through the membrane, where they combine with an oxygen atom and two of the electrons from the external circuit to form a water molecule (H_2O).

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Due to the high energetic content of hydrogen and high efficiency of fuel cells (55%), this great technology can be used in many applications like transport (cars, buses, forklifts, etc) and backup power to produce electricity during a failure of the electricity grid.

Detailed functions of different components:

The anode, the negative post of the fuel cell, has several jobs. It conducts the electrons that are freed from the hydrogen molecules so that they can be used in an external circuit. It has channels etched into it that disperse the hydrogen gas equally over the surface of the catalyst.

The cathode, the positive post of the fuel cell, has channels etched into it that distribute the oxygen to the surface of the catalyst. It also conducts the electrons back from the external circuit to the catalyst, where they can recombine with the hydrogen ions and oxygen to form water.

The electrolyte is the proton exchange membrane. This specially treated material, which looks something like ordinary kitchen plastic wrap, only conducts positively charged ions. The membrane blocks electrons. For a PEMFC, the membrane must be hydrated in order to function and remain stable.

The catalyst is a special material that facilitates the reaction of oxygen and hydrogen. It is usually made of platinum nanoparticles very thinly coated onto carbon paper or cloth. The catalyst is rough and porous so that the maximum surface area of the platinum can be exposed to the hydrogen or oxygen. The platinum-coated side of the catalyst faces the PEM.

As the name implies, the heart of the cell is the proton exchange membrane. It allows protons to pass through it virtually unimpeded, while electrons are blocked. So, when the H_2 hits the catalyst and splits into protons and electrons (remember, a proton is the same as an H+ ion) the protons go directly through to the cathode side, while the electrons are forced to travel through an external circuit. Along the way they perform useful work, like lighting a bulb or driving a motor, before combining with the protons and O_2 on the other side to produce water.

Advantages of the technology:

By converting chemical potential energy directly into electrical energy, fuel cells avoid the "thermal bottleneck" (a consequence of the 2nd law of thermodynamics) and are more efficient in extracting energy from a fuel. Waste heat from some cells can also be harnessed, boosting system efficiency still further.

Thus fuel cells are inherently more efficient than combustion engines, which must first convert chemical potential energy into heat, and then mechanical work.

- Direct emissions from a fuel cell vehicle are just water and a little heat. This is a huge improvement over the internal combustion engine’s litany of greenhouse gases.
- Fuel cells have no moving parts. They are thus much more reliable than traditional engines.
- Hydrogen can be produced in an environmentally friendly manner, while oil extraction and refining is very damaging.

So why can't I go out and buy a fuel cell?

Drawbacks of Fuel Cells:

The basic workings of a fuel cellis are simple. But building inexpensive, efficient, reliable fuel cells is a far more complicated business in terms of the choice of electrolyte, the design of electrodes and purity of fuel. Today, the main electrolyte types are alkali, molten carbonate, phosphoric acid, proton exchange membrane (PEM) and solid oxide.

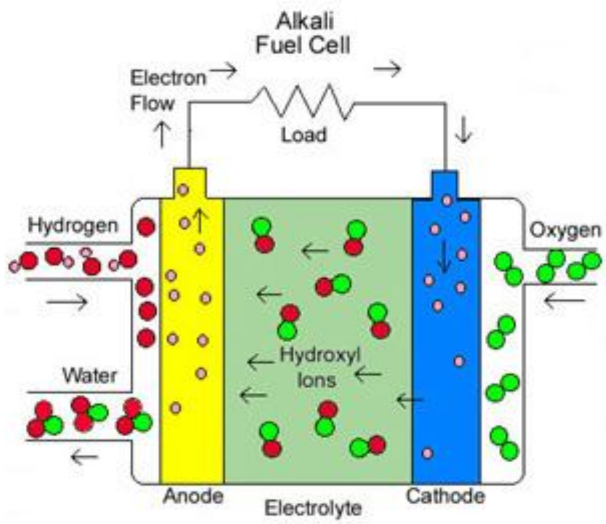
The type of fuel also depends on the electrolyte. Some cells need pure hydrogen, and therefore demand extra equipment such as a "reformer" to purify the fuel. Other cells can tolerate some impurities, but might need higher temperatures to run efficiently.

The type of electrolyte also dictates a cell's operating temperature–"molten" carbonate cells run hot, just as the name implies.

Each type of fuel cell has advantages and drawbacks compared to the others, and none is yet cheap and efficient enough to widely replace traditional ways of generating power, such as coal-fired, hydroelectric, or even nuclear power plants.

Different types of fuel cells.

Alkali fuel cells operate on compressed hydrogen and oxygen. They generally use a solution of potassium hydroxide (chemically, KOH) in water as their electrolyte. Efficiency is about 70 percent, and operating temperature is 150 to 200 degrees C.

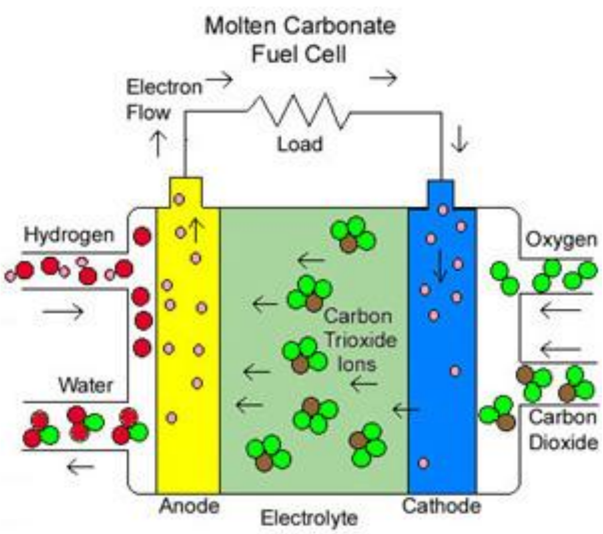


Drawing of an alkali cell.

In these cells, hydroxyl ions (OH-) migrate from the cathode to the anode. At the anode, hydrogen gas reacts with the OH- ions to produce water and release electrons. Electrons generated at the anode supply electrical power to an external circuit then return to the cathode. There the electrons react with oxygen and water to produce more hydroxyl ions that diffuse into the electrolyte.

Applications:

Alkali cells were used in Apollo spacecraft to provide both electricity and drinking water. They require pure hydrogen fuel, however, and their platinum electrode catalysts are expensive. And like any container filled with liquid, they can leak.



Drawing of a molten carbonate cell

Molten Carbonate fuel cells (MCFC) use high-temperature compounds of salt (like sodium or magnesium) carbonates (chemically, CO_3) as the electrolyte. Efficiency ranges from 60 to 80 percent, and operating temperature is about 650 degrees C.

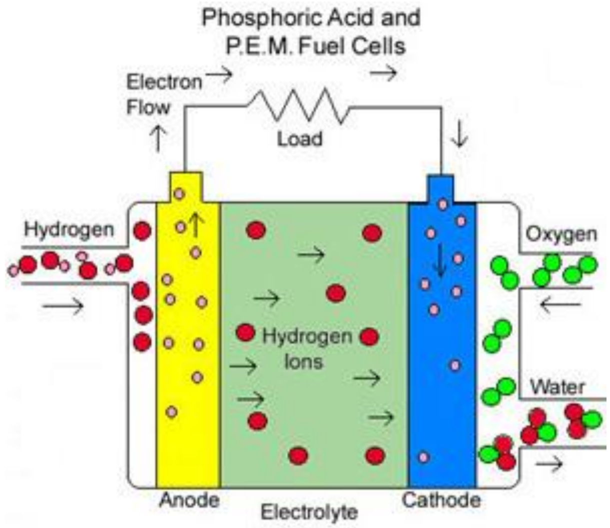
The salts melt and conduct carbonate ions (CO3) from the cathode to the anode. At the anode, hydrogen reacts with the ions to produce water, carbon dioxide, and electrons. The electrons travel through an external circuit, providing electrical power along the way, and return to the cathode. There, oxygen from air and carbon dioxide recycled from the anode react with the electrons to form CO3 ions that replenish the electrolyte and transfer current through the fuel cell.

Applications

Molten carbonate fuel cells demand such high operating temperatures that most applications for this kind of cell are limited to large, stationary power plants. Yet consumers might benefit from this type of cell, even if they never see it in their homes. The high operating temperature opens the opportunity of using waste heat to make steam for space heating, industrial processing, or in a steam turbine to generate more electricity. Many modern gas-fired power plants exploit this type of system, called cogeneration.

The high temperature limits damage from carbon monoxide "poisoning" of the cell and waste heat can be recycled to make additional electricity. Their nickel electrode-catalysts are inexpensive compared to the platinum used in other cells. But the high temperature also limits the materials and safe uses of MCFCs–they would probably be too hot for home use. Also, carbonate ions from the electrolyte are used up in the reactions, making it necessary to inject carbon dioxide to compensate.

Phosphoric Acid fuel cells (PAFC) use phosphoric acid as the electrolyte. Efficiency ranges from 40 to 80 percent, and operating temperature is between 150 to 200 degrees C. PAFCs tolerate a carbon monoxide concentration of about 1.5 percent, which broadens the choice of fuels they can use. Hydrogen for the fuel cell is extracted from a hydrocarbon fuel in an external reformer. If the hydrocarbon fuel is gasoline, sulfur must be removed or it will damage the electrode catalyst. Platinum electrode-catalysts are needed, and internal parts must be able to withstand the corrosive acid.



Drawing of how both phosphoric acid and PEM fuel cells operate.

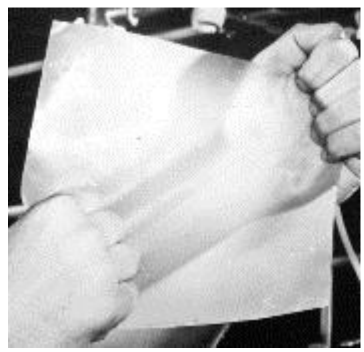
Application:

It has found use in electric vehicles.

Proton Exchange Membrane (PEM)

Proton exchange membrane (PEM) fuel cells work with a polymer electrolyte in the form of a thin, permeable sheet. This membrane is small and light, and it works at low temperatures (about 80 degrees C, or about 175 degrees F). Other electrolytes require temperatures as high as 1,000 degrees C.

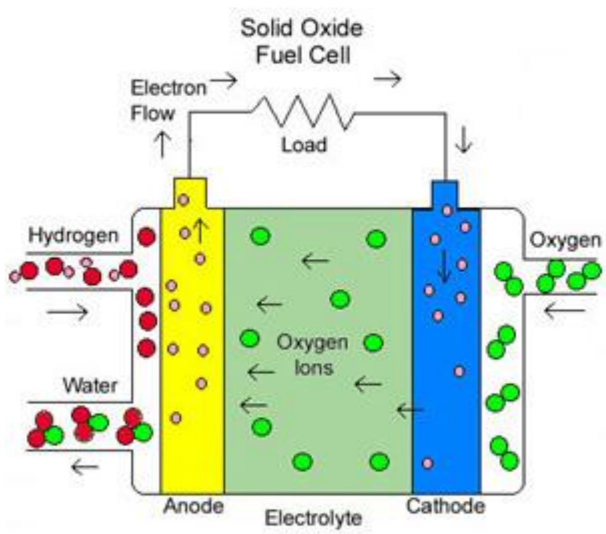
To speed the reaction a platinum catalyst is used on both sides of the membrane. Hydrogen atoms are stripped of their electrons, or "ionized," at the anode, and the positively charged protons diffuse through one side of the porous membrane and migrate toward the cathode. The electrons pass from the anode to the cathode through an exterior circuit and provide electric power along the way. At the cathode, the electrons, hydrogen protons and oxygen from the air combine to form water. For this fuel cell to work, the proton exchange membrane electrolyte must allow hydrogen protons to pass through but prohibit the passage of electrons and heavier gases.


GE's Russell Hodgdon shows a polymer electrolyte in 1965

Efficiency for a PEM cell reaches about 40 to 50 percent. An external reformer is required to convert fuels such as methanol or gasoline to hydrogen. Currently, demonstration units of 50 kilowatt (kw) capacity are operating and units producing up to 250 kw are under development.

Application:

In spacecrafts, automobiles and at home.



Drawing of a solid oxide cell

Solid Oxide fuel cells (SOFC)

A solid oxide fuel cell (SOFC) uses a hard ceramic electrolyte instead of a liquid and operates at temperatures up to 1,000 degrees C (about 1,800 degrees F). A mixture of zirconium oxide and calcium oxide form a crystal lattice, though other oxide combinations have also been used as electrolytes. The solid electrolyte is coated on both sides with specialized porous electrode materials.

At these high operating temperature, oxygen ions (with a negative charge) migrate through the crystal lattice. When a fuel gas containing hydrogen is passed over the anode, a flow of negatively charged oxygen ions moves across the electrolyte to oxidize the fuel. The oxygen is supplied, usually from air, at the cathode. Electrons generated at the anode travel through an external load to the cathode, completing the circuit and supplying electric power along the way. Generating efficiencies can range up to about 60 percent.

Applications

Like molten carbonate fuel cells, solid oxide cells require high operating temperatures, and their most common application is in large, stationary power plants. The high temperatures open the opportunity for "cogeneration"–using waste heat to generate steam for space heating, industrial processing, or in a steam turbine to make more electricity.

General applications of fuel cells:

Portable power systems[edit]

Portable fuel cell systems are generally classified as weighing under 10 kg and providing power of less than 5 kW.[159] The potential market size for smaller fuel cells is quite large with an up to 40% per annum potential growth rate and a market size of around $10 billion, leading a great deal of research to be devoted to the development of portable power cells.[160] Within this market two groups have been identified. The first is the microfuel cell market, in the 1-50 W range for power smaller electronic devices. The second is the 1-5 kW range of generators for larger scale power generation (e.g. military outposts, remote oil fields).

Microfuel cells are primarily aimed at penetrating the market for phones and laptops. This can be primarily attributed to the advantageous energy density provided by fuel cells over a lithium-ion battery, for the entire system. For a battery, this system includes the charger as well as the battery itself. For the fuel cell this system would include the cell, the necessary fuel and peripheral attachments. Taking the full system into consideration, fuel cells have been shown to provide 530Wh/kg compared to 44 Wh/kg for lithium ion batteries.[160] However, while the weight of fuel cell systems offer a distinct advantage the current costs are not in their favor. while a battery system will generally cost around $1.20 per Wh, fuel cell systems cost around $5 per Wh, putting them at a significant disadvantage.[160]

Also they have found applications in power generation, cogeneration (generation of electricity and heat together), automobiles, buses, boats, submarines, froklifts, aeroplanes, motorcycles, etc.

Criticism**[edit]**

Some commentators believe that hydrogen fuel cell cars will never become economically competitive with other technologies[108][109][110] or that it will take decades for them to become profitable.[72][111] Elon Musk, CEO of battery-electric vehicle maker Tesla Motors, stated in 2015 that fuel cells for use in cars will never be commercially viable because of the inefficiency of producing, transporting and storing hydrogen and the flammability of the gas, among other reasons.[112]

Power Generation

Stationary fuel cells are used for commercial, industrial and residential primary and backup power generation. Fuel cells are very useful as power sources in remote locations, such as spacecraft, remote weather stations, large parks, communications centers, rural locations including research stations, and in certain military applications. A fuel cell system running on hydrogen can be compact and lightweight, and have no major moving parts. Because fuel cells have no moving parts and do not involve combustion, in ideal conditions they can achieve up to 99.9999% reliability.

Since fuel cell electrolyzer systems do not store fuel in themselves, but rather rely on external storage units, they can be successfully applied in large-scale energy storage, rural areas being one example.[75] There are many different types of stationary fuel cells so efficiencies vary, but most are between 40% and 60% energy efficient.[43] However, when the fuel cell's waste heat is used to heat a building in a cogeneration system this efficiency can increase to 85%.[43] This is significantly more efficient than traditional coal power plants, which are only about one third energy efficient.[76] Assuming production at scale, fuel cells could save 20–40% on energy costs when used in cogeneration systems.[77] Fuel cells are also much cleaner than traditional power generation; a fuel cell power plant using natural gas as a hydrogen source would create less than one ounce of pollution (other than CO2) for every 1,000 kW·h produced, compared to 25 pounds of pollutants generated by conventional combustion systems.[78] Fuel Cells also produce 97% less nitrogen oxide emissions than conventional coal-fired power plants.

Fuel cells can be used with low-quality gas from landfills or waste-water treatment plants to generate power and lower methane emissions.

Cogeneration[edit]

Combined heat and power (CHP) fuel cell systems, including micro combined heat and power (MicroCHP) systems are used to generate both electricity and heat for homes (see home fuel cell), office building and factories. The system generates constant electric power (selling excess power back to the grid when it is not consumed), and at the same time produces hot air and water from the waste heat. As the result CHP systems have the potential to save primary energy as they can make use of waste heat which is generally rejected by thermal energy conversion systems.[82] The waste heat from fuel cells can be diverted during the summer directly into the ground providing further cooling while the waste heat during winter can be pumped directly into the building.

Automobiles[edit]

As of 2017, about 6500 FCEVs have been leased or sold worldwide.[95] Three fuel cell electric vehicles have been introduced for commercial lease and sale: the Honda Clarity, Toyota Mirai and the Hyundai ix35 FCEV. Additional demonstration models include the Honda FCX Clarity, and Mercedes-Benz F-Cell.[96] As of June 2011 demonstration FCEVs had driven more than 4,800,000 km (3,000,000 mi), with more than 27,000 refuelings.[97] Fuel cell electric vehicles feature an average range of 314 miles between refuelings.[98] They can be refueled in less than 5 minutes.[99] The U.S. Department of Energy's Fuel Cell Technology Program states that, as of 2011, fuel cells achieved 53–59% efficiency at one-quarter power and 42–53% vehicle efficiency at full power,[100] and a durability of over 120,000 km (75,000 mi) with less than 10% degradation.[101] In a Well-to-Wheels simulation analysis that "did not address the economics and market constraints", General Motors and its partners estimated that per mile traveled, a fuel cell electric vehicle running on compressed gaseous hydrogen produced from natural gas could use about 40% less energy and emit 45% less greenhouse gasses than an internal combustion vehicle.[102][103] A lead engineer from the Department of Energy whose team is testing fuel cell cars said in 2011 that the potential appeal is that "these are full-function vehicles with no limitations on range or refueling rate so they are a direct replacement for any vehicle. For instance, if you drive a full sized SUV and pull a boat up into the mountains, you can do that with this technology and you can't with current battery-only vehicles, which are more geared toward city driving."[104]

In 2015, Toyota introduced its first fuel cell vehicle, the Mirai, at a price of $57,000.[105] Hyundai introduced the limited production Hyundai ix35 FCEV under a lease agreement.[106] In 2016, Honda started leasing the Honda Clarity Fuel Cell.[107]

Buses[edit]

Toyota FCHV-BUS at the Expo 2005.

As of August 2011, there were about 100 fuel cell buses running around the world, including in Whistler, Canada; San Francisco, United States; Hamburg, Germany; Shanghai, China; London, England; and São Paulo, Brazil.[121] Most of these were manufactured by UTC Power, Toyota, Ballard, Hydrogenics, and Proton Motor. UTC buses had driven more than 970,000 km (600,000 mi) by 2011.[122] Fuel cell buses have from 39% to 141% higher fuel economy than diesel buses and natural gas buses.[102][123]

Forklifts[*edit*]

A fuel cell forklift (also called a fuel cell lift truck) is a fuel cell-powered industrial forklift truck used to lift and transport materials. In 2013 there were over 4,000 fuel cell forklifts used in material handling in the US,[125] of which 500 received funding from DOE (2012).

Most companies in Europe and the US do not use petroleum-powered forklifts, as these vehicles work indoors where emissions must be controlled and instead use electric forklifts.[134][135] Fuel cell-powered forklifts can provide benefits over battery-powered forklifts as they can be refueled in 3 minutes and they can be used in refrigerated warehouses, where their performance is not degraded by lower temperatures.

Motorcycles and bicycles[*edit*]

In 2005 a British manufacturer of hydrogen-powered fuel cells, Intelligent Energy (IE), produced the first working hydrogen-run motorcycle called the ENV (Emission Neutral Vehicle). The motorcycle holds enough fuel to run for four hours, and to travel 160 km (100 mi) in an urban area, at a top speed of 80 km/h (50 mph).

Aerolanes[*edit*]

In 2003, the world's first propeller-driven airplane to be powered entirely by a fuel cell was flown. The fuel cell was a stack design that allowed the fuel cell to be integrated with the plane's aerodynamic surfaces.[147] Fuel cell-powered unmanned aerial vehicles (UAV) include a Horizon fuel cell UAV that set the record distance flown for a small UAV in 2007.

Boats[*edit*]

The world's first certified fuel cell boat (HYDRA), in Leipzig/Germany

The world's first fuel-cell boat HYDRA used an AFC system with 6.5 kW net output. Iceland has committed to converting its vast fishing fleet to use fuel cells to provide auxiliary power by 2015 and, eventually, to provide primary power in its boats. Amsterdam recently introduced its first fuel cell-powered boat that ferries people around the city's canals.[155]

Submarines[*edit*]

The Type 212 submarines of the German and Italian navies use fuel cells to remain submerged for weeks without the need to surface.

The U212A is a non-nuclear submarine developed by German naval shipyard Howaldtswerke Deutsche Werft.[156] The system consists of nine PEM fuel cells, providing between 30 kW and 50 kW each. The ship is silent, giving it an advantage in the detection of other submarines.[157] A naval paper has theorized about the possibility of a nuclear-fuel cell hybrid whereby the fuel cell is used when silent operations are required and then replenished from the Nuclear reactor (and water).[158]

Other applications[edit]

- Providing power for base stations or cell sites[164][165]
- Distributed generation
- Emergency power systems are a type of fuel cell system, which may include lighting, generators and other apparatus, to provide backup resources in a crisis or when regular systems fail. They find uses in a wide variety of settings from residential homes to hospitals, scientific laboratories, data centers,[166]
- telecommunication[167] equipment and modern naval ships.
- An uninterrupted power supply (*UPS*) provides emergency power and, depending on the topology, provide line regulation as well to connected equipment by supplying power from a separate source when utility power is not available. Unlike a standby generator, it can provide instant protection from a momentary power interruption.
- Base load power plants
- Solar Hydrogen Fuel Cell Water Heating
- Hybrid vehicles, pairing the fuel cell with either an ICE or a battery.
- Notebook computers for applications where AC charging may not be readily available.
- Portable charging docks for small electronics (e.g. a belt clip that charges a cell phone or PDA).
- Smartphones, laptops and tablets.
- Small heating appliances[168]
- Food preservation, achieved by exhausting the oxygen and automatically maintaining oxygen exhaustion in a shipping container, containing, for example, fresh fish.[169]