UMP OPEN COURSEWARE

Universiti Malaysia PAHANG
Engineering • Technology • Creativity

CHAPTER

Fuel Cell

Expected Outcomes

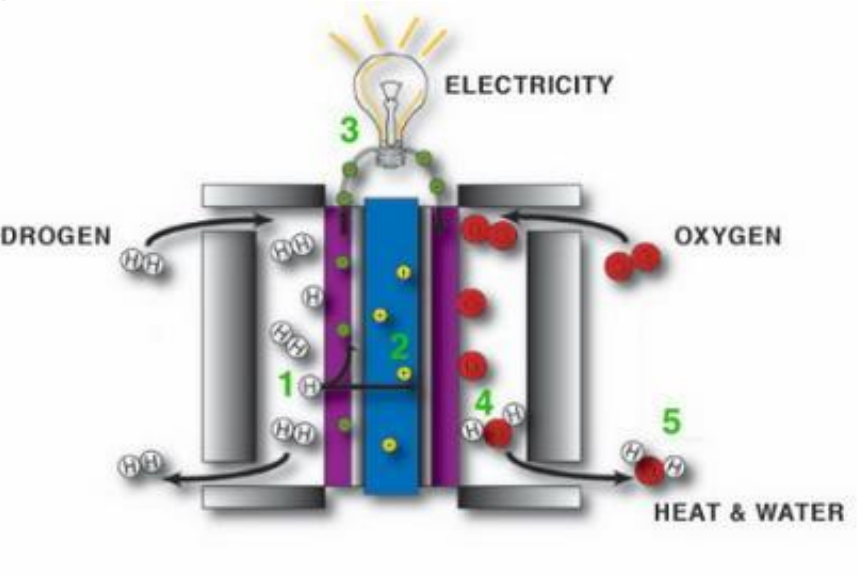
Types of fuel cells, energy density of fuel cells, Factors affecting the performance of fuel cells, Operational conditions, and Applications of fuel cells

• Contents

- What is a Fuel cell ?
- Basic components of fuel cell
- Types of fuel cells
- Applications
- Advantages and disadvantages

• What is a fuel cell?

- A **fuel cell** is an electrochemical device, made up of two compartments that is the anode and the cathode. A fuel is oxidized at the anode that produces electrons, which are reduced at the cathode. The chemical energy released from this redox reaction is used to generate electricity.



Complete reaction

$2H_2\,(g) + O_2 \longrightarrow H_2O$ + Energy

$2H_2\,(g) + O_2 \longrightarrow H_2O$ + (electrical power+ heat)

Anode : $2H_2 \longrightarrow 4\,e^- + 4\,H^+$

Cathode : $O_2 + 4\,e^- + 4\,H^+ \longrightarrow H_2O$

(D. Hart, J. Power Sources, 2000, 86: 23)

- All the chemicals are stored inside a battery, which are converted into electricity.
- In a battery, the chemicals constantly flow into the cell, therefore it doesn't go dead soon. The battery continues to generate the electricity as long as there is a flow of chemicals into the cell.
- Nowadays hydrogen and oxygen are used as the chemicals in most of the fuel cells.
- Fuel Cells differs from the battery in a way, we can continuously add fuel in the fuel cells while only limited chemicals are present in the battery.
- Fuel cells are ecofriendly because they do not release harmful gases in the environment, only electrical energy is generated.

(F.D. Melle, J. Power Sources, 1998, 17, 7)

• Fuel Cell Basics Components

- **Anode:** The electrode where the oxidation of the fuel takes place and releases electrons.
- **Cathode:** The electrode where the reduction takes place and accepts the electrons.
- **Electrolyte:** A chemical compound that conducts ions from one electrode to the other inside a fuel cell.
- **Catalyst:** A substance that speeds up a chemical reaction without itself being affected.
- **Cogeneration:** The process that utilizes of waste heat to generate electricity.
- **Reformer:** A device that extracts pure hydrogen from hydrocarbons.

(D. Hart, J. Power Sources, 2000, 86, 23)

• Thermodynamics

$$H_2(g) + ½O_2(g) \longrightarrow H_2O(l)$$

- Other gases in the fuel and air inputs (such as N_2 and CO_2) may be present, but they do not need to be considered in the energy calculations as they are not involved in the electrochemical reaction.

Table 1 Thermodynamic properties at 1Atm and 298K

	H_2	O_2	H_2O (l)
Enthalpy (H)	0	0	-285.83 kJ/mol
Entropy (S)	130.68 J/mol·K	205.14 J/mol·K	69.91 J/mol·K

- Enthalpy is defined as the energy of a system plus the product of volume and pressure of the system.

- Entropy can be considered as the measure of disorganization of a system, or as a measure of the amount of energy that is unavailable to do work.

(Mark W. Zemansky (1968), *Heat and Thermodynamics*, Chapter 11 (5th edition) page 275, McGraw Hill, New York.)

Enthalpy of the chemical reaction using Hess' Law:

$$\Delta H = \Delta H_{reaction} = \Sigma H_{products} - \Sigma H_{reactants}$$
$$= (1mol)(-285.83\ {}^{kJ}/_{mol}) - (0)$$
$$= -285.83\ kJ$$

Entropy of chemical reaction:

$$\Delta S = \Delta S_{reaction} = \Sigma S_{products} - \Sigma S_{reactants}$$
$$= [(1mol)(69.91\ {}^{J}/_{mol\cdot K})] - [(1mol)(130.68\ {}^{J}/_{mol\cdot K}) + (½mol)(205.14\ {}^{J}/_{mol\cdot K})]$$
$$= -163.34\ {}^{J}/_{K}$$

Heat gained by the system:

$$\Delta Q = T\Delta S$$
$$= (298K)(-163.34\ {}^{J}/_{K})$$
$$= -48.7\ kJ$$

(Mark W. Zemansky (1968), *Heat and Thermodynamics*, Chapter 11 (5th edition) page 275, McGraw Hill, New York.)

- <u>The Gibbs free energy is then calculated by:</u>

$$\Delta G = \Delta H - T\Delta S$$
$$= (-285.83\ kJ) - (-48.7\ kJ)$$
$$= -237\ kJ$$

- The external work done on the reaction, assuming reversibility and constant temp.

$$W = \Delta G$$

- The work done on the reaction by the environment is:

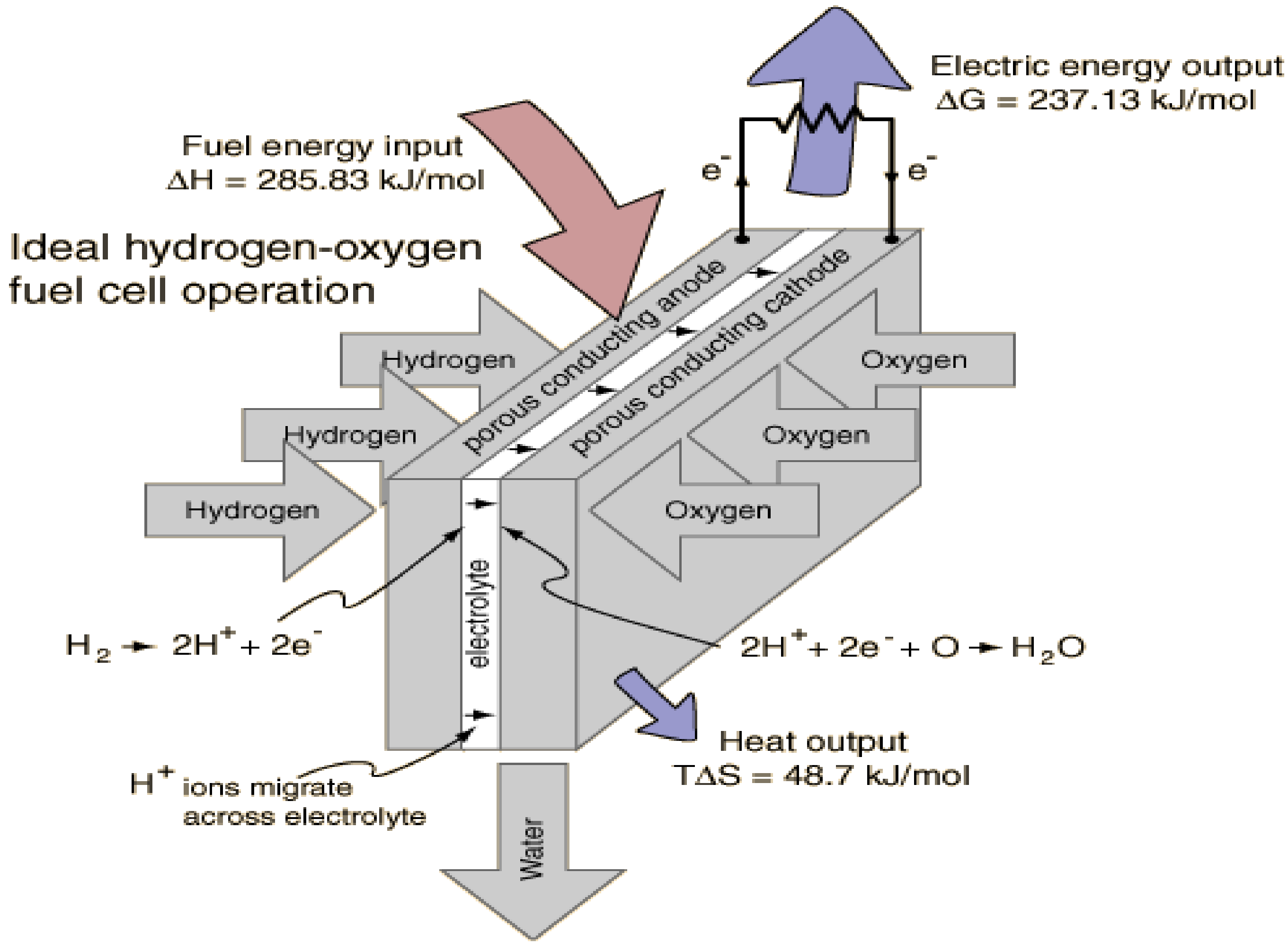
$$W = \Delta G = -237\ kJ$$

- The heat transferred to the reaction by the environment is:

$$\Delta Q = T\Delta S = -48.7\ kJ$$

- More simply stated: The chemical reaction can do 237 kJ of work and produces 48.7 kJ of heat to the environment.

(Mark W. Zemansky (1968), *Heat and Thermodynamics*, Chapter 11 (5th edition) page 275, McGraw Hill, New York.)



(Kakati et al, *Energy & Fuels* 2007, 21: 1681–1687)

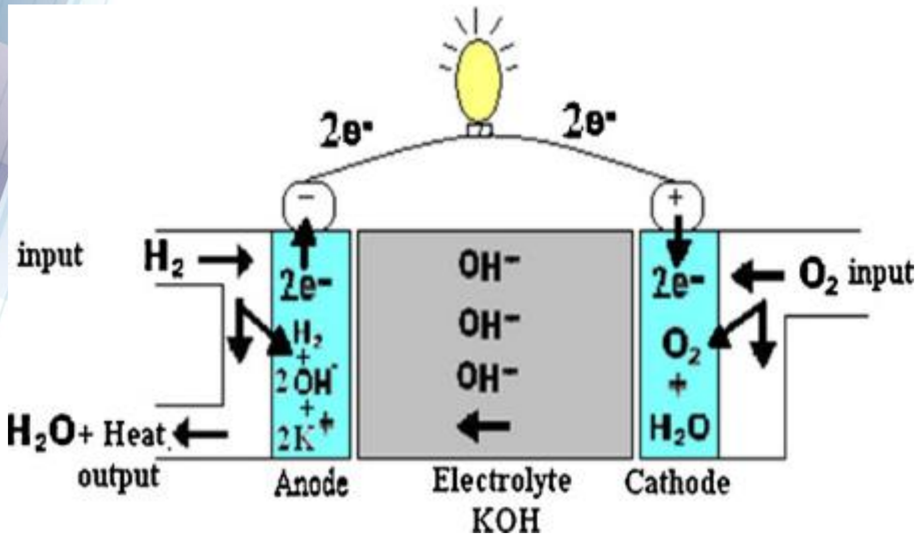
• Types of Fuel cells

- The fuel cells are of different types according to their operating temperature, efficiency, applications and costs. Typically, these are classified based on the choice of fuel and electrolyte and are classified into 5 major groups-

1. Alkali
2. Molten Carbonate
3. Phosphoric Acid
4. Solid Oxide
5. Proton Exchange Membrane

(Larminie, James). *Fuel Cell Systems Explained, Second Edition,* 1 May 2003)

1. Alkali Fuel Cell (AFC)



Oxidation – $2H_2 + 4OH^- \longrightarrow 4H_2O + 4\ e^-$

Reduction – $O_2 + 2H_2O + 4\ e^- \longrightarrow 4OH^-$

- In AFCs, an alkaline electrolyte is used they are named so. Generally, alkaline potassium hydroxide (KOH) is used as with a conc. of approximately 85% particularly when AFCs are operated at higher temperatures such as 415˚ C.
- the fuel must be pure.
- ~70% efficiency
- 60˚C - 70˚C operating temp.
- 5 kW -20 kW output
- Nickel as catalyst

(McLean, G. F., et al. *International Journal of Hydrogen Energy, 2002,* 27: 507-526.)

- The catalyst nickel is very cheap.

- If the fuel is not pure and contains the gases like CO and CO_2, the electrolyte KOH reacts with the gases to form potassium carbonate (K_2CO_3) that can consequently poison the fuel cell.

- AFC typically uses the pure oxygen which in turn increases the cost of fuel cell.

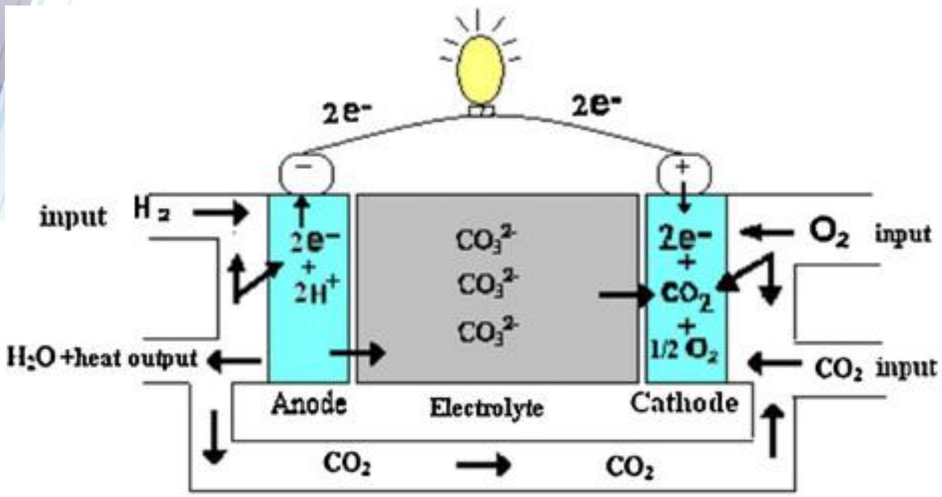
- National Aeronautics and Space Administration (NASA) used AFCs the first time.

- Nowadays, AFCs are used in boats, forklift trucks, submarines, and niche transportation applications.

- The by-product of the electrochemical reaction produced by AFC is the water that can be used for drinking purpose.

(McLean, G. F., et al. *International Journal of Hydrogen Energy, 2002,* 27: 507-526.)

2. Molten Carbonate Fuel Cell (MCFC)



(Oxidation 1) - $H_2 + CO_3^{2-} \longrightarrow H_2O + CO_2 + 2e^-$

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

Reduction – $(½)\ O_2 + CO_2 + 2e^- \longrightarrow CO_3^{2-}$

- MCFCs are operated on a high-temperature range that is between 600 and 700° C. These type of fuel cells use an electrolyte made up of a mixture of alkali metal carbonates suspended in a ceramic matrix of lithium aluminate LiAlO2.

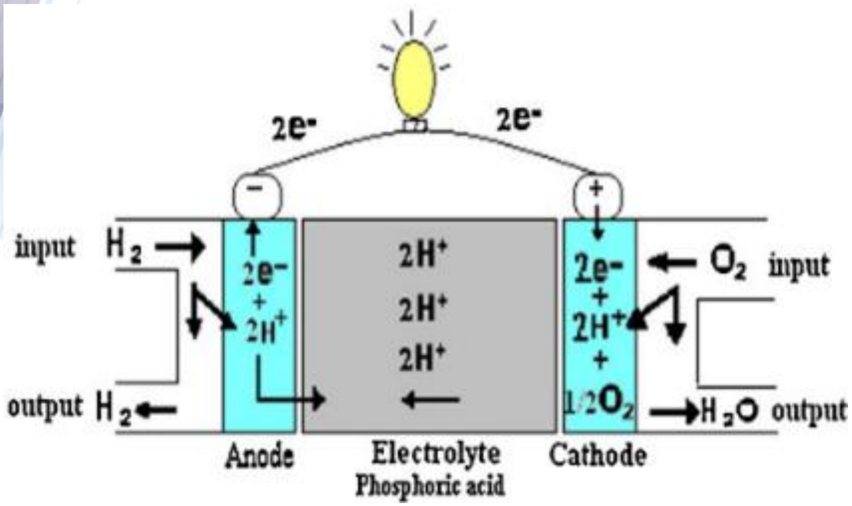
- carbonate salt electrolyte
- 60 – 80% efficiency
- ~650˚C operating temp.

(Dicks, Andrew L. *Current Opinion in Solid State and Materials Science* 2004, 8: 379-383)

- MCFCs are nowadays are widely used power plants which operated by natural gas and coal in electrical efficacy and industrial application.
- The fuels like hydrogen, carbon monoxide, natural gas and propane can be directly used in MCFCs.
- MCFCs can be operated without metal catalysts for oxidation and reduction reactions.
- MCFCs do not need any infrastructure development.
- The operation period is generally longer in MCFCs because it takes much time to reach to the operating temperature and generating power.

(Dicks, Andrew L. *Current Opinion in Solid State and Materials Science* 2004, 8: 379-383)

3. Phosphoric Acid Fuel Cell (PAFC)



Oxidation: $2H_2 \longrightarrow 4H^+ + 4e^-$

Cathode : $O_2 + 4e^- + 4H^+ \longrightarrow H_2O$

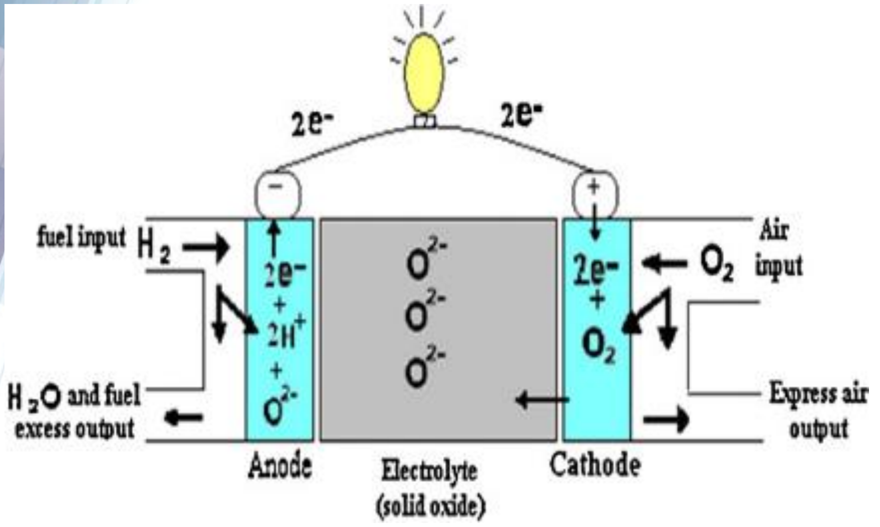
- The Phosphoric acid fuel cells (PAFC) are so named because concentrated phosphoric acid is used as electrolyte in the fuel cells. This is because the relative stability of phosphoric acid is higher than the other acid. Such fuel cells are operated at high temperature such as 150˚C - 200˚C .
- phosphoric acid as electrolyte
- 40 – 80% efficiency
- 150˚C - 200˚C operating temp.
- Platinum as catalyst

(Bagotsky, Vladimir S. *Fuel Cells: Problems and Solutions, Second Edition,* 2012: 99-106.)

- PAFC does not involve pure oxygen for its operation since carbon dioxide does not affect the electrolyte or cell performance.
- H_3PO_4 has long term stability.
- PAFCs are widely used to generate the power with capacity upto 200 KW and systems with higher capacities (11 MW).
- PAFCs are not cheaper because platinum is used as the catalyst that is very expensive.

(Bagotsky, Vladimir S. *Fuel Cells: Problems and Solutions, Second Edition,* 2012: 99-106.)

4. Solid Oxide Fuel Cell (SOFC)



Oxidation – (½) O_2 (g) + $2e^-$ → O^{2-} (s)

Reduction- O^{2-} (s) + H_2 (g) → H_2O (g) + $2e^-$

- SOFCs are operated at very high temperatures such as 600- 1000˚C. Typically, a solid non-porous metal oxide is used as an electrolyte. Co-Ni-ZrO2 or ZrO2 is used as the anode and Sr doped perovskites LaMnO2 is used as the cathode.
- Yttria stabilized zirconia (YSZ) (zirconium dioxide + yttrium oxide) is most commonly used electrolyte
- ~60% efficient
- ~1000˚C operating temp.
- output from 100 kW-200 MW

(Stambouli and A. Boudghene. *Renewable and Sustainable Energy Reviews*, 2002, 6, 433–455.

- SOFCs are *in vogue* with large scale distributed power generation systems with capacity of hundreds of MWs.

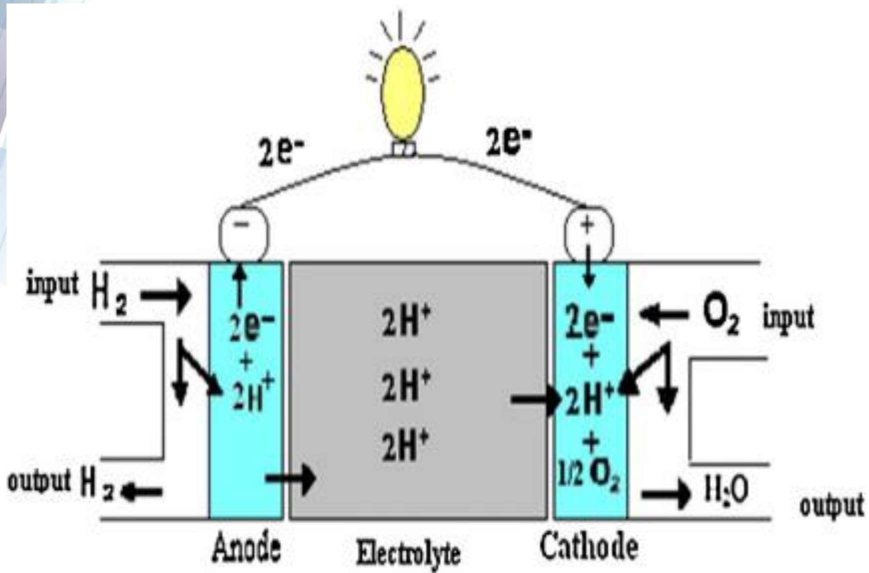
- They are widely used in rural areas and are usually economic as the cost of the materials used in such cells is very low as compared to other fuel cells

- SOFCs do not make any noise while on operation and have low maintenance costs.

- Long start-up time and long times to cool down the system limit the use of SOFCs.

(Stambouli and A. Boudghene. *Renewable and Sustainable Energy Reviews*, 2002, 6: 433–455)

5. Proton Exchange Membrane Fuel Cell (PEMFC)



Oxidation: $2H_2 \longrightarrow 4\ H^+ + 4\ e^-$

Reduction : $O_2 + 4\ e^- + 4\ H^+ \longrightarrow H_2O$

- In PEMFCs, a proton permeable membrane is used between the anode and the cathode. At the anode, hydrogen is converted into electrons and protons. The electrons are transferred to the cathode via an external circuit while protons are passed through the membrane to the cathode. The electrons and protons combine with oxygen at the cathode to produce water.
- Proton permeable polymer sheet e.g., Nafion membrane
- 40 – 50% efficiency
- 50 – 250 kW
- 80˚C operating temperature

(Ralph, T. R. *Platinum metals review* ,1997, 41: 102-112)

- The operating temperature for such fuel cells is comparatively lower than other fuels cells that allows rapid start-up of the fuel cells.

- A higher power density can be achieved in such fuel cells.

- PEMFCs are usually used in fuel cell vehicles (FCV).

- PEFC cells are relatively sensitive to the contamination of CO, sulfur and ammonia.

(Ralph, T. R. *Platinum metals review* ,1997, 41: 102-112)

Microbial fuel cells (MFCs)

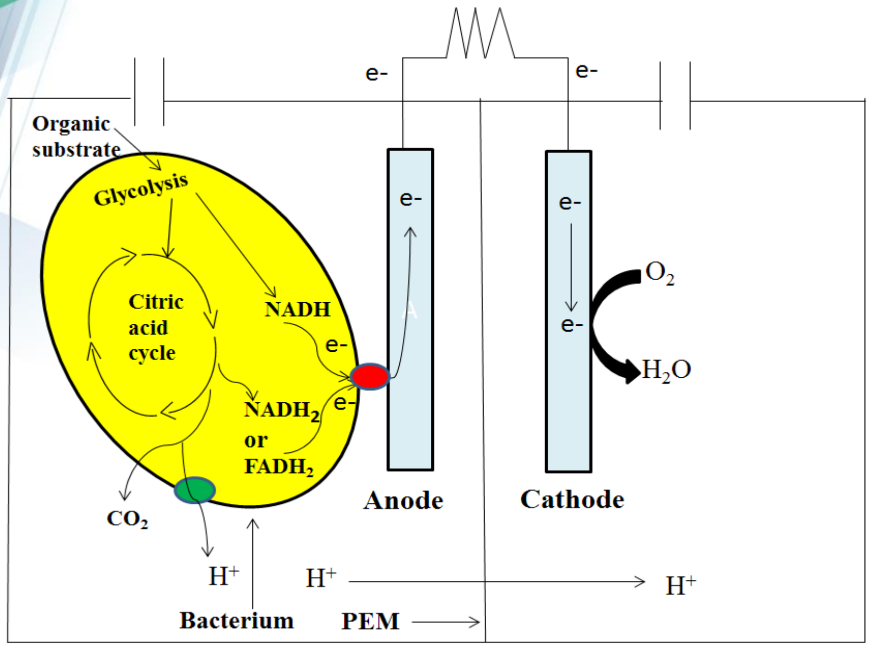


Fig. General principle of a double chamber MFC

- A **microbial fuel cell** (**MFC**) is a kind of fuel cell. Bacteria or microbes are used in the MFCs, this is because are so called. The bacteria oxidizes the substrates at the anode into electrons, protons and carbon dioxide. Anode and cathode are made up of metal or non metal electrodes. A proton or an ion exchange membrane is used.

Anode Reaction

$C_{12}H_{22}O_{11} + 13H_2O \text{ ---> } 12CO_2 + 48H^+ + 48e^-$

Cathode Reaction:

$4H^+ + O_2 + 4e^- \rightarrow 2H_2O$

(Logan, Bruce E. *Microbial fuel cells*. John Wiley & Sons, 2008.)

- MFCs, in future can replace the wastewater treatment plants for electricity generation .
- Any organic or inorganic wastewater can be used for electricity generation.
- The power outputs are vey low.
- The chief applications of MFCs are:
    - Electricity generation
    - Wastewater treatment
    - Bioremediation of heavy metals
    - Biosensors
    - Biohydrogen production

(Logan, Bruce E. *Microbial fuel cells*. John Wiley & Sons, 2008.)

• Applications of fuel cells

• Automotive Industry

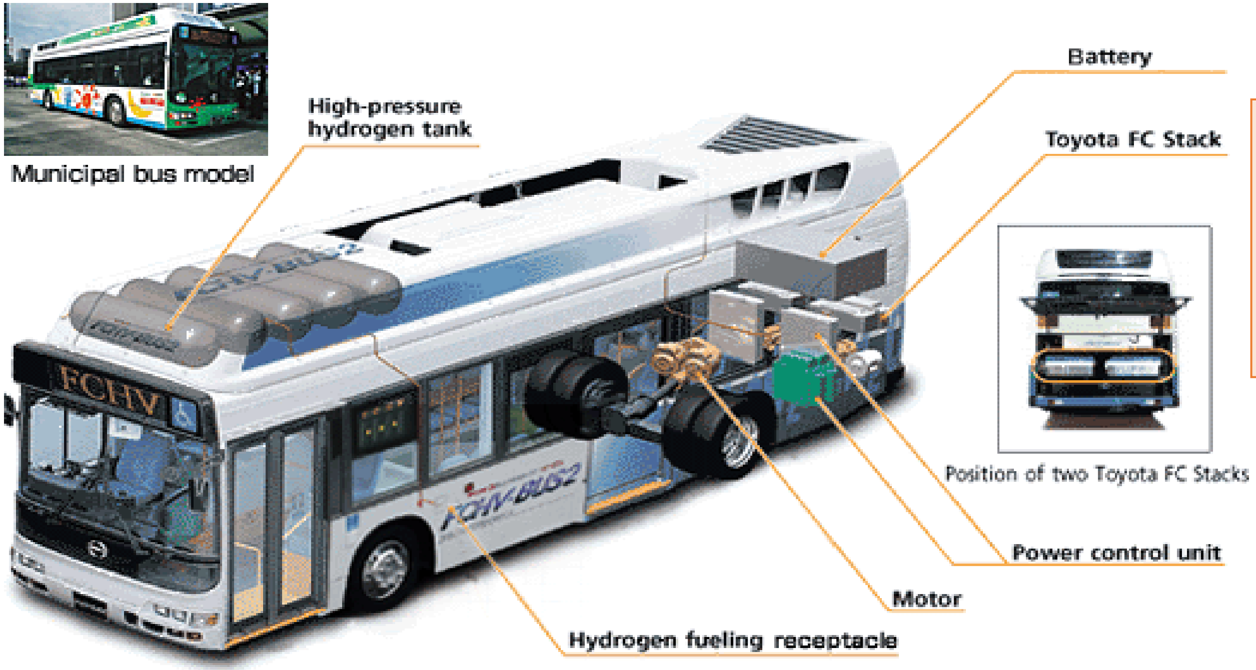
- Most of the major auto manufacturers have fuel cell vehicle (FCV) projects currently under way, which involve all sorts of fuel cells and hybrid combinations of conventional combustion, fuel reformers and battery power.

- Considered to be the first gasoline powered fuel cell vehicle by General Motors (GM):

- GMC S-10 (2001)
fuel cell battery hybrid
low sulfur gasoline fuel
-40 mpg
-112 km/h top speed

(Pettit, William Henry. "Fuel cell system with combustor-heated reformer." U.S. Patent No. 6,077,620. 20 Jun. 2000.)

Mercedes-Benz: Citaro fuel cell bus on the streets of London. Engine supplied by Ballard.



Toyota: The FCHV-BUS2 is a fuel-cell hybrid bus.

.

(National Fuel Cell Bus Program Awards. Calstart, October 31, 2012)

- **Fuel cells for portable power**

Casio: World's smallest fuel cell for use in laptop PC..

Samsung Electronics:

(Dyer, Christopher K. "Fuel cells for portable applications." *J. Power Sources* 2002, 106: 31-34.)

- **Fuel cells for stationary power**

UTC Fuel Cells: 200kW of electricity.

UTC (United technologies Corporation) Fuel Cells:.

(Singhal and Subhash C. *Solid State Ionics* 2002, 152: 405-410.)

• Advantages of fuel cells

- The prominent advantage of the fuel cells is that they do not cause pollution, as the end product of the electrochemical reaction in fuel cells is water.
- The other advantage of fuel cells is, they can be operated continuously for a long time as the fuel can be continuously added for electricity generation.
- The fuel cells can provide high power densities as well as have a higher efficiency than diesel or gas engines.
- Most of the fuel cells do not cause noise pollution as they operated silently.
- The maintenance cost of the fuel cells is lower than the conventional engines.
- The fuel cells can be used in the vehicles that can reduce the air pollution and can help to keep the environment more clean and reduce the climate change.

• Disadvantages of fuel cells

- Some materials used in fuel cells are very expensive that make the fuel cells less economic.
- The fuel are comparatively larger in size than the batteries, therefore are inconvenient for transportation.
- The refuelling of the fuel and the start time in fuel cells are longer.
- The electrolytes used in the fuel cells may react with some gases like carbon dioxide and carbon monoxide, which consequently can poison the fuel cell.

Thank You