BMM4753 RENEWABLE ENERGY RESOURCES

Chapter 10. Fuel Cell

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Energy Sustainability Focus Group

Chapter 10. Fuel Cell

Summary

10.1 Introduction

Electrolysis of water produces hydrogen and oxygen while in a fuel cell the process is reversed in which the gases combine in an electrochemical cell to generate electricity and water.

- Phosphoric Acid Fuel Cell (PAFCs) are highly efficient - total efficiency of 90 percent is achievable
- Process heat produced by the fuel cell is used for co-generation (combined heat and power).
- PAFCs are relatively new fuel cell technology which began in 1960's compared to solid oxide in 1930's and molten carbonate in 1950’s
- PAFC’s were the first fuel cells commercialized for stationary applications and have benefited from more than 20 years of field experience, technology improvements and cost reduction.
- Transportation fuel cells (buses and automobiles) use Proton Exchange Membrane (PEM) technology.

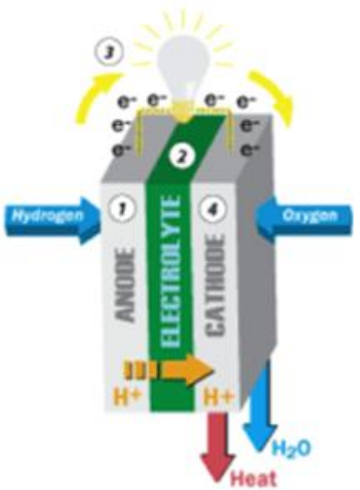
10.1 Introduction – History

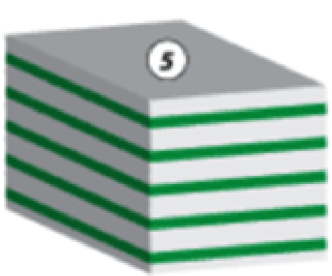
Electrochemical device that converts the chemical energy of a fuel into electricity without involving a combustion cycle.

- The first fuel cell was developed in 1839 in England by Sir William Grove.
- Its application of fuel cell was first demonstrated by Francis T. Bacon in 1959 when his model generated 5 kW at 24 V.
- Its practical application began during the 1960s when the US space program chose fuel cells over nuclear power and solar energy.
- Fuel cells provided power to the Gemini, Apollo and Skylab spacecraft, and continue to be used to provide electricity and water to space shuttles.

10.1 Introduction – How Fuel Cells Work

- Hydrogen flows into the fuel cell **anode**, a catalyst layer on the anode helps to separate the hydrogen atoms into protons (hydrogen ions) and electrons.
- Electrolyte in the center allows only the protons to pass through the electrolyte to the cathode side of the fuel cell.
- Electrons cannot pass through the electrolyte and must flow through an **external circuit,** producing electric current.
- Oxygen flows into the fuel cell **cathode**, another catalyst layer helps the oxygen protons and electrons combine to produce pure water and heat.
- Individual fuel cells can be combined into a **Fuel Cell Stack** to increase the total electrical output



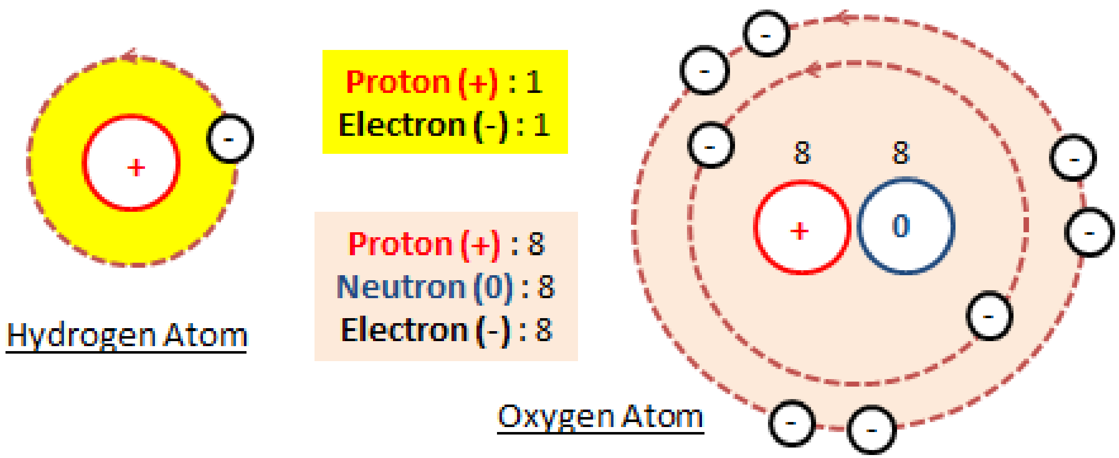


10.1 Introduction – Applications

- Substitute for storage batteries and primary cells in higher kW & Ah ratings.
- Replacement for internal combustion engines in tractors, automobiles, etc.
  - Fuel Cells will 'deliver electric power to drive the electric motor.
  - IC Engine can be substituted by fuel cell-generator, high torque DC motor.
- Source of electrical power
  - remote installations
  - space ships, ocean-ships, passenger boats, submarines,
  - auxiliary and emergency supplies, and utility power plants
  - Public transportation in electrical vehicles, electrical locomotives.
- Configuration of a typical module of H_2-0_2 fuel cell
  - Size: 15 cm x 15 cm x 45 cm
  - Weight: 24 kg
  - Number of cells: 35 Temperature ; 60°C
  - Rated power: 500 W at 1 atm and 1 kW at 5 atm.

10.2 Principle and Operation – Acidic fuel cell

- Atoms are particles of elements in an substance that could not be broken down further without changing the chemical nature of the substance.
- Atoms are made up of 3 types of particles
  - **Electrons** are tiny, very light particles that have (–)ve charge
  - **Protons** are much larger and heavier than electrons and (+)ve charge
  - **Neutrons** are large and heavy like protons but without electrical charge.
- Ion is when the atom loses its electron



10.2 Principle and Operation – Acidic fuel cell

8.2.1 Fundamental in Atomic Structure

- Atom is a basic unit of matter that consists of a dense central nucleus surrounded by a cloud of negatively charged electrons.
- Atomic nucleus contains a mix of positively charged protons and electrically neutral neutrons (except in hydrogen in which there is with no neutrons).
- Electrons of an atom are bound to the nucleus by the electromagnetic force
- Group of atoms to each other form a molecule.
- Atom containing an equal number of protons and electrons is electrically neutral, otherwise it has a positive charge if there are fewer electrons or negative charge if there are more electrons.
- Positively or negatively charged atom is known as an ion.
- Atom is classified according to the number of protons and neutrons in its nucleus
- Number of protons determines the chemical element
- Number of neutrons determines the isotope of the element.

10.2 Principle and Operation – Acidic fuel cell , H_2SO_4

Hydrogen dissociates on anode surface forms hydrogen ions and electrons

- Hydrogen ions migrate internally from anode region to the catalytic surface of the cathode; through the electrolyte and the porous barrier
- Electrons move from anode to cathode catalytic surface via external circuit
- Oxygen, hydrogen and electrons combine on the catalytic surface of cathode to form water

Anode Reaction	:	H_2	→	$2H + 2e$
Cathode Reaction	:	$½O_2 + 2H + 2e$	→	H_2O
Overall Reaction	:	$H_2 + ½O_2$	→	$H_2O + (\Delta H)$

- The net reaction in the fuel cell is hydrogen and oxygen supplied to the fuel cell produce electrical energy, water, heat (ΔH)

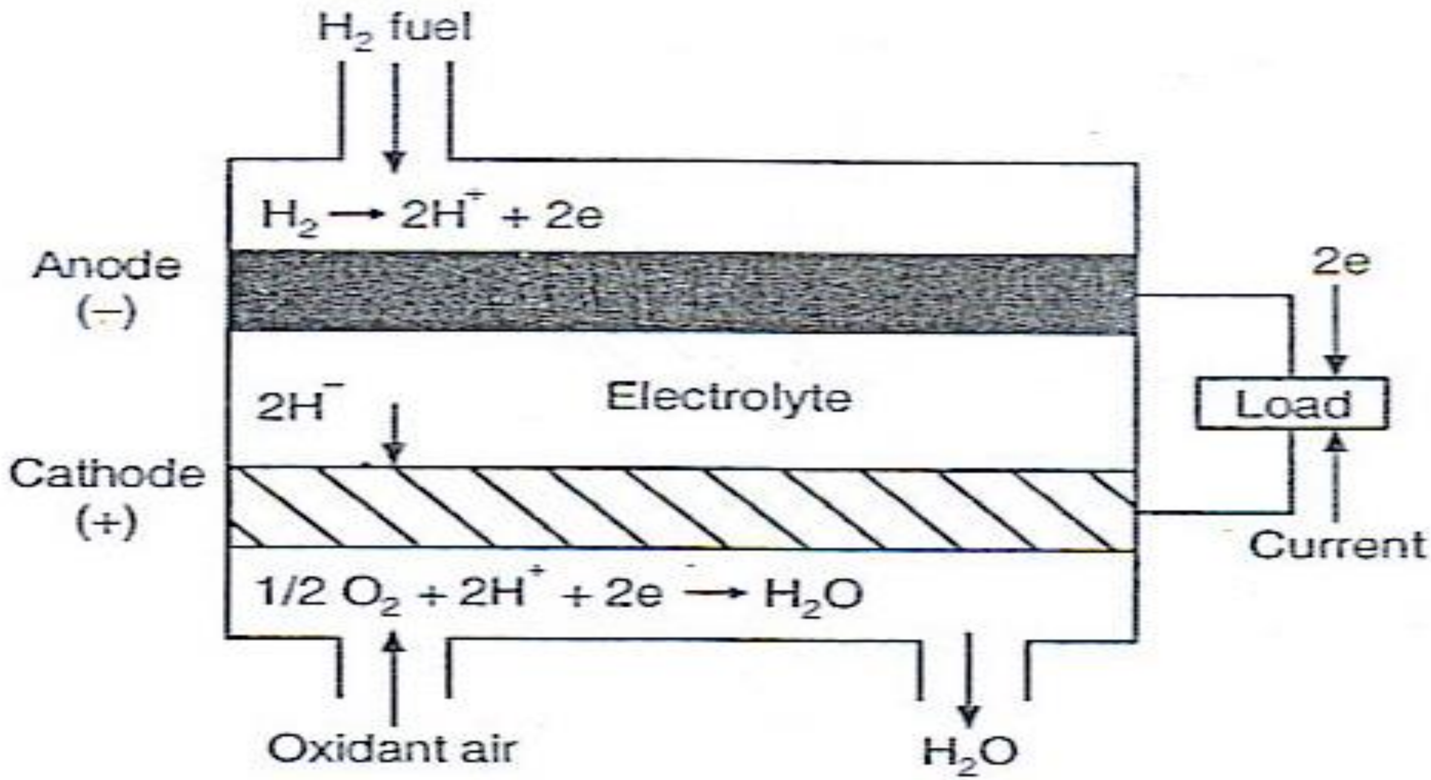
10.2 Principle and Operation – Alkaline fuel cell, KOH

- Major migration is by hydroxyl ion (OH).
- Electrochemical reaction in electrolyte

Anode Reaction	:	$H_2 + 2OH^-$	$\rightarrow$	$2H_2O + 2e$
Cathode Reaction	:	$½O_2 + 2e + H_2O$	$\rightarrow$	$2OH$
Overall Reaction	:	$H_2 + ½O_2$	$\rightarrow$	$H_2O + (\Delta H)$

- The net reaction in the fuel cell is hydrogen and oxygen supplied to the fuel cell produce electrical energy, water, heat (ΔH)

10.2 Principle and Operation – Phosphoric acidic fuel cell



Fuel cell operation.

10.2 Principle and Operation – Phosphoric acidic fuel cell

Consider a basic hydrogen-oxygen fuel cell with phosphoric acid as electrolyte. Fuel cell electrodes are made porous in order to provide a large number of pockets where the gas, the electrolyte and the electrode are in contact for chemical reaction. A fuel cell like any other battery consists of two electrodes (anode and cathode) and an electrolyte. A fuel cell differs from a battery in the sense that both the reactants (hydrogen and oxygen) are not permanently contained in the electrochemical cell, but are fed into it from an external supply, when electric power is required. In fuel cells, platinum coated special graphite plates are used as the electrodes, separated by an electrolyte. The fuel is hydrogen gas which is supplied at the anode side where the hydrogen molecules are effectively reduced to hydrogen ions which move on into the electrolyte.

$$\underset{\text{(gas)}}{H_2} \longrightarrow \underset{\text{(ion)}}{2H^+} + 2e^-$$

10.2 Principle and Operation – Phosphoric acidic fuel cell

Electrons so liberated at the anode build up a negative potential and travel towards the cathode through an externally connected circuit. Oxygen gas is supplied at the cathode where it is reduced by hydrogen ions to produce water.

$$4\mathrm{H}^{+} + \mathrm{O}_2 + 4e^{-} \longrightarrow 2\mathrm{H}_2\mathrm{O}$$

Electrochemical reactions coupled with movement of hydrogen ions through the electrolyte generate an electric potential, which causes electric current to flow through the load.

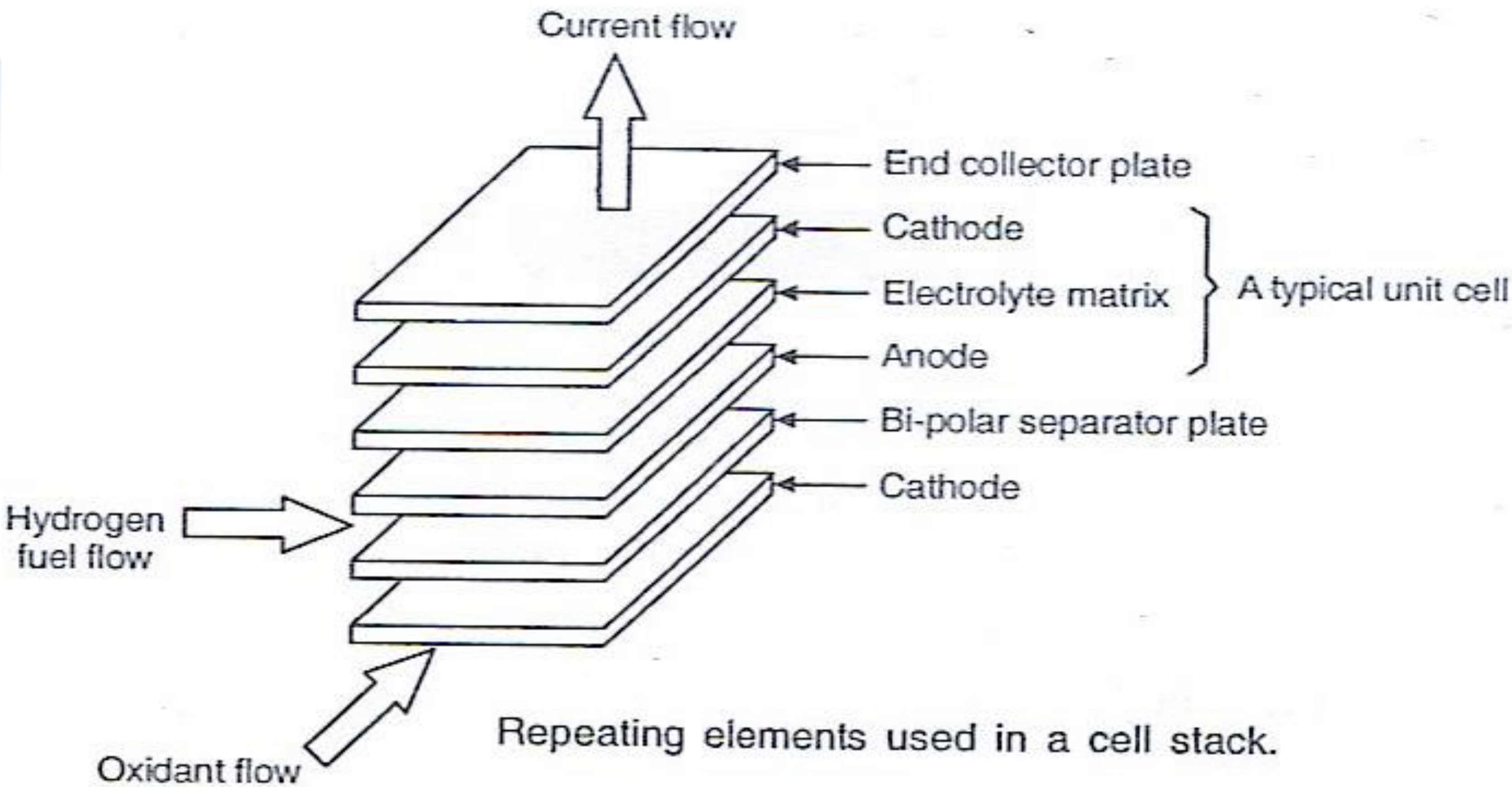
$$2H_2 + O_2 \xrightarrow{\text{Fuel cell}} 2\mathrm{H}_2\mathrm{O} + \text{Electrical energy generated} + \text{Heat released}$$

This reaction is exothermic, which results in heating up the cell. A stream of air is circulated on the cathode side of the cell which absorbs enough heat to maintain outlet air and steam at l80°C which is optimum for best performance of the cell.

10.3 Configuration

- Individual cell produces a small voltage, in the range of 0.55 to 0.75 V.
- A number of cells are arranged in 'stacks' to provide the required level of voltage.
- Electrode size (area) determines the total amperage, and current density in the range of 100-500 mA/cm^2 can be achieved.
- In any given power rating, an appropriate electrode size and the requisite number of cells are selected.
- **In** a typical fuel cell 'stack', a number of individual cells are stacked together using bipolar plates.
- A bipolar plate has two functions, namely to facilitate the distribution of fuel and oxident to the cells, and to provide continuity in electrical circuit between the cells.
- To meet this requirement, the plate should be impervious to gas diffusion and possess low electrical resistance. A set of such repeating elements.

10.3 Configuration

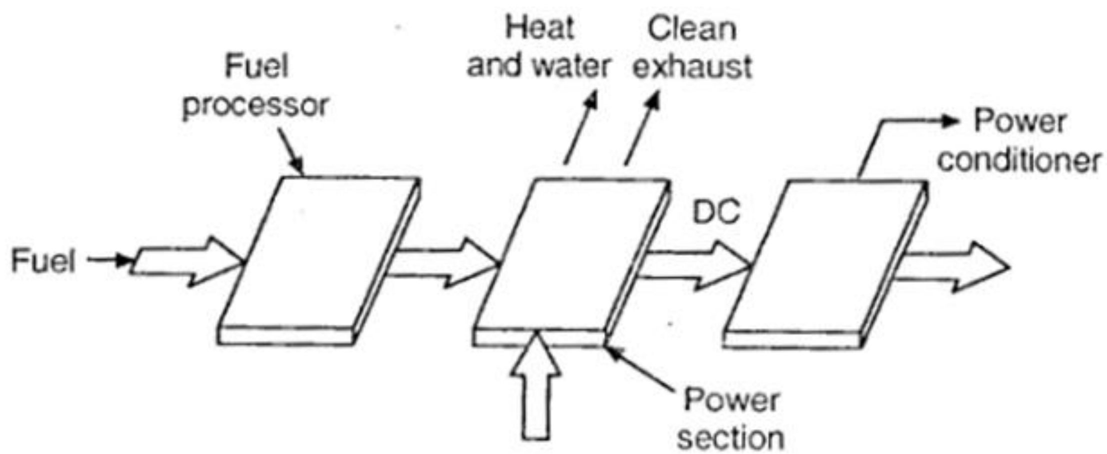


Repeating elements used in a cell stack.

10.3 Configuration

Apart from the cell stack assembly, a fuel cell power plant consists of a number of other sub-systems, namely:-

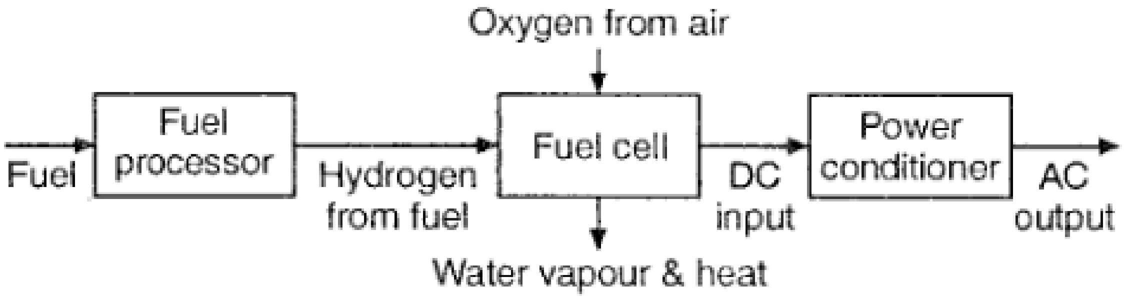
i. a fuel processing system,
ii. an inverter system,
iii. a control and instrumentation system, and
iv. a water and heat recovery system.



Major sub-systems in a fuel cell power plant.

10.4 Fuel Processor

- Fuel cells generally run on hydrogen or any hydrogen-rich material can also serve as a fuel source including:-
  i. fossil fuels-methanol,
  ii. ethanol,
  iii. natural gas,
  iv. petroleum distillates,
  v. liquid propane and
  vi. gasified coal.
- Fuels containing hydrogen require a 'fuel processor' to extract hydrogen gas.



Energy flow diagram in a fuel cell.

10.4 Fuel Processor

- Steam reformer combines the fuel with steam by vaporizing them together at high temperatures. Hydrogen is then separated out using membranes. It is an endothermic process, which means that energy is consumed-energy is obtained by burning fuel or excess hydrogen from the outlet of the fuel cell stack.
- Partial oxidation reformers combine fuel with oxygen to produce hydrogen and carbon monoxide, which then reacts with steam to produce more hydrogen. Partial oxidation releases heat which is utilized elsewhere in the system.
- Auto-thermal reformers combine the fuel with steam and oxygen, thus, the reaction remains in heat balance. In general, both methanol and gasoline can be used in any of the three reformer designs. Differences in the chemical nature of the fuels, however, can favor one design over another.
- Fuel cells are ideal for power generation, particularly for on-site service in areas that are inaccessible for grid supply.

10.5 Hydrogen From Renewable Resources

- Renewable energy of the sun and wind can be utilized to generate hydrogen, by using power from PV solar cells or wind turbines, from electrolysis of water.
- Thus, hydrogen becomes an energy carrier that transports power from generation site to another location for use in fuel cells
- If it is difficult to arrange supply of hydrogen, fuel cells can easily operate on methanol.

10.6 Methanol Fuel Cell (Methyl Alcohol)

- In places where hydrogen is not readily available, methanol (CH_30H) can be used as fuel. To generate one kilowatt of power the fuel cell uses about 12 liters of hydrogen gas, obtained from 0.6 liter of methanol.
- Overall efficiency of the cell, from fuel to electricity, is about 60%. The efficiency of fuel cell directly depends upon its use; besides electricity generation the waste heat by-product, is also utilized in industry.
- Methanol, liquid hydrocarbon fuel, can directly be introduced from the anode side of the fuel cell without converting to hydrogen. Such an arrangement is used in mobile applications of fuel cells like in buses and in remote military sites where noise and smoke discharge from diesel generators, are prohibited. Methanol can directly be oxidized to operate as fuel.

$$2CH_3OH + 3O_2 \longrightarrow 2CO_2 + 4H_2O$$

- In another method, methanol is converted to hydrogen and carbon oxides which in turn are fed into the fuel cells to generate electrical energy.

10.7 Types of Fuel Cells

- Fuel cells are identified by their most important component, electrolyte which determines
  - the operating temperature,
  - the catalysts to be applied to the electrodes and
  - the requirement of the process gas.

- There are five types of 'fuel cells' based on the electrolyte used.
  i. Alkaline Fuel Cells (AFC)
  ii. Proton Exchange Membrane Fuel Cells (PEMFC)
  iii. Phosphoric Acid Fuel Cells (PAFC)
  iv. Molten Carbonate Fuel Cells (MCFC)
  v. Solid Oxide Fuel Cells (SOFC)

10.7 Types of Fuel Cells

Type	Temperature °C	Size (kW)	Applications
Alkaline Fuel Cell (AFC)	70-100	1-100	Space and military
Proton Exchange Membrane Fuel Cell (PEMFC)	50-100	0.1-100	Residential, portable laptops, cellular phones, video cameras, buses, cars, trains
Phosphoric Acid Fuel Cell (PAFC)	160-210	5-200 (also MW plants)	Dedicated power (+heat), trains
Molten Carbonate Fuel Cell (MCFC)	650	100-2000	Dispersed power and utility power
Solid Oxide Fuel Cell (SOFC)	800-1000	2.5--250 < 100 MW plant	Domestic & commercial utility power, mobile applications for trains

10.7 Types of Fuel Cells – Alkaline Fuel Cells (AFCs)

Alkaline fuel cells use KOH as electrolyte with porous electrodes of carbon having nickel as the electro catalyst. Hydrogen is used as fuel and oxygen as oxidant, as shown. Its operating temperature is about 80°C. At anode the hydrogen gas reacts with hydroxide ions present in the electrolyte solution to form water, and electrons are released.

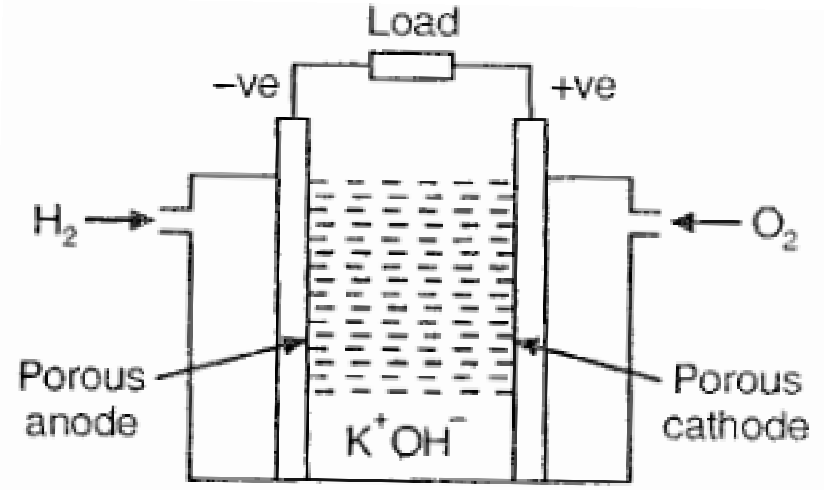
$$H_2 + 2(OH)^- \rightarrow 2H_2O + 2e$$

Electrons so produced build up a negative potential and move towards the cathode through an externally connected circuit.

$$\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2(OH)^-$$

combine with hydrogen ions to form water.

$$H^+ + OH^- \rightarrow H_2O$$



Alkaline electrolyte fuel cell

10.7 Types of Fuel Cells – Alkaline Fuel Cells (AFCs)

Thus, with hydrogen and oxygen continuously supplied, the fuel will steadily be oxidized by the ions produced in the process to generate electric power, causing current to flow in the external circuit. The voltage across the terminals of the cell is about 1 volt. For greater outputs a number of single cells can be connected in series. The efficiency of fuel cells is high, about 70%. The Apollo have developed AFC-based power packs in 2 kW to 25 kW range.

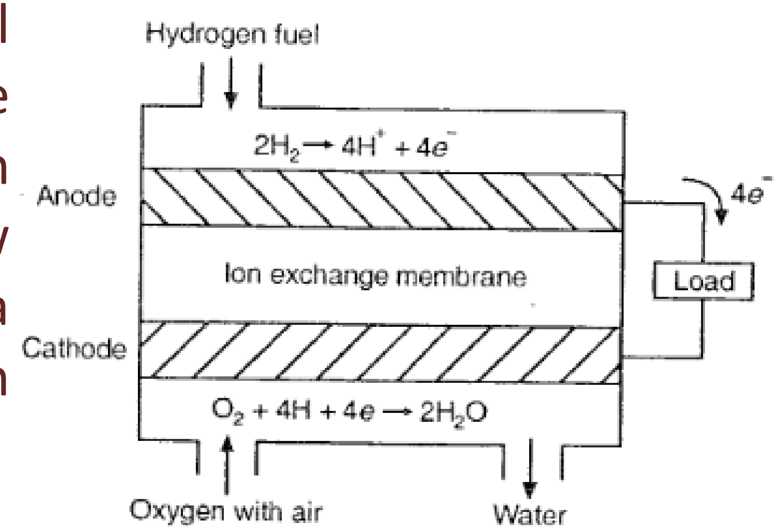
As the KOH electrolyte used in AFCs readily reacts with the CO_2 to form K_2C0_3, so this cell is not considered suitable for terrestrial applications. Even traces of CO_2 present in the ambient air limits the life of fuel cells.

However, where pure H_2 and O_2 reactants are available, as in rockets and spacecraft, there is no other fuel cell that can compete with the high power densities offered by AFCs.

10.7 Types of Fuel Cells – Proton Membrane Exchange Fuel Cell

A polymer electrolyte fuel cell, Proton Membrane Exchange Fuel Cell (PEMFC), consists of a solid electrolyte which is an ion exchange membrane. The fuel used is hydrogen with air as the oxidant. The membrane is impermeable to gases but allows the hydrogen ions to move across it which makes the current to flow in the circuit.

It is especially suitable for small stationary applications in the power range below 1 MW and operates with an efficiency level of more than 60% at low temperatures (80-100°C) and create a noiseless, pollution free power pack with short start-up and shut-down times.



Polymer electrolyte fuel cell.

10.7 Types of Fuel Cells – Phosphoric Acid Fuel Cell

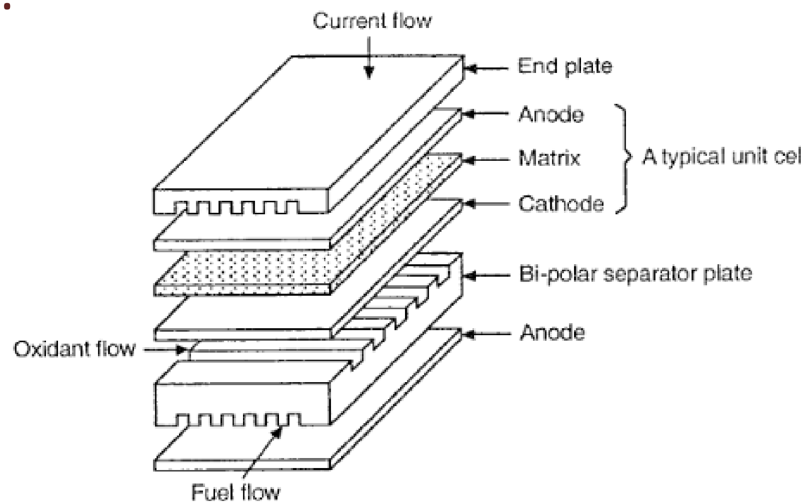
Phosphoric Acid Fuel Cell (PAFC) consists of an anode of porous graphite substrate with platinum alloy as the catalyst. The cathode in similar to the anode but made with a noble-metal catalyst. The electrolyte matrix contains concentrated phosphoric acid and is located between anode and cathode. Stacking of individual cells is accomplished with a bipolar plate. This plate provides the electrical contact between the anode of one cell and the cathode of the adjacent cell, as shown.

It is a low temperature fuel cell and requires high purity hydrogen. The low-temperature fuel cell systems comprises a second pre-processing step called the 'water gas-shift reaction' in which CO reacts with steam and is converted into hydrogen and CO_2, Such pre-processing steps are performed in separate reactors, and the fuel cell system is referred to as an 'external reforming system'.

10.7 Types of Fuel Cells – Phosphoric Acid Fuel Cell

The International Fuel Cell Corporation, a joint venture of United Technology & Toshiba are the sole world leaders in this field. More than 200 units of their 200 kW Fuel Cell Power Plants (FCPPs) have already been sold. Recently FCPPs have been integrated with digester gas from sewage treatment plants in large cities.

Another niche area is their use in combined Heat & Power (CHP) mode. CHP application of fuel cells can be more than 80% efficient, i.e. 40% electrical efficiency with another 40% energy made available as heat.

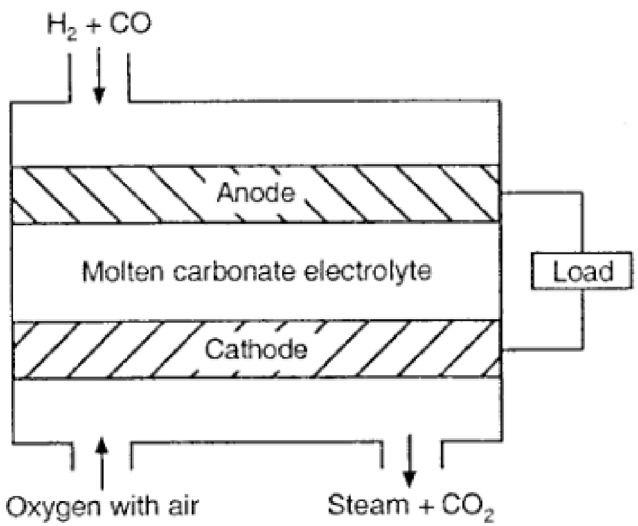


Schematic of repeating elements in a PAFC stack.

10.7 Types of Fuel Cells – Molten Carbonate Fuel Cell

A molten carbonate fuel cell (MCFCs) needs a molten mixture of alkali carbonates as an electrolyte. Its operating temperature is around 650°C which allows the use of catalysts like nickel in the electrodes. High temperature keeps the carbonate electrolyte in liquid phase. The electrolyte is retained between two porous nickel electrodes.

The by-products, steam and CO_2 at 545°C in addition to electricity it also provides industrial process heat. The waste heat can generate steam in a boiler to drive a generator for additional electric power generation, thus improving the total efficiency of the system.



Molten carbonate fuel cell

$$H_2 + CO_3^{--} \longrightarrow H_2O + CO_2 + 2e$$ At anode

$$CO + CO_3^{--} \longrightarrow CO_2 + 2e$$

$$1/2\, O_2 + CO_2 + 2e \longrightarrow CO_3^{--}$$ At cathode

10.7 Types of Fuel Cells – Molten Carbonate Fuel Cell

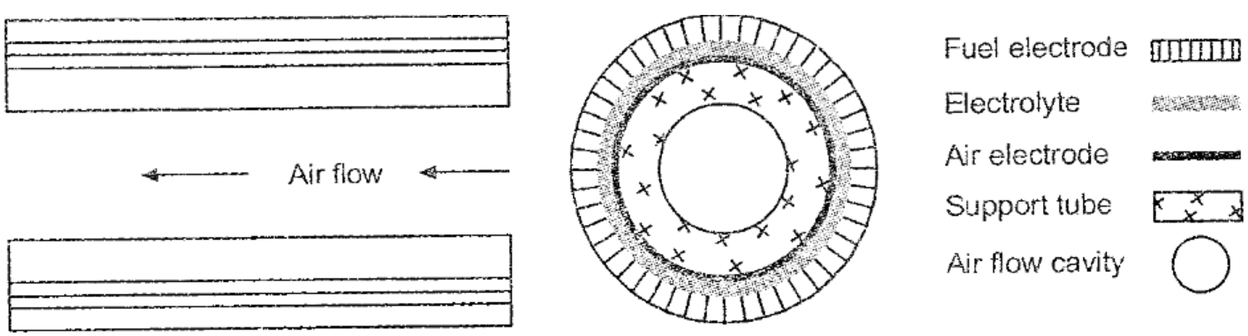
- A fuel gas derived from fossil fuels contains CO_2 and CO. The MCFC is insensitive to CO_2 and with nickel/nickel oxide electrodes it is also immune to poisoning by CO.
- Being a high temperature fuel cell, there is an internal reforming system which takes place almost simultaneously with the electro-chemical reactions. The CO is oxidized, via the water-gas shift reaction, to CO_2 with the production of hydrogen.
- The oxidizing agents for hydrogen are carbonate ions which are formed at the cathode. Thus, the oxidant gas must contain CO_2.
- CO_2 is provided by recycling the anode off-gas to the cathode.
- The by-products of this cell are, steam and carbon dioxide at a high temperature of 545°C and a source of cogeneration.

10.7 Types of Fuel Cells – Solid Oxide Fuel Cell

- Solid Oxide Fuel Cell (SOFC) is based on a solid metal oxide electrolyte (zirconium dioxide) called zirconia, allows ionic conductivity of oxygen ions from cathode to anode.
- Operate at high temperature range 800°C-1000°C, high enough for internal reforming of natural gas in the anode chamber. The electrodes are electric conductors with a high porosity. The water gas shift reaction takes place at the anode, utilizing H_2 and CO mixtures as fuel feedstock.
- The construction materials are metal oxides and ceramics. The central hollow space is for air flow that acts as an oxidant. It operate efficiently at l000°C and 1 atmospheric pressure. Fuel gas flows through the outermost layer of the fuel electrode, next to its electrolyte layer. Fuel gas permeates through the porous electrodes and oxidized by air containing oxygen. The air electrode is next to electrolyte and air flows axially through the central hollow space. Both fuel gas and oxidant are fed into the cell, get consumed and delivers electrical energy.

10.7 Types of Fuel Cells – Solid Oxide Fuel Cell

- Large-scale SOFC can be fuelled with coal gas and gases derived from biomass and integration with gas and steam turbines is possible.
- SOFC fuelled by natural gas can attain a high electrical efficiency rating up to 55%. Each cell delivers 25 A current at 0.7 V and a pack of 50 cells gives an output of 1000 W. Natural gas is clean, efficient and economically versatile than fossil fuels.
- Solid oxide fuel cells promise a vast potential in utilization of low grade, high ash, graded coals through Fluidized Bed Gasification



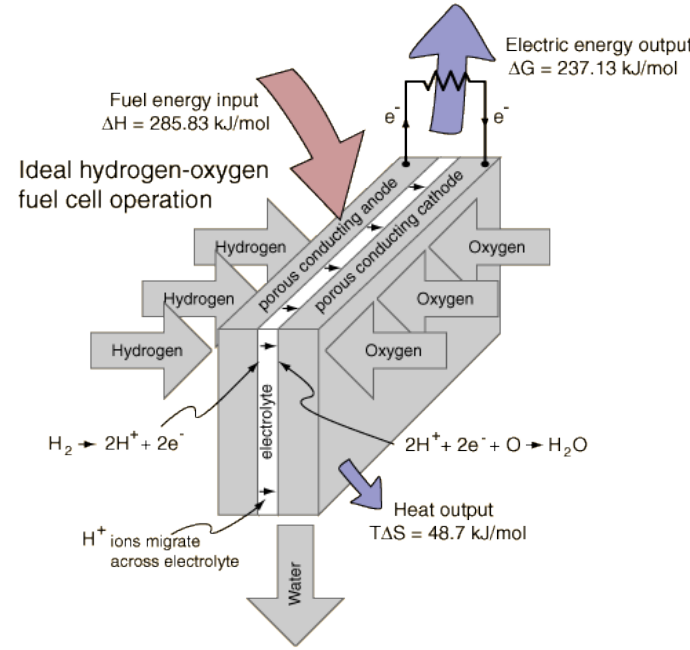
Solid oxide fuel cell (tubular shape).

10.8 Advantages of Fuel Cell Power Plants

1. Eco-friendly, noiseless, carry no rotating components. In contrast, in coal-based stations, ash slurry, discharge of smoke through chimney adversely affect the environment.
2. Decentralized plant, can be operated in isolation for military installations and hospitals where noise and smoke are prohibited without transmission loss.
3. Fuel cell power sources attain a high efficiency up to 55% whereas conventional thermal plants operate at 30% efficiency.
4. A large degree of modularity is available, with capacity range 5 kW - 2 MW.
5. There is a wide choice of fuels for fuel cells including natural gas, ethanol, methanol, LPG and biogas supplied from local biomass.
6. Fuel cells can operate at landfills and wastewater treatment plants from the methane gas they produce.
7. Supply hot water, space heat and steam as by-products.
8. Fuel cells have cogeneration capabilities to enhance system efficiency.
9. Ideally suited for dispersed stand-alone, remote power plants

10.9 Hydrogen Fuel Cell Analysis

- H_2 and O_2 to produce electrical energy
- Chemical reaction to provide an external voltage like in a battery, but differs in that the fuel is continually supplied in the form of H_2 and O_2 gas.
- Produce electrical energy at a higher efficiency than just burning the hydrogen to produce heat to drive a generator because it is not subject to the thermal constraints.
- Only product is water, pollution-free.



Quantity	H_2	$0.5O_2$	H_2O	Change Δ
Enthalpy kJ	0	0	-285.83	$\Delta H = -285.83$
Entropy J/K	130.68	0.5 x 205.14	69.91	$T\Delta S = -48.7$

10.9 Hydrogen Fuel Cell Analysis

Energy is produced by the combination of the atoms and also from the decrease in volume of both the gases. At temperature 298 K and one atmosphere pressure,

$$W = p\Delta V = (101.3 \times 10^3 Pa)(1.5\, moles)(-22.4 \times 10^{-3}\, m^3/mol\, (298\, K/273\, K)$$

$$\boxed{2H_2 + O_2 \rightarrow 2H_2O}$$

From definition of enthalpy *H* = *U* + *P V*, the change in internal energy ΔU is given by

$$\Delta U = \Delta H - p\Delta V = -285.83 \text{ kJ} --3.72 = -282.1 \text{ kJ}$$

The entropy of the gases decreases by 48.7 kJ in the process of combination as the total number of water molecules is less than the total molecules of hydrogen and oxygen. The total entropy will not decrease in the reaction, the excess entropy in the amount *TΔs* must be expelled to the environment as heat at temperature *T.* The amount of energy per mole of hydrogen that can be provided as electrical energy is the change in the Gibbs free energy:

$$\Delta G = \Delta H - T\Delta s = -285.83 \text{ kJ} - 48.7 \text{ kJ} = -237.1 \text{ kJ} \quad \boxed{G = H - Ts}$$

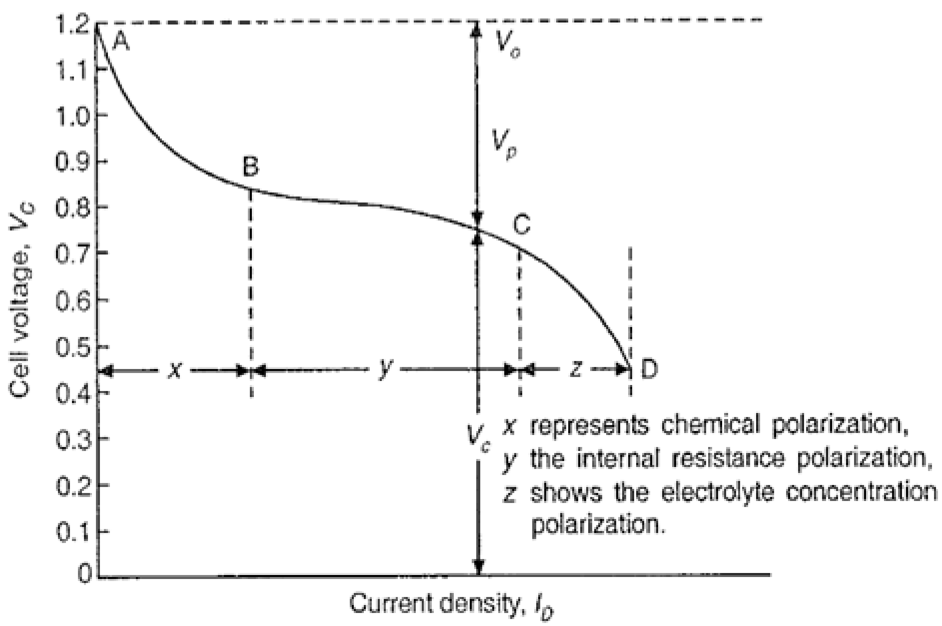
For this ideal case, the fuel energy is converted to electrical energy at an efficiency of 83%

$$\eta = \frac{237.1}{285.8} \times 100\% = 83\%$$

The efficiency is far greater than any electric power plant which burns fossil fuel.

10.10 Operating Characteristics

Energy is harnessed via chemical reaction into electricity to the extent of 65% only. The performance of a fuel cell can be evaluated from a curve of the cell voltage V_c drawn against current density I_D at electrode surface at a given temperature, difference in open-circuit voltage *(V_o)* and closed-circuit voltage *(V_c)* is due to the polarization effect within the cell.



Voltage drop, $V_o = V_c + V_p$

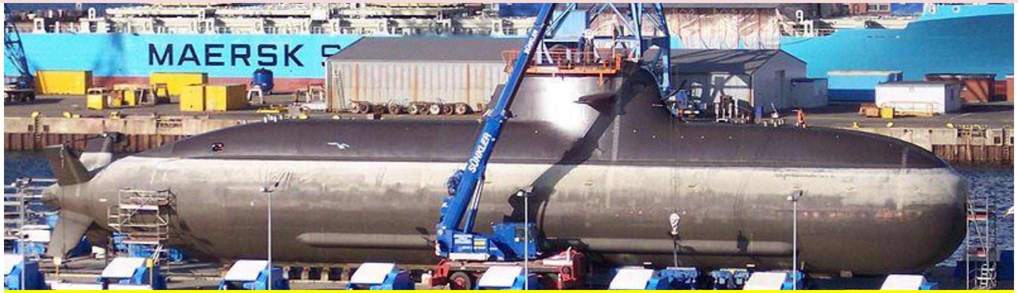
Polarization/electrode losses at the electrodes denotes the difference in the open-circuit voltage and the closed-circuit voltage in 3 categories:

- chemical polarization,
- internal resistance polarization,
- electrolyte concentration polarization

10.11 Future Potential of Fuel Cells

- Large-scale application of fuel cells is expected to enter into the niche market of high technology electronic devices like cellular phones, laptop computers and video cameras.
- Casio computers have released a notebook PC powered by a fuel cell using methanol reforming. MTI Micro Fuel Cells, USA, has developed an external fuel cell for use in cell phones.
- The real revolution is expected to come from the vehicular application of fuel cells. It will help the developed countries to propel their compliance of Kyoto protocol, i.e. cut down the "greenhouse gas emissions" to levels that are 5% below the 1990 level.
- With all-round applications, the generation of electricity from fuel cells is expected to jump to 15000 MW in 2011 from a mere 75 MW in 2001. It will cover all the three market segments, i.e. portable, stationary and vehicular.

10.11 Future Potential of Fuel Cells



Siemens Proton Exchange Membrane (PEM) Hydrogen Fuel Cells in Submarine

- German **Type 212** class is a highly advanced design of non-nuclear submarine (U-boat) developed by Howaldtswerke-Deutsche Werft AG (HDW) for the German Navy
- Italian **Todaro** class in Italian Navy
- Diesel propulsion and an additional air-independent propulsion (AIP) system using Siemens proton exchange membrane (PEM) hydrogen fuel cells
- Operate at high speed on diesel power or switch to the AIP system for silent slow cruising, staying submerged for up to three weeks with no exhaust heat.
- Vibration-free, extremely quiet and virtually undetectable.
- Type 212 is the first of the only two fuel cell propulsion system equipped submarines, ready for series production in 2007
- Other being the Project 677 Lada class submarine, Russian Rubin Design Bureau

Problems 10-1: Hydrogen flow rate in PAFC/PEFC

Determine hydrogen flow rate to generate 1.0 ampere of current in a fuel cell. Consider PAFC and PEFC because of the simplicity of the anode (fuel) reaction, although the rule of two electrons per diatomic hydrogen molecule (H_2) holds true for all fuel cell types. For every molecule of hydrogen (H_2) that reacts within a fuel cell, two electrons are liberated at the fuel cell anode.

$$H_2 \rightarrow 2H^+ + 2e^-$$

Data:

- Molar mass of hydrogen gas (H_2) is 2.0158g.
- One equivalence of electrons is 1 g mol of electrons or 6.022 $\times 10^{23}$ electrons (Av No’s)
- This quantity of electrons has the charge of 96,487 coulombs (C) (Faraday’s constant)
- Thus, the charge of a single electron is 1.602 x10 $^{-}$19 C
- One (1) ampere of current is defined as 1 C/sec.

Problems 10-1: Hydrogen flow rate in PAFC/PEFC

Solution

The moles of hydrogen liberated to generate 1 ampere

$$\mathbf{n_{H_2}} = 1.0\mathrm{A}\left(\frac{1\ \mathrm{coulomb/s}}{1\mathrm{A}}\right)\left(\frac{1\ \mathrm{equiv\ of\ e^-}}{96{,}487\ \mathrm{coulombs}}\right)\left(\frac{1\ \mathrm{g\ mol\ H_2}}{2\ \mathrm{equiv\ of\ e^-}}\right)\left(\frac{3600\ \mathrm{s}}{1\ \mathrm{hr}}\right)$$

$$= \mathbf{0.018655\,\frac{g\ mol}{hr.A}\,H_2}$$

Mass of fuel hydrogen required to supply desired fuel cell output

$$\mathbf{m_{H_2}} = 0.018655\,\frac{\mathrm{g\ mol}}{\mathrm{hr.A}}\,\mathrm{H_2}\left(\frac{2.0158\ \mathrm{g}}{1\ \mathrm{g\ mol\ H_2}}\right)\left(\frac{1\ \mathrm{kg}}{1000\ \mathrm{g}}\right)$$

$$= \mathbf{37.605\times10^{-6}\,\frac{kg\ H_2}{hr.A}\ or\ 0.037605\ \frac{kg\ H_2}{hr.kA}}$$

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Problems 10.2: Hydrogen and air flow rate in PAFC/PEFC

Consider a 1.0 MW_{DC} fuel cell stack operating with 700 mV on pure hydrogen with a utilization fuel U_f = 80%. Take PAFC/PEFC, mass flow of fuel m_{H2} = $0.037605\ \frac{\text{kg H}_2}{\text{hr.kA}}$, determine,

i. how much hydrogen will be consumed in kg/hr,
ii. what is the required fuel flow rate in kg/hr, and
iii. what is the required air flow rate in kg/hr for a 25% oxidant utilization U_{ox}

Solution

i. Assume fuel stack, current from basic electricity, $I = \frac{P}{V} = \left(\frac{1.0\ MW}{0.7\ V} \times \frac{10^6 W}{1\ MW}\right)\left(\frac{1\ VA}{1\ W} \times\right.$

Problems 10.2: Hydrogen and air flow rate in PAFC/PEFC

Solution

ii. From definition,

$$U_f = \frac{H_2 consume}{H_2 supply} \Rightarrow H_2 supply = \frac{H_2 consume}{U_f} = \frac{53.74}{0.80} \frac{\text{kg H}_2}{hr} = 67.175 \frac{\text{kg H}_2}{hr}$$

iii. Stoichiometric ratio hydrogen to oxygen is 2:1, moles of oxygen required

$$\mathrm{n}_{\mathrm{O}_2,\text{consume}} = \left(53.74 \frac{\text{kg H}_2}{\text{hr}}\right)\left(\frac{\text{kg mol H}_2}{2.0158 \text{ kg H}_2}\right)\left(\frac{1 \text{ kg mol O}_2}{2 \text{ kg mol H}_2}\right) = 13.33 \frac{\text{kg mol O}_2}{hr}$$

Assume 25% oxidant $\mathrm{n}_{\mathrm{O}_2,\text{supplied}}$

$$= \left(13.33 \frac{\text{kg mol O}_2}{hr}\right)\left(\frac{1\ kg\ mol\ O_2,supplied}{0.25\ mol\ O_2,consumed}\right) = 53.32 \frac{\text{kg mol O}_2}{hr}$$

Mass flow rate of air $m_{air,supplied}$

$$= \left(53.32 \frac{\text{kg mol O}_2}{hr}\right)\left(\frac{1\ kg\ mol\ air}{0.21\ kg\ mol\ O_2}\right)\left(\frac{28.85\ kg\ dry\ air}{1\ kg\ mol\ air}\right) = 7{,}325 \frac{kg\ dry\ air}{hr}$$

Problems 10.3: Hydrogen, air and water flow rate in PAFC

A PAFC, operating on reformed natural gas (900 lb) and air, has a fuel and oxidant utilization of 86% and 70% respectively. With the fuel and oxidant composition and molecular weights listed below determine,

i. how much hydrogen will be consumed in lb mol/hr,
ii. how much oxygen is consumed in lb mol/hr,
iii. what is the required air flow rate in lb mol/hr and lb/hr,
iv. how much water is generated, and
v. what is the composition of the effluent (spent) fuel and air streams in mol %.

Fuel Data	mol %
CH_4	4.0
CO	0.4
CO_2	17.6
H_2	75.0
H_2O	3.0
Total	100.0
MW	10.55

Air Data	mol %, dry	mol %, wet
H_2O	0.00	1.00
N_2	79.00	78.21
O_2	21.00	20.79
Total	100.00	100.00
MW	28.85	28.74

Problems 10.3: Hydrogen, air and water flow rate in PAFC

Solution

i. Hydrogen consume in lb mol/hr,

$$n_{fuel,supplied} = \left(900\,\frac{lb\ fuel}{hr}\right)\left(\frac{1\ lb\ mol\ fuel}{10.55\ lb\ fuel}\right) = 85.29\ \frac{lb\ mol\ fuel}{hr}$$

$$n_{H_2 supplied} = \left(85.29\ \frac{lb\ mol\ fuel}{hr}\right)\left(\frac{75\ lb\ mol\ H_2}{100\ lb\ mol\ fuel}\right)\left(\frac{86\ lb\ mol\ H_2 consumed}{lb\ mol\ H_2 supplied}\right)$$

$$= 55.01\ \frac{lb\ mol\ H_2}{hr}$$

ii. Oxygen consume in lb mol/hr, from overall fuel cell reaction

$$H_{2(g)} + {}^{1}/_{2}\,O_{2(g)} \longrightarrow H_2O_{(g)}$$

$$n_{O_2 consumed} = \left(55.01\,\frac{lb\ mol\ H_2}{hr}\right)\left(\frac{{}^{1}/_{2} lb\ mol\ O_2}{1\ lb\ mol\ H_2}\right) = 27.51\ \frac{lb\ mol\ O_2}{hr}$$

iii. Required air flow rate in lb mol/hr,

$$n_{air,required} = \left(27.51\ \frac{lb\ mol\ O_2}{hr}\right)$$

Problems 10.4: Configuration of fuel cell

Given a desired output of 2.0 MW_{DC} at operating point of 600 mV and 400 mA/cm^2 determine,

i. how much fuel cell area is needed, and

ii. How many stacks needed if cell area is 1.0 m^2/cell and 280 cells /stack.

Solution

i. Basic electricity, $I = \frac{P}{V} = \left(\frac{2.0\ \text{MW}}{0.6\ \text{V}} \times \frac{10^6 \text{W}}{1\ \text{MW}}\right)\left(\frac{1\ \text{VA}}{1\ \text{W}} \times \frac{1\ \text{kA}}{1000\text{A}}\right) = 3{,}333\ \text{kA}$

Area $= \frac{I}{\text{Current density}} = \left(\frac{3{,}333}{400\frac{\text{mA}}{\text{cm}^2}}\right)\left(\frac{1000\ \text{mA}}{1\ \text{A}}\right)\left(\frac{1000\ \text{A}}{1\ \text{kA}}\right) = 8.333 \times 10^6 \text{cm}^2$

ii. Number of cells required $= \left(\frac{8.333\times10^6 \text{cm}^2}{\frac{1.0\ \text{m}^2}{\text{cell}}}\right)\left(\frac{1\ \text{m}^2}{10{,}000\ \text{cm}^2}\right) \sim 833\ \text{cells}$

Number of stacks required $= \frac{833\ \text{cells}}{280\,\frac{\text{cells}}{\text{stack}}} = 2.98\ \text{stacks} \sim 3\ \text{stacks}$

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