Chapter 18
Fuel Cell Technology: The Future Ahead

Arpan Tewary and Chandan Upadhyay

Abstract Fuel cells are one of the most promising, clean and highly efficient sources for energy production. They have tremendous potential to deliver sustainable energy to satisfy human energy needs for a longer period of time. Since their invention, a lot of innovative progress has taken place over the years in terms of capacity building, improved efficiency, better design, niche engineering, portability, cost-effectiveness, etc. Fuel cells have the required potential to resolve issues like climate change, global warming and energy insecurity/shortage. This will help us to live sustainably and hand over a sustainable future to our upcoming generations. In the case of fuel cells, the basic principle is that a continuous feed of hydrogen and oxygen is required to run a pair of redox reactions which ultimately results in power generation. The major output is power and the by-product is pure water. Fuel cells are classified into several types based on the electrolyte they use, their operating temperature, etc. In this chapter, we shall comprehensively discuss the theory behind the fuel cell, its working principle, different types of fuel cells and their major components, their working procedure, loss-making factors and the major applications of fuel cells in various domains.

Keywords Fuel cells · Energy insecurity · Sustainable future · Niche engineering · Redox reactions · Power generation

18.1 Introduction

The global environment is currently facing very typical and stiff challenges in the form of climate change and global warming. This could be easily felt because of the frequent occurrence of natural disasters around us along with issues like health hazards (chronic respiratory diseases and lung cancer), etc. With the continuous surge

---

A. Tewary (✉) · C. Upadhyay (✉)
Department of Sciences and Humanities, Rajiv Gandhi Institute of Petroleum Technology
(An Institution of National Importance), Jais, Amethi, Uttar Pradesh, India

D. K. Ashish, J. de Brito (eds.), *Environmental Concerns and Remediation*,
https://doi.org/10.1007/978-3-031-05984-1_18

in human development, ruthless exploitation of natural resources has brought us to the brink of self-destruction. Therefore, mankind has realized the importance of reducing its dependence on fossil fuels and satisfying its own energy needs from clean and renewable energy resources. The fuel cell is one such clean and renewable energy resource.

Fuel cells are basically defined as an electrochemical energy conversion device capable to convert chemical energy into electrical energy following the simple principle of a pair of redox reactions. The most attractive feature of this device is that it emits the least emission and hence is considered to be an eco-friendly energy source. As we are targeting a carbon-neutral economy both nationally and internationally, fuel cells are definitely going to play a major role in this global transformation by acting as a major workhorse of this process and beyond.

Previously, British scientists Nicholson and Carlisle, in 1800, had described the process of decomposing water into hydrogen and oxygen using electricity. But Grove's idea to combine the gases for producing electricity and water was indeed an unprecedented innovation. Grove also realized that a series combination of several sets of these electrodes might also have some noticeable effect. He soon made his idea realistic and named the device a "gas battery" also called the world's first fuel cell. The invention of the fuel cell is therefore credited to Sir William Grove, a Welsh lawyer turned scientist who invented this device in 1838 using a combination of iron sheet, porcelain plates, copper, dilute acid and a solution of copper sulphate. He is known as a pioneer in fuel cell technology and also the developer of Grove voltaic cell. After this revolutionary innovation, in the 1880s, laboratories in Europe and the United States started to design workable gas batteries. Grove's gas battery came to be initially called a "fuel battery" and later on came to be known as "fuel cell". Many more research initiatives were taken by several other scientists worldwide like Ludwig Mond, Charles Wright, C. Thompson, W.W. Jacques and Emil Baur, to name a few, in this area, and each of them developed their own fuel cells with different characteristics. But finally, a major breakthrough was achieved in the year 1932 when British scientist Francis Thomas Bacon developed the world's first commercial H_2–O_2 (hydrogen-oxygen) fuel cell. After the commercialization of fuel cells, the area opened up very rapidly, and finally, after a few years, the space agencies started to use them for their space missions. US-based space agency NASA successfully used this technology in their Apollo moon mission followed by some other countries.

18.1.1 Basic Needs of Fuel Cells

Fossil fuel-based energy resources are non-renewable in nature and hence not reliable:

- Global climate concerns and global warming
- Increasing energy needs may create energy insecurity in the future

- Eco-friendly energy source with no noise pollution
- Considered to be a promising and futuristic technology with high efficiency and increased longevity and could be cost-effective in the future.

18.2 The Theory Behind Fuel Cells

Fuel cells, as explained previously, are electrochemical energy conversion devices capable of effectively converting chemical energy in the form of hydrogen (as fuel) and air/O2 (as an oxidant) into electricity as the primary product and water as a by-product. A pair of redox reactions occurs constantly within the system for the fuel cells to run continuously. Therefore, an uninterrupted supply of fuel and oxidants should be maintained for successful power generation (Fig. 18.1).

18.2.1 Electrochemical Reactions

Cathode: $4H^{+} + O_2 + 4e^{-} \rightarrow 2H_2O$
Anode: $2H_2 \rightarrow 4H^{+} + 4e^{-}$

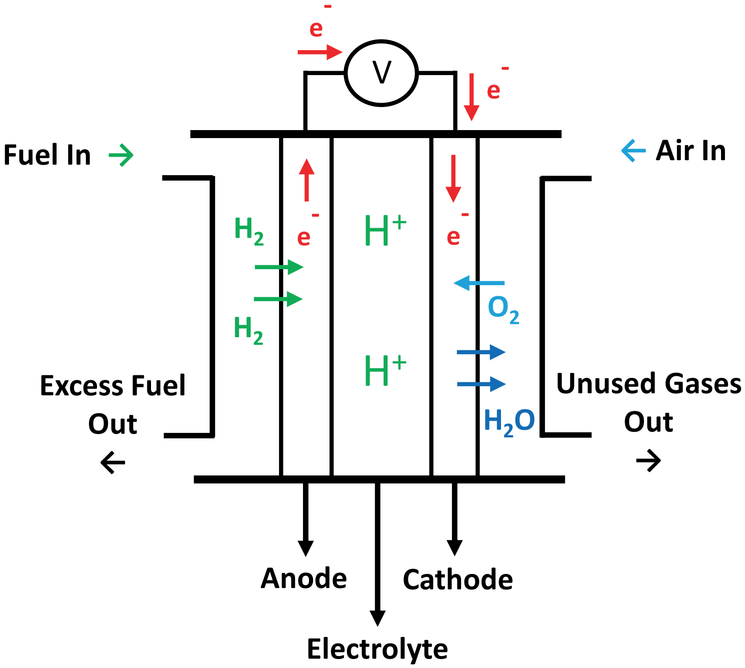

Fig. 18.1 Schematic diagram of a simple fuel cell

Overall: $O_2 + 2H_2 \rightarrow 2H_2O$

Fuel cells are built with the main motive or objective of producing sustainable power for specific as well as common use. Chemical reactions involved in the functioning of a fuel cell determine the amount of power produced from the cell. Every fuel cell works in its own manner keeping the basic principle of operation the same. Generally, in fuel cells, the reactant, for example, hydrogen, when enters the cell at the anode gets oxidized; therefore, its electrons are detached from the atoms.

Due to the loss of electrons, the hydrogen atoms become ionized thereby carrying positive charges. On the other hand, when oxidant, for example, oxygen, which enters through the cathode gets reduced, it gets attached to the electrons coming into the cathode through the external circuit. The hydrogen ions coming through the electrolyte now combine with reduced oxygen to form water. In some other types of fuel cells, the oxygen picks up electrons at the cathode, after which it travels through the electrolyte medium to the anode, where hydrogen ions combine with it and form water as the by-product.

Electrolyte plays a very vital role in the charge transfer process during fuel cell operation. It should be highly selective in nature for only allowing the passage of selective ions between the cathode and the anode as the movement of other things can badly affect the chemical reactions and retard them causing a drop in fuel cell performance. The combination of hydrogen and oxygen wherever takes place whether at the cathode or at the anode always leads to the formation of water which is a by-product during fuel cell operation. A fuel cell will continue to generate energy as long as it is provided with hydrogen and oxygen on demand. Many fuel cells are serially stacked in series to increase power production, but the principle of operation remains the same.

Each type of fuel cell has its own advantages and disadvantages. In the case of an alkaline fuel cell where the advantage lies in the use of nonprecious metal catalysts, the drawback is that Alkaline Fuel Cells (AFCs) often suffer from problems like electrolyte degradation and liquid electrolyte management. In the case of molten carbonate fuel cells, we see that they can easily tolerate high carbon monoxide (CO) concentrations, but the problem lies with the electrolyte which is molten and corrosive in nature; moreover, the cell components are also very expensive.

Scientific inventions always have both boons (advantages) and banes (disadvantages) associated with them; similarly, fuel cells, which are also a scientific innovation, are not an exception.

18.2.1.1 Advantages of a Fuel Cell

A. Fuel cells deliver least toxic gaseous emissions; hence, they are considered to be eco-friendly in nature.
B. They are small sized and hence portable in nature; therefore, they can be carried to far-flung places where conventional power supply is hard to reach.

C. The by-product of a fuel cell is pure water which can be used for several other purposes.
D. Fuel cells operate very silently; hence, they do not produce any noise pollution.
E. Fuel cells have very high efficiency; hence, they are much better than several other energy resources.

18.2.1.2 Disadvantages of a Fuel Cell

A. Ensuring continuous availability of hydrogen (fuel) and oxygen (oxidant) to run the fuel cell is a major concern.
B. Production and storage of hydrogen to run the fuel cell are also tough.
C. Several fuel cell types are still under research; hence, many of them are not yet completely commercialized for common/industrial use.
D. Fuel cells are still not cost-effective; hence, they could hardly compete with other energy resources.
E. There is still a huge lack of awareness regarding this energy resource; hence, it is not so popular among the masses.
F. Lack of proper government policies is also responsible for the slow absorption of this technology in our society.

From Fig. 18.2, on a volumetric power density scale, energy technologies such as combustion engines and batteries easily outclass fuel cells, but on a gravimetric power density scale, hydrogen is in a close race with them.

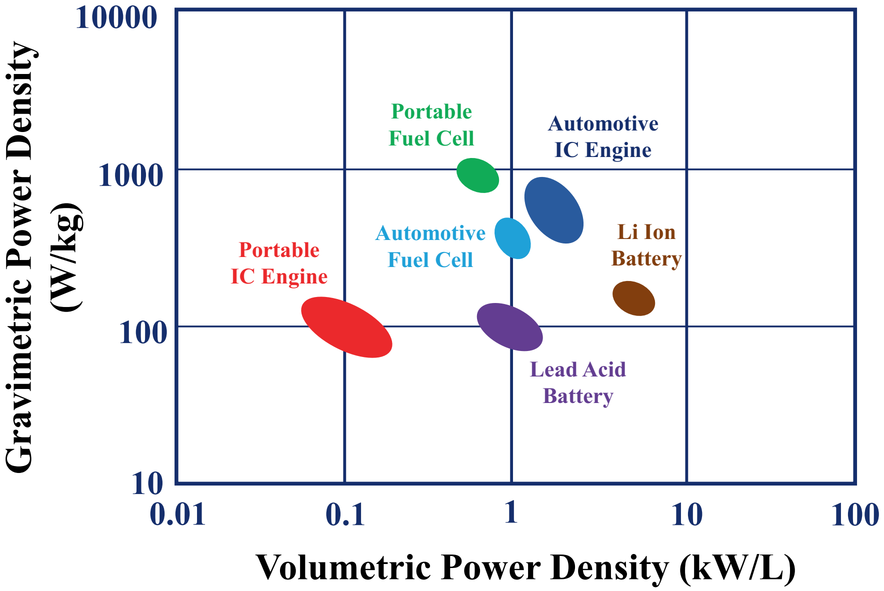

Fig. 18.2 Power density of hydrogen compared with some other energy sources

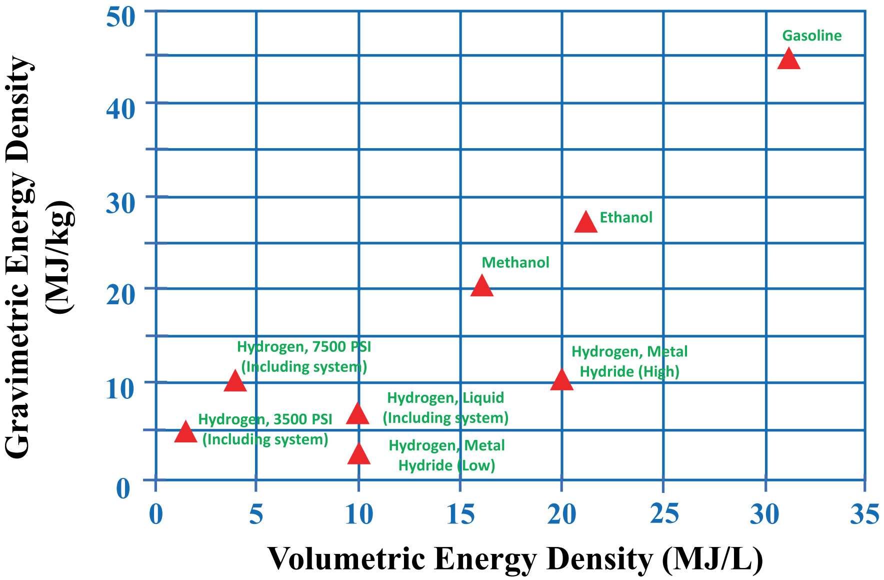

Fig. 18.3 Energy density of hydrogen compared with some other fuels

From Fig. 18.3, we can infer that hydrogen which is the most suitable fuel for running the fuel cells is not easily available due to issues in large-scale production and storage; it also has a low volumetric energy density in comparison to other fuels such as methanol, ethanol and gasoline, which adds to its disadvantage.

18.2.2 Major Components of a Fuel Cell

A fuel cell has several components that function coordinately with each other to perform the entire process of power generation. To name a few are anode, cathode and electrolyte, which play a very major and decisive role in the functioning of a fuel cell. We shall briefly deal with them one by one.

18.2.2.1 Electrolyte in Fuel Cell

Electrolytes play the role of a central character in the functioning of a fuel cell. It acts as the charge transfer medium in a fuel cell. Therefore, the best suitable electrolyte is always preferred. Different kinds of fuel cells have specific types of electrolytes (to be specifically described in Sect. 18.4) to suit the desired purpose. The choice of an electrolyte is based on operating voltage and power requirement. For fuel cells, there are three main types of electrolyte materials:

(a) Aqueous electrolytes
(b) Ceramic electrolytes
(c) Polymer electrolytes

The following characteristics are considered to be good enough for an ideal electrolyte:

- Ionic conductivity should be higher.
- Electronic conductivity should be lower.
- Stability should be high in case of both oxidizing and reducing environments.
- Fuel crossover should be low.
- Appreciable mechanical strength.
- Easy manufacturing.

The electrodes have to possess the following properties to ensure a smooth operation of the fuel cell:

- Electrical conductivity should be high.
- Catalytic activity should be high.
- Surface area should be high.
- Electrolyte compatibility.

18.2.2.2 Cathode in Fuel Cell

It is an important part of the fuel cell. During electrochemical reactions, reduction of chemical species occurs here. The cathode in a fuel cell has to withstand a harsh oxidizing environment; therefore, materials for cathode should be chosen carefully keeping in mind the following properties of an ideal cathodic material for a fuel cell. The oxygen reduction reaction (ORR) occurs here.

The following characteristics are considered to be good enough for an ideal cathode:

- Higher electronic conductivity
- Appreciable thermodynamic stability
- Sufficient porosity
- Electrocatalytic activity that should be high for favouring the oxygen reduction reaction (ORR)
- Chemically stable therefore less prone to corrosion
- Thermally stable and efficient
- Machinable into thin sheets for fuel cell stacking
- Excellent contact properties with both the electrolyte and the current collector

18.2.2.3 Anode in Fuel Cell

The anode is also an important part of the fuel cell. However, unlike cathode, oxidation of chemical species occurs here during electrochemical reactions. The anode in a fuel cell shall also be chosen conscientiously keeping in mind the following properties of an ideal anodic material for a fuel cell. Here, the hydrogen oxidation reaction (HOR) takes place.

The following characteristics are considered to be good enough for an ideal anode:

- Large surface area of the triple phase boundary (TPB)
- Prominent porous microstructure
- Better chemical stability
- Higher order of electronic conductivity
- Higher electrocatalytic activity to facilitate the hydrogen oxidation reaction (HOR)
- Thermally stable and efficient

18.3 Principle of Working

Fuel cells are electrochemical devices; hence, they follow a series of steps one after another for completing the entire process for power generation in a fuel cell.

The steps are listed below:

Step 1) Reactant delivery
Step 2) Electrochemical reactions
Step 3) Both electronic and ionic conductions taking place through the external circuit and electrolyte, respectively
Step 4) Product removal (Fig. 18.4)

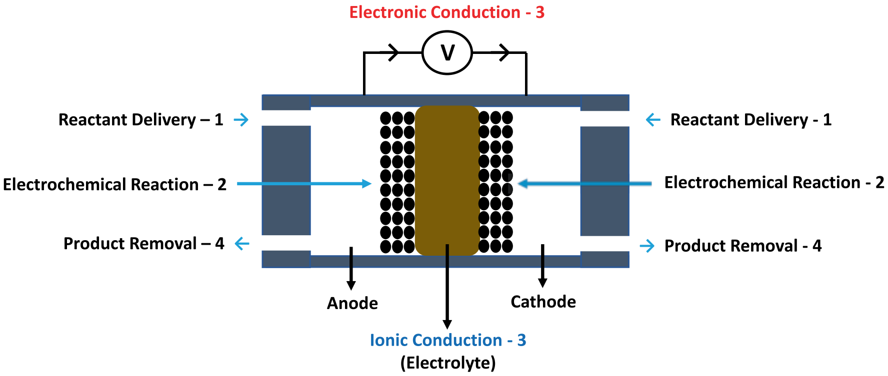

Fig. 18.4 Step-by-step process of an electrochemical reaction within a fuel cell

18.3.1 Step 1: Reactant Delivery

This is the very first step involved in the functioning of a fuel cell. For continual power generation, a fuel cell needs a constant supply of hydrogen (fuel) and oxygen (oxidant). With increased output current, the reactant supply must be ramped up. But there are a few things that make this simple-looking step quite complicated to handle. The interruption or undue reduction in the supply of reactants to the fuel cell in running conditions reduces its performance rapidly; this is quite undesired and may be injurious to the life of the fuel cell. On the other hand, the production and storage of a huge quantity of hydrogen to maintain a smooth supply are also a big task if not herculean because both are still a big issue. The channels which supply the reactants to the fuel cell are highly responsible for the cell performance. Flow field plates, which have multiple channels and grooves for effective distribution of reactants at reaction sites in the fuel cell where the reaction is more facilitated, are generally selected to ensure a smooth supply (uniform rate) of reactant delivery. A lot of research is being carried out worldwide to develop better flow channels so that reactant delivery can be effectively assured to enhance fuel cell performance. Researchers globally are therefore tirelessly working on the development of very specific state-of-the art design, size, shape and patterns of flow channels to enhance cell performance for general as well as specific use at different environmental conditions of temperature and pressure. Development of materials is keeping in view the optimized electrical, thermal, mechanical and corrosion properties to achieve the desired performance. A lot of research is also taking place to clearly understand the fluid mechanics, flow behaviour, material property and porous electrode geometry in a fuel cell to get a deeper insight into its performance and then design the future products accordingly.

18.3.2 Step 2: Electrochemical Reactions

This is considered to be the central step in the power generation process. The first step facilitates the second step (electrochemical reactions). The output in terms of the current of a fuel cell is highly dependent on how fast the electrochemical reactions are proceeding within the cell. This step is largely dependent on factors like the rate of reactant supply and the flow of reactants through the channels/grooves as they determine the effective distribution of the reactant on the reaction surface where the reaction is actually taking place. Therefore, the designing of flow channels shall be done advertently. Now, the output is completely dependent on how fast the electrochemical reactions occur on the surface. Reaction kinetics of electrochemical reactions largely influence the fuel cell performance. Hence, catalysts are often employed to ensure better reaction kinetics and faster reactions to boost the fuel cell performance in terms of higher current output and better efficiency. Therefore, it is always wise enough to choose a catalyst that could serve the desired purpose.

18.3.3 Step 3: Ionic and Electronic Conduction

This is a very important step involved during fuel cell operation and impacts cell performance significantly. This step involves the transfer of charges that takes place during various electrochemical reactions which occur within the fuel cell. In electrochemical reactions, ions and electrons are produced in one electrode and they get consumed in the other electrode. This phenomenon of generation and consumption of ions and electrons takes place to maintain the necessary charge balance in an electrochemical reaction, and this charge transfer takes place through a proper pathway. Although electrons are allowed to flow through a specialized external circuit, giving power output from the cell, ions require a medium to go through. Therefore, the flow of electrons between the two electrodes is quite easy through an electrically conductive medium, but in the case of ions that are bigger in size, movement is a bit difficult. Therefore, a conductive medium is needed to ensure the hopping mechanism (in most cases) that is often opted by ions for a safe passage through the electrolyte. The transfer of electrons is quite faster in comparison to that of the ions because as already said they are bigger in size and higher in mass and therefore follow the hopping mechanism. This process of ionic charge transfer is very crucial and plays a very vital role in fuel cell performance as the sluggish movement of ions will delay chemical reactions leading to lower power output and fuel wastage. Therefore, it is always wise to choose thin and conductive electrolytes accordingly so that they can best facilitate faster ion transfer and better electrode boosting cell performance.

18.3.4 Step 4: Product Removal

This is the last step of the entire process. Fuel cells not only produce electricity as their major product but also produce water as the by-product during cell operation. There should be a good mechanism to immediately remove the products from the fuel cell as soon as they are produced to prevent any kind of hindrance and water stagnation/flooding within or outside the cell which can possibly cause a reduction in cell performance. Factors like the rate of product removal, the technique involved, the concepts of fluid mechanics, etc., which were considered during fuel delivery, cannot be ignored during product removal as well.

18.4 Power Generation and Performance of a Fuel Cell

The power density curve of a fuel cell depicts the power density of a fuel cell as a function of the same fuel cell's current density. To generate this curve, just multiply the voltage by the appropriate current density at each point on the I–V curve. The power density of a fuel cell reaches a maximum with rising current density levels and then gradually decreases at even greater current density levels. As a result, most fuel cells are deliberately constructed to operate at or below their maximum power density. When fuel cells run at current densities below their optimum power density, both voltage efficiency and power density decrease. Many fuel cells are serially stacked together in series for a variety of practical applications that require larger power output to run various systems. The power produced is added together, resulting in the generation of a large amount of electricity to fulfil the intended purpose. However, it is quite unfortunate that there still exist a few problems like series resistance, un-uniform stacking, etc. while stacking these fuel cells; all together they possibly limit the fuel cell performance to some or higher extent. Therefore, it is always advised to take utmost precautions and follow the standard practices while stacking the fuel cells in series to prevent any undesired power loss during cell operation (Fig. 18.5).

18.5 Losses in Fuel Cells

In fuel cells, all types of losses are connected to power production, either directly or indirectly. As we try to draw more current from the fuel cell, losses increase. As the current drawing increases, cell voltage starts dropping from the open-circuit voltage (OCV). In case of a condition where there will be no losses, the cell voltage would remain the same as the theoretical voltage keeping it independent of the cell current. The formula below can be used to calculate the ideal cell voltage (E_{rev}) of a fuel cell:

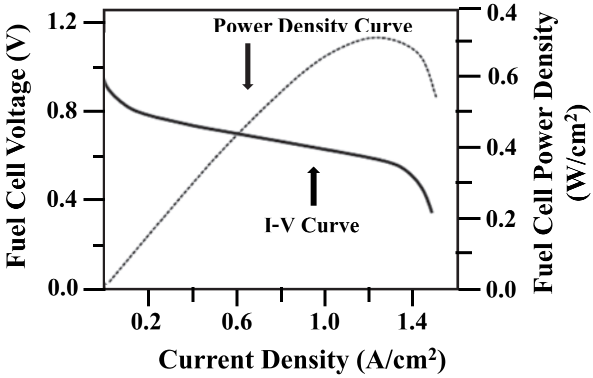

Fig. 18.5 Power density curve in a fuel cell

$$E_{\text{rev}} = -\frac{\Delta G}{nF}$$

where

"G" represents Gibbs free energy
"n" represents the number of electrons transported during the electrochemical process
"F" represents the Faraday constant (94685 C/mole)

For expressing cell efficiency, we use the formula:

$$\eta = \frac{E_{\text{Cell}}}{E_{\text{Rev}}}$$

There are a few specific and major types of losses in fuel cells which are mentioned below:

1. Fuel crossover and internal current losses
2. Activation losses
3. Ohmic losses
4. Mass transport losses (Fig. 18.6)

18.5.1 Fuel Crossover and Internal Current Losses

These kinds of losses arise due to the flow of electric current and fuel in the electrolyte. The electrolyte is only supposed to transport ions, but somehow fuel and electron flow also occurs. But undesirably, even though the internal current is small and

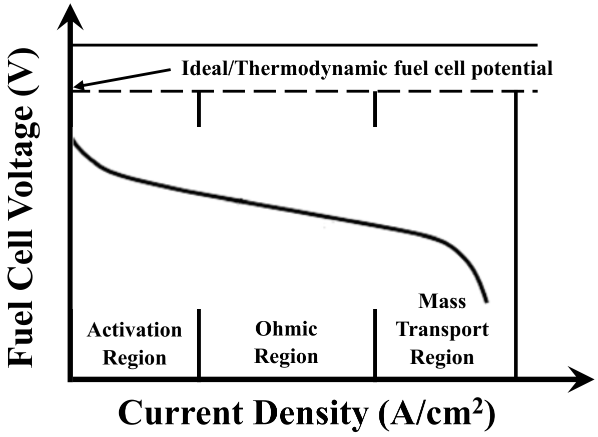

Fig. 18.6 Losses in a fuel cell

the loss of fuel is also less, they are still mainly responsible for the lower value of OCV in comparison to the E_{rev}.

18.5.2 *Activation Losses*

It may be described as the smallest amount of voltage required to overcome an electrochemical reaction's activation energy and then allow the process to proceed. Such losses are attributed to the slow speed of the reactions taking place on electrode surfaces. Such losses occur at low current densities. The reaction kinetics of electrochemical reactions are also considered responsible for the reduction in voltage. Therefore, a catalyst is used to reduce the activation barrier and quickly start the electrochemical reactions. "Activation losses" have a major impact on the first part of an I–V curve.

The mathematical expressions for activation overpotential can be obtained easily from the Butler-Volmer equation. It can be expressed as

$$\Delta V_{\text{act}} = E_r - E = \frac{RT}{\alpha F} \ln\left(\frac{i}{i_0}\right)$$

where

"i_0" stands for the reaction exchange current density
"i" is the current density

The reaction rate is represented by the exchange current density.

Tafel equation can also express activation losses through the formula as mentioned below:

$$V_{\text{act}} = -\mathrm{b} * \log\left(\frac{i}{i_0}\right) \text{ where } b = \frac{R * T_K}{2 * \alpha * F}$$

where

"α" stands for transfer coefficient
"i_0" stands for exchange current density
"F" stands for Faraday's constant (Coulombs) = 96487
$R = 8.314$ for ideal gas constant (J/molK)
"K" stands for temperature in degree Kelvin

18.5.3 *Ohmic Losses*

In the case of materials that are conductive in nature showing an intrinsic charge flow resistance behaviour resulting in cell voltage loss, this phenomenon is called "ohmic polarization". The contribution to this ohmic losses comes mainly from the *electrolyte*, *catalyst*, *bipolar plates*, *gas diffusion layer*, connections in the terminals, contacts in the interface, etc. Voltage reduction in a fuel cell is largely due to internal ohmic resistances causing "ohmic losses", which includes contributions from both the electronic (R_{elec}) and ionic (R_{ionic}) to the total fuel cell resistance. This type of loss is wholly credited to the sluggish movement of ions and electrons in the electrolyte and through the external circuit/cell junctions, etc., respectively. Here, it is worth noticing that the voltage drop (V) proportionally corresponds to the current density (A/cm^2). Since the free movement of ions and electrons is anyhow hindered due to several factors as already stated creating unwanted resistance which finally results in output voltage drop, it is referred to as "ohmic losses". The following expression helps us to calculate ohmic losses:

$$v_{\text{ohmic}} = i\left(R_{\text{elec}} + R_{\text{ionic}}\right)$$

During an electrochemical reaction, R_{ionic} dominates when ionic transport is more difficult than electronic charge transport. R_{ionic} stands for ionic resistance of the electrolyte, and R_{elec} stands for the electrical resistance of contacts, bipolar plates and cell interconnections including any other cell components. In an I–V curve, "ohmic losses" significantly affect the middle section of the curve.

18.5.4 Mass Transport Losses

Basically, the name itself is quite good enough to speak about this kind of loss. Such kinds of losses occur due to the irregular supply of reactants at the reaction sites specifically on the electrode surface. This irregular supply can be due to the intermittent supply of reactants to the fuel cell or due to the presence of improper flow channels which restrict proper reactant delivery to the electrode surface. At the point when the fuel cell is producing maximum power, the reactants start to react as soon as they are released on the electrode surface; in that case, nothing is left behind. When a proper supply of reactant is not available to the electrode surface reaction, sites go vacant resulting in a decrease in the fuel cell efficiency, thereby undesirably producing less power. To achieve optimal fuel cell efficiency, a fuel cell must be continuously supplied with fuel and oxidant to produce electricity, while simultaneously removing the by-product, which is primarily water. The performance of a fuel cell is determined by the concentration of both reactant and product within the catalyst layer. We usually aim to improve mass transport in the electrodes and flow structures of a fuel cell to reduce concentration losses. At the tail end of an I–V curve, "concentration losses" have a major impact.

The mass transport loss in a fuel cell may be calculated using the following formula:

$$v_{\text{conc}} = c \ln\left(\frac{i_L}{i_L - i}\right)$$

where

“c” is a constant which can be further approximately expressed as

$$c = \frac{RT}{\alpha F}\left(1 + \frac{1}{\alpha}\right)$$

Significant concentration loss limits fuel cell performance.

The following equation may be used to represent the real voltage output of a fuel cell:

$$V = E_{\text{thermo}} - \eta_{\text{act}} - \eta_{\text{ohmic}} - \eta_{\text{conc}}$$

where

“V” stands for real output voltage of fuel cell
“E_{thermo}” denotes thermodynamically predicted fuel cell voltage output
“η_{act}” stands for activation losses due to reaction kinetics
“η_{conc}” stands for concentration losses due to mass transport
“η_{ohmic}” stands for ohmic losses from ionic and electronic conduction

18.6 Fuel Cell Efficiency

In the most lucid manner, efficiency for a device, system, etc. can be defined as the amount of input/total energy that can be successfully converted into output/useful energy. In other words, it is the ratio between useful energy and the total energy. It is often expressed in terms of percent:

$$\varepsilon = \frac{\text{Useful Energy}}{\text{Total Energy}}$$

Efficiency plays a very vital role in determining and measuring the performance of any device. The same thing is similarly applicable to the fuel cells as well. In the case of fuel cells, we generally talk about the two major kinds of cell efficiency. One is ideal/reversible fuel cell efficiency and the other is real or practical fuel cell efficiency. The real cell efficiency is always less than the ideal cell efficiency due to several unavoidable losses which occur during cell operation. Moreover, it is also worth mentioning that the ideal cell efficiency is not 100%; this limitation is attributed to the value of ΔG which is at par with fuel cell thermodynamics stating that

ΔG limits the amount of electrical work that could be made available from a fuel cell.

18.6.1 Ideal/Reversible Fuel Cell Efficiency

Ideal/reversible cell efficiency is expressed as

$$\varepsilon_{\mathbf{thermo}} = \frac{\Delta g}{\Delta h}$$

where

"Δg" is a change in Gibbs free energy
"Δh" is a change in enthalpy

18.6.2 Real/Practical Fuel Cell Efficiency

Real/practical cell efficiency is expressed as

$$\varepsilon = \left(\varepsilon_{\text{thermo}}\right) \times \left(\varepsilon_{\text{voltage}}\right) \times \left(\varepsilon_{\text{fuel}}\right)$$

where

$\varepsilon_{\mathbf{thermo}} = \frac{\Delta g}{\Delta h}$ (reversible thermodynamic efficiency), $\varepsilon_{\mathbf{voltage}} = \frac{V}{E}$ (voltage efficiency of the fuel cell) and $\varepsilon_{\mathbf{fuel}} = \frac{i / nF}{v_{\text{fuel}}}$ (fuel utilization efficiency).

18.7 Types of Fuel Cells

Researchers globally have been carrying out tremendous research on fuel cells; therefore, new things are emerging very often. Also, it is worth mentioning that in the existing and widely known fuel cells, appreciable research and development are yielding newer facts, figures and several other core informations rapidly everyday. However, till today, a very few and specific types of fuel cells have been developed. There are many subtypes of these major fuel cells. Based on the use of electrolytes, the temperature of operation and the purpose of use, fuel cells are classified broadly into five major types which are extensively described below.

18.7.1 Low Temperature Fuel Cells

Fuel cells having low working temperatures, namely, up to 250 °C, come under this category. PEMFC, AFC and PAFC are generally the three major types of such fuel cells. They are as described below.

18.7.1.1 Polymer Electrolyte Membrane Fuel Cells (PEMFCs)

PEMFCs are a kind of fuel cell developed specifically for the purpose of transport applications. However, they are also used for other purposes like in both stationary and portable fuel cell applications. Such fuel cells have a very special proton-conducting polymer electrolyte membrane (perfluorinated acid polymer) which actually acts as the electrolyte. This kind of fuel cell can work under low temperature and pressure conditions. PEMFCs actually have a sandwich structure called the membrane electrode assemblies (MEA) which includes several components like the electrodes, electrolyte, catalyst and gas diffusion layers, all stacked together. MEA is even less than 1 mm thick. The triple-phase boundary (TPB), where the electrolyte, catalyst and reactants combine, is the most important portion of this PEMFC. This is where the actual cell reactions take place.

In recent times, researchers worldwide have used Pt-/Co-based materials for PEMFC fabrication and have achieved appreciable efficiency at low temperature conditions. There have also been several initiatives taken up to recycle the used platinum in the fuel cell, and such recovery was done with a success rate of approximately 80%. Nowadays, a research group has demonstrated “A hydrogen-storable polymer (HSP), which is a solid-state organic hydride, and may be used as the hydrogen storage media in ‘all-polymer type’ rechargeable PEMFC (RCFC)”. To produce high-power and inventive energy conversion systems, a significant amount of research effort has been dedicated towards the synthesis of Pt-based catalysts with improved performance and longevity than typical polycrystalline Pt nanoparticles. Presently, efforts are being made to boost catalysts’ intrinsic activity in the oxygen reduction reaction (ORR) process by increasing their electrochemically active surface area (ECSA) (Fig. 18.7).

Electrochemical Reactions
Cathode reaction: $2H^+ + ½O_2 + 2e^- \rightarrow H_2O$
Anode reaction: $H_2 \rightarrow 2H^+ + 2e^-$
Overall reaction: $½O_2 + H_2 + \rightarrow H_2O$

Characteristics

- Electrolyte → polymer membrane (acidic in nature)
- Charge carrier → H^+
- Temperature of operation → < 90 °C
- Efficiency → 40–50%
- Power density → 500–2500 (mW/cm^2)
- Power range → 1–20 (kW)

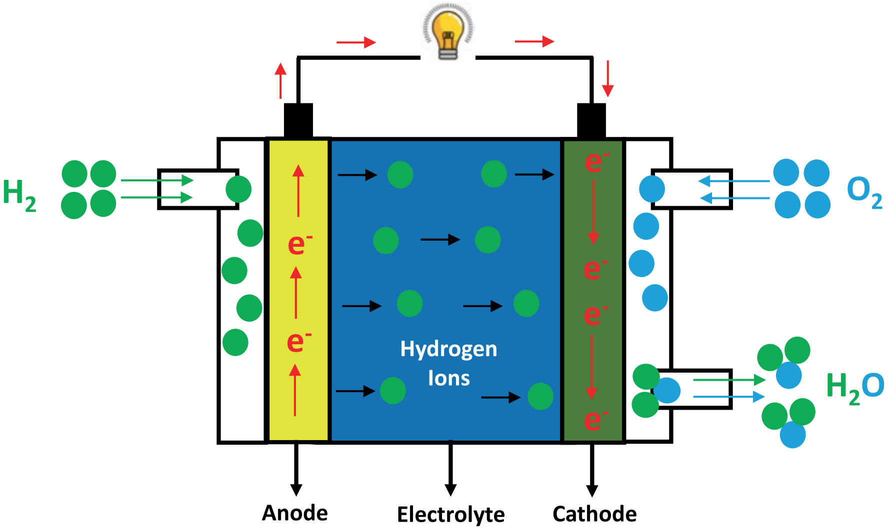

Fig. 18.7 Schematic diagram of a PEMFC

Advantages

- Among all the fuel cell classifications, PEMFCs have the highest power density.
- Portable in nature due to low temperature operation.
- Excellent start and stop capabilities.

Disadvantages

- Poor tolerance towards carbon monoxide (CO) and sulphur (S).
- Water management is an issue.
- Expensive polymer membrane and ancillary components.
- Expensive platinum catalyst is used.

Applications

- Used as a power source in light-duty transportation applications
- Prime mover for automobiles

18.7.1.2 Alkaline Fuel Cells (AFCs)

It is also referred to as the Bacon fuel cell. It is named after its inventor Francis Thomas Bacon, a British scientist. It is a fuel cell with a low operating temperature. It uses hydrogen as the fuel and pure oxygen as an oxidant to generate heat and power and potable water as major products and by-products, respectively. AFCs were the first type of fuel cells commercialized and used for space application. The detailed cell characteristics are mentioned below.

With the introduction of anion exchange membranes (AEM), the area of alkaline-based fuel cells has taken off. AEMFCs have come a long way in replacing

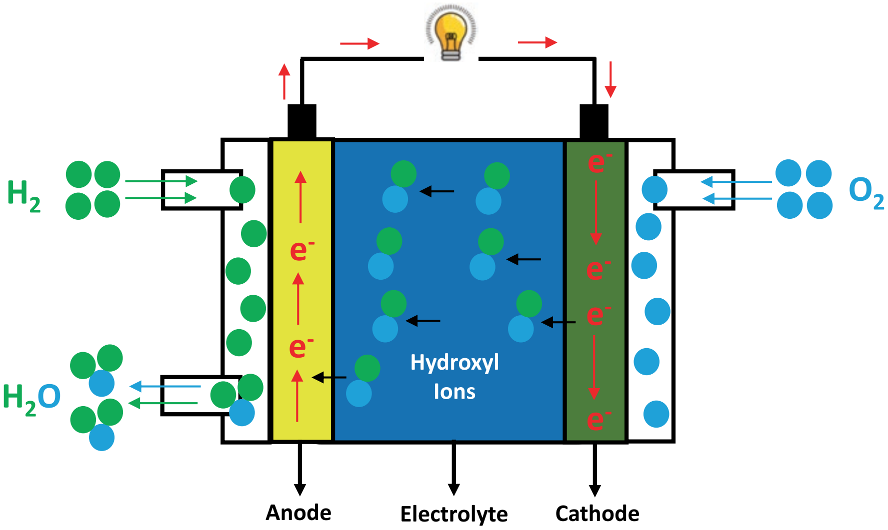

Fig. 18.8 Schematic diagram of an AFC

traditional alkaline liquid electrolyte fuel cells (AFCs). Excellent AEMFC performance is reported, although it is usually achieved through the use of platinum group metals (PGM), thus emphasizing the importance of R&D involving non-PGM materials. It is also worth mentioning that tremendous advances in polymer science have resulted in the development of highly conductive and mechanically stable AEM types, such as the Poly aryl piperidinium (PAP), High Density Polyethylene (HDPE), Poly(norbornene) PNB, etc. In another approach, we see that new anion exchange membranes based on spirobifluorene (fused ring system) without aryl ethers have been synthesized. The obtained films show high alkalinity and oxidation stability. In addition, the film is highly soluble in various organic solvents due to its helical structure (giant molecule) and is highly resistant to swelling. These materials show promise for solid ionomeric materials that could be used in both alkaline fuel cells and alkaline water electrolysers (Fig. 18.8).

Electrochemical Reactions

Cathode reaction: $H_2O + ½O_2 + 2e^- \rightarrow 2OH^-$

Anode reaction: $H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$

Overall reaction: $½O_2 + H_2 \rightarrow H_2O$

Characteristics

- Electrolyte → KOH (aqueous)
- Charge carrier → OH^-
- Temperature of operation → 60–250 °C
  (depends on the concentration of KOH in the electrolyte)
- Efficiency → 50%
- Power density → 150–400 (mW/cm^2)
- Power range → 1–100 (kW)

AFC Advantages

- Nonprecious metal catalysts can be used.
- Lower electrolyte and other material costs.
- Cathode performance is better.

AFC Disadvantages

- Mandatory use of pure $H_2 – O_2$
- Occasional replenishment of the electrolyte
- Regular removal of water from the anode

Applications

- AFCs are used in sectors like military, space, backup power and transportation.
- AFCs were first specifically developed by NASA for use in its space missions to produce both electricity and water, aboard spacecraft.

18.7.1.3 Phosphoric Acid Fuel Cells (PAFCs)

PAFC is a kind of fuel cell that uses liquid orthophosphoric acid as an electrolyte. It is a type of primary fuel cell that was commercialized. It was first developed in the mid-1960s and widely tested since then. They have improved significantly in terms of stability, performance and cost-effectiveness which is credited to the more and more innovation which has taken place in due course of time. The electrodes are made from a carbon-coated material with a finely dispersed platinum catalyst on it.

Recent scientific reports state that a high-temperature phosphoric acid and polybenzimidazole-based composite membrane fuel cells which use FeSA-G as the cathode material show power density of 325 mW/cm^2 at 230 °C, which is higher than 313 mW/cm^2 as achieved in the case of Pt/C being used for the same purpose. Considerable work is also being done in one-dimensional, two-dimensional and three-dimensional dynamic/steady-state modelling of PAFCs. A keen consideration of material selection is also done beforehand in order to manage thermal stresses and maintain electrode planarity and membrane electrode assembly for ensuring better performance and scaling up the output (Fig. 18.9).

Electrochemical Reactions

Cathode reaction: $2H^+ + ½O_2 + 2e^- \rightarrow H_2O$

Anode reaction: $H_2 \rightarrow 2H^+ + 2e^-$

Overall reaction: $½O_2 + H_2 \rightarrow H_2O$

Characteristics

- Electrolyte → liquid H_3PO_4 (either pure or highly concentrated)
- Charge carrier → H^+
- Temperature of operation → 180–210 °C
- Efficiency → 40%

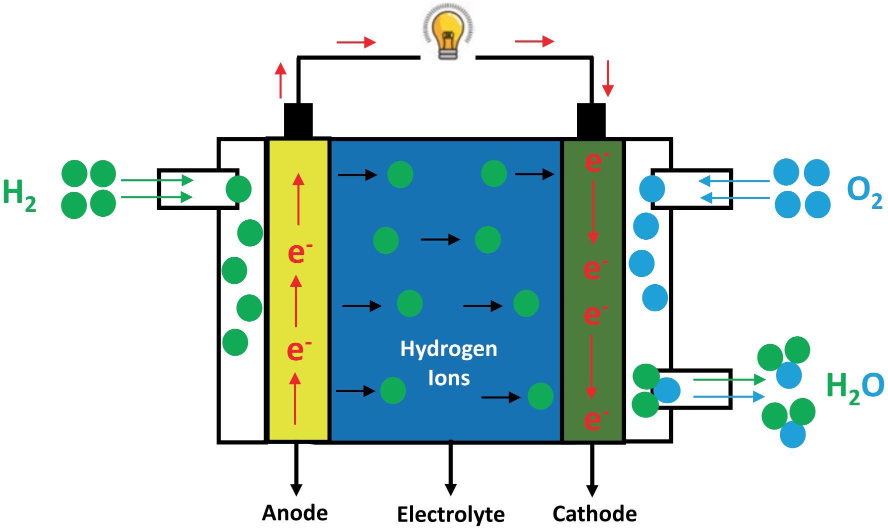

Fig. 18.9 Schematic diagram of a PAFC

- Power density → 150–300 (mW/cm^2)
- Power range → 50–200 (kW)

PAFC Advantages

- Uses a very relatively low-cost electrolyte.
- PAFC is a mature technology.
- Promises excellent reliability as well as long-term performance.

PAFC Disadvantages

- Replenishment of the corrosive electrolyte.
- Highly susceptible to CO and S poisoning.
- Platinum catalyst used is very expensive.

Applications

- It is also finding applications in the transport sector, especially in large vehicles.
- It is used in stationary power generations with output in the range of 50–200 kW to power many commercial places.

18.7.2 High-Temperature Fuel Cells

Fuel cells that operate at a very high temperature around 600–1000 °C are included in this category. MCFC and SOFC are the two major types of such fuel cells. They are discussed below.

18.7.2.1 Molten Carbonate Fuel Cells (MCFCs)

MCFCs are one of the high-temperature fuel cells. Their electrolyte consists of a molten carbonate salt mixture which is suspended in a porous and chemically inert ceramic matrix of BASE (beta-alumina solid electrolyte). As they operate at very high temperatures of 650 °C and above, non-precious metals can be easily used as good catalysts both at the anode and at the cathode which reduces the cost significantly. MCFCs are not prone to poisoning by CO or CO_2 which is an added advantage. They can also make use of carbon oxides as fuel thus making them more attractive for fuelling with coal-made gases. Since MCFCs are more impervious to impurities than other fuel cell types, scientists not only hope but also believe that they might be utilized for internal coal reforming, providing that they can be made more resistant to contaminants like sulphur that result from burning coal into hydrogen gas.

Efforts are now being made globally to utilize molten carbonate fuel cell for multipurpose applications simultaneously, like electricity generation, in a heating process heat exchanger for generating superheated steam, in a generator-absorber heat exchanger cycle for providing cooling load as well as powering a desalination subsystem to produce freshwater. In another scientific study, we see that the waste heat from a molten carbonate fuel cell is used to power a heat recovery steam generator, which produces high-temperature steam for running the steam electrolysis process which results in hydrogen production (Fig. 18.10).

Electrochemical Reactions

Cathode reaction: $\frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$

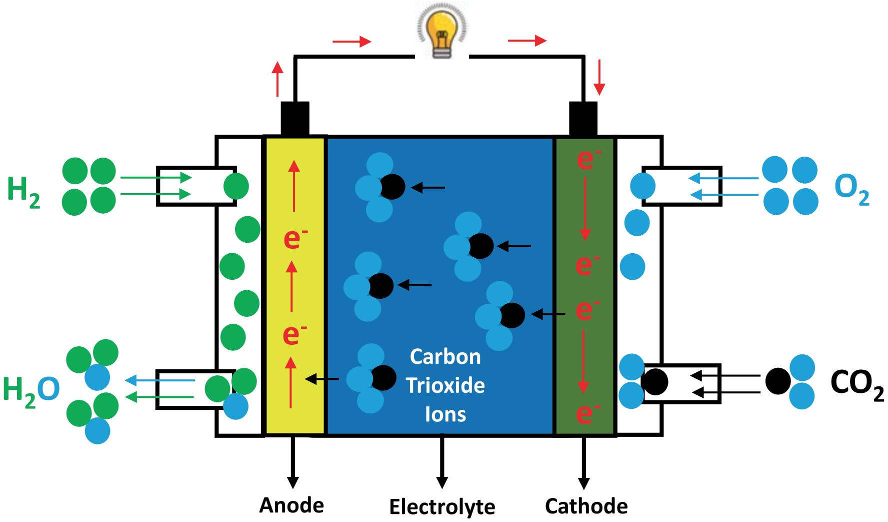

Fig. 18.10 Schematic diagram of a MCFC

Anode reaction: $H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$
Overall cell reaction: $\frac{1}{2}O_2 + H_2 \rightarrow H_2O$

Characteristics

- Electrolyte – molten mixture of alkali carbonates, Li_2CO_3 and K_2CO_3, immobilized in a LiO–AlO_2 matrix
- Charge carrier → CO_3^{2-}
- Temperature of operation → 650 °C
- Efficiency → 45–55%
- Power density → 100–300 (mW/cm^2)
- Power range → 100–100,000 (kW)

MCFC Advantages

- Metal catalyst used is non-precious.
- Waste heat produced during cell operation is used for cogeneration applications.
- Flexibility of the fuel used.

MCFC Disadvantages

- Issues with degradation and longevity.
- Expensive cell components.
- Mandatory implementation of CO_2 recycling.
- Molten electrolyte is corrosive.

Applications

- Used specifically for large-scale stationary power generation purpose.
- Large-scale power plants use MCFCs, like any other large CHP (combined heat and power) and CCP (combined cycle power) plants.

18.7.2.2 Solid Oxide Fuel Cells (SOFCs)

SOFCs are also high-temperature fuel cells. Such types of fuel cells feature a solid oxide or ceramic electrolyte. A SOFC is formed from four layers, three of which are made of ceramics. A single cell consisting of four layers is stacked together having a typical thickness of only a few millimetres. Hundreds of such fuel cells are then connected serially to make the “SOFC stack”. In SOFCs, the ceramics used do not become active both ionically and electrically until they reach a very high temperature. Therefore, the fuel cell stacks have to run at very high temperatures ranging from 600 to 1000 °C. At the cathode, oxygen gets reduced to oxygen ions. These ions now travel through the solid electrolyte following the principle of diffusion and reach the anode where they oxidize the fuel. Water is as usual the by-product of this fuel cell.

In a few recent developments, we see that switching operations between the fuel-cell and electrolyser mode is a significant new research path in solid oxide cells (SOCs) for balancing power-grid load or integrating heat-electricity-gas connectivity. For high conversion/energy efficiencies, rational design of strong and high-performance materials for SOCs is essential. Iron is plentiful and has a redox

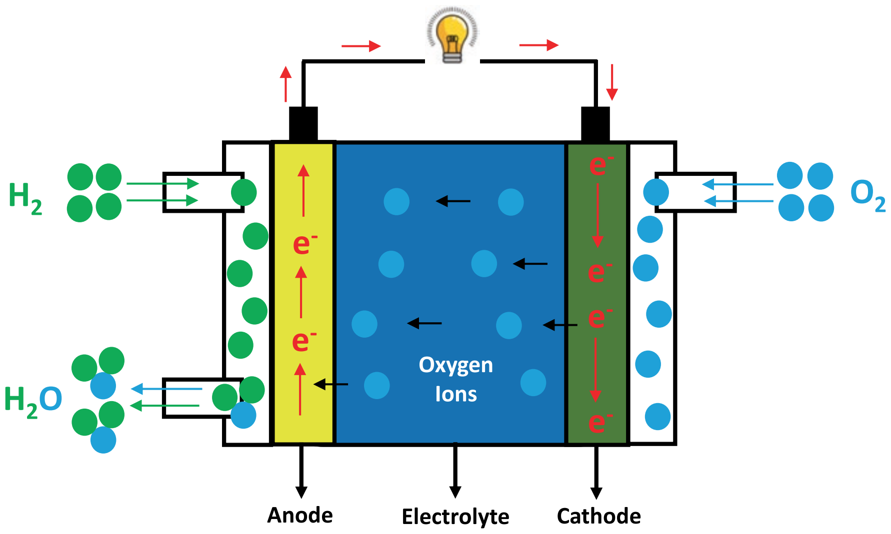

Fig. 18.11 Schematic diagram of a SOFC

chemistry that is suited for both operation modes. Because of their inexpensive cost and, more significantly, the adequate valence stability of the Fe–O bond for outstanding redox activity over a wide variety of electrode functions, iron-based oxide materials are being studied extensively for SOCs. Also, we see in one of the scientific reports that although the low basicity of Ca makes it an undesirable doping element in standard thought, doping a $LaMnO_3$ cathode with the Ca element creates a $La_{0.5}Ca_{0.5}MnO_3$ cathode that outperforms all similar cells for proton-conducting solid oxide fuel cells. Furthermore, rather than sacrificing electrochemical performance in the name of chemical stability, $La_{0.5}Ca_{0.5}MnO_3$ exhibits good chemical stability, making it a suitable candidate for proton-conducting solid oxide fuel cells (Fig. 18.11).

Electrochemical Reactions

Cathode reaction: $O_2 + 4e^- \rightarrow 2O^{2-}$
Anode reaction: $2O^{2-} + 2H_2 \rightarrow 2H_2O + 4e^-$
Overall cell reaction: $O_2 + 2H_2 \rightarrow 2H_2O$

Characteristics

- Electrolyte → solid ceramic electrolyte (popularly YSZ)
- Charge carrier → $O_{\backslash}^{2-}$
- Temperature of operation → 600–1000 °C
- Efficiency → 50–60%
- Power density → 250–500 (mW/cm^2)
- Power range (kW) → 10–100,000

SOFC Advantages

- Relative power density is high.
- Electrolyte used is solid.

- Catalysts made of non-precious metals are used.
- Cogeneration applications can utilize waste heat.
- Flexibility of the fuel used.

SOFC Disadvantages
- Issues with sealing
- Expensive fabrication parts/components
- Material issues at very high temperature

Applications
- Micro-SOFCs (watt range) can be used for small portable charging applications.
- Extensively used for both small- and large-scale stationary power generations.
- SOFCs find application in off-grid power generators (100 kW range) and smaller cogeneration systems (few kW ranges), such as domestic CHPs.

Here is a table for a quick and comprehensive view of different fuel cell types along with their important characteristics.

Biological fuel cells and direct liquid-fuelled fuel cells include direct borohydride, direct formic acid and direct methanol fuel cells. Metal air cells, solid acid fuel cells, protonic ceramic fuel cells and membraneless fuel cells are several other types of fuel cells that exist.

18.8 Applications of Fuel Cells

With the emerging use of hydrogen as a potential future energy resource, the importance of fuel cells cannot be ignored. In view of the present global energy scenario, we can easily see that the use of fuel cells is gradually increasing everyday in most of the sectors both commercially and domestically. Since various countries globally are now desiring to quickly shift towards a hydrogen-driven economy owing to the menace that fossil fuel-powered economy is creating, it is quite an inalienable fact that fuel cells are going to play a very substantive role in this global transformation. Given below are a few of those areas where the use of fuel cells is rapidly gaining importance.

18.8.1 Power Production

Power production/generation is the purpose where fuel cell finds almost 90% of its use. Since fuel cells are generally portable in nature, they can be used to generate power even at the most remote locations of the Earth; therefore, domestic and commercial human settlements at such extreme places can also use them for satisfying their own daily energy requirements. Fuel cells are used in various space applications. It mainly supplies the necessary power to satellites, spacecraft, space stations and interplanetary missions and is also a source of water onboard spacecraft. Fuel cells are also used by the armed forces and security agencies to run equipments associated with defence and security in far-flung areas for several operations, surveillance, training, etc. In the last two to three decades, we see that there has been an excellent rise in the share of power production from fuel cells. This has reduced dependence on fossil fuels favouring a shift towards a carbon-free economy to power our future.

18.8.2 Cogeneration

This is a method that involves the simultaneous generation of both heat and power. Certain fuel cell systems can be used for both of these applications. Residential services, offices, multi-floored buildings, industries and community centres all employ combined heat and power (CHP) fuel cell systems to generate both heat and power. The system continuously produces electrical energy simultaneously with hot air. Water can also be heated using the waste heat produced during cell operation. Excess power generated which goes unconsumed is fed back into the grid. As a result, CHP systems might possibly conserve primary energy by using waste heat, which is often discharged by thermal energy conversion systems. CHP systems when linked to the absorption chillers the waste heat could be used for refrigeration purposes as well. A group of researchers at the University of Minnesota in the United States were successful in fabricating a fuel cell system capable of diverting waste heat from the fuel cells directly into the ground during the summer, allowing for additional cooling, while waste heat during the winter can be easily pumped into the building directly. Such a system indeed enhances human comfort, but most importantly, it opens up newer horizons of research on fuel cells in the coming days.

An efficiency of 85% is now very common in cogeneration systems powered by fuel cells. The distribution of this efficiency is like 40–60% from electrics, and the remainder is contributed by thermal. Mostly, we see that the phosphoric acid fuel cells (PAFCs) that facilitated fuel cell systems are used in CHP systems' cogeneration purposes as they are capable to provide an overall efficiency of close to 90%. Sometimes, other high-temperature-based fuel cell systems such as SOFC and MCFC are also used for the said purpose. However, there are still a few problems associated with CHPs like slow rates of ramping up and down, shorter longevity and higher cost. These are indeed some major areas of research in the future.

18.8.3 Automobiles

Hydrogen-powered vehicles are rapidly emerging in the transportation sector. Therefore, fuel cell-based electric vehicles (FCEVs) are highly in demand. They also have futuristic features such as being environmentally friendly and easy maintenance making it more user friendly. FCEVs generally have shown an average range of 300 miles between each refuelling. They can be easily refuelled within five minutes. The US Department of Energy (DOE)-sponsored Fuel Cell Technology Program mentions that till 2011, fuel cells were able to achieve an efficiency of 53–59% at one-quarter power and 42–53% vehicle efficiency at full power and the distance covered was over 120,000 km with minor degradation of less than 10%. When an FCEV runs on compressed gaseous hydrogen fuel, it uses around 40% less energy and emits 45% lesser greenhouse gases per mile travelled than an internal combustion vehicle.

18.8.4 Submarines

Diesel generators and nuclear-powered submarines are the two very commonly used submarines by almost all the nations globally having submarines as a part of their navy. However, nowadays, we see that a new type of submarine is emerging which are being powered by fuel cells. Such submarines are much safer and less polluting in comparison to the other two. Fuel cells are eco-friendly; hence, they will not pollute the environment/seawater through their toxic discharges. Diesel generator-based submarines cause pollution due to the burning of diesel which is a fossil fuel. In the case of a nuclear-powered submarine, any kind of leakage can cause nuclear pollution in seawater thus affecting both flora and fauna in it. When they are further consumed by mankind, it can result in long-lasting health hazards in them as well. But submarines when powered by fuel cell do not have any such risk of pollution and health hazard as the by-product is only water. Design, fabrication, operation and maintenance of such submarines are also very easy and economical; hence, these kinds of submarines are now being preferred by several nations globally (Fig. 18.12).

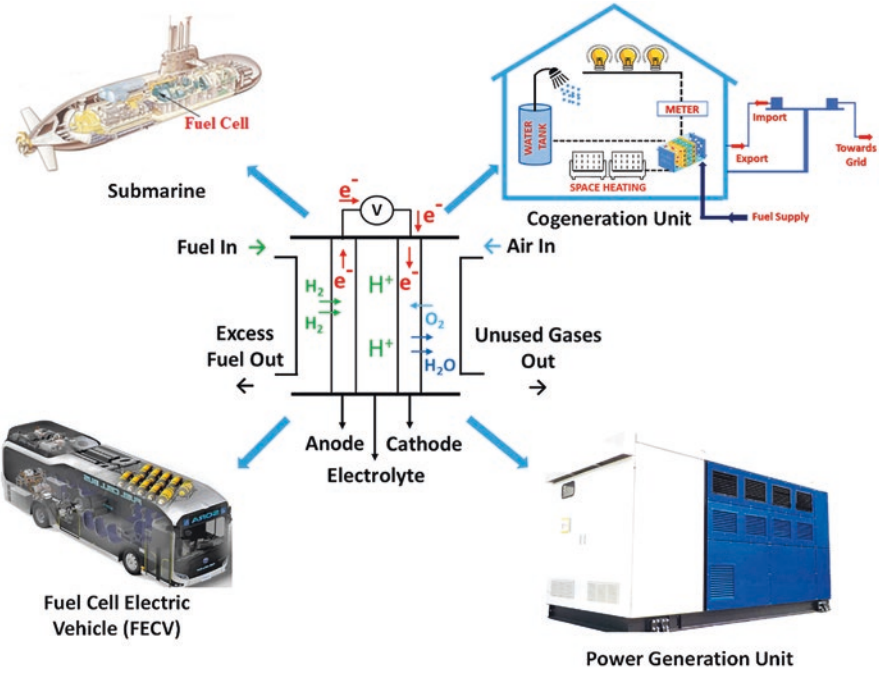

Fig. 18.12 Various applications of fuel cell

Table 18.1 Different fuel cell types along with their important characteristics

Fuel cell type	PEMFC	AFC	PAFC	MCFC	SOFC
Electrolyte	Polymer membrane (acidic)	Potassium hydroxide (Aq.)	Liquid phosphoric acid	Lithium/ potassium carbonate	Yttria -stabilized zirconia (YSZ)
Charge carrier	H^+	OH^-	H^+	CO_3^{2-}	O^{2-}
Cell components	Carbon based	Carbon based	Carbon based	Stainless based	Ceramic based
Electrodes	Carbon	Transition metals	Carbon	Nickel and nickel oxide	Perovskite and perovskite/metal cermet
Catalyst	Platinum (Pt)	Platinum (Pt)	Platinum (Pt)	Nickel (Ni)	Perovskite/ ceramic
Working temperature	80–100 °C	60–220 °C	180–210 °C	650 °C	600–1000 °C
Power density (mW/cm^2)	500–2500	150–400	150–300	100–300	250–500
Power range (kW)	1–20	1–100	50–200	10–100,000	10–100,000
Efficiency	40–50%	50%	40%	45–55%	50–60%
Fuel compatibility	Methanol, H_2	H_2	H_2	CH_4, H_2,	H_2, CO, CH_4

18.9 Conclusion

Through our exhaustive review and discussion, we can critically draw several conclusions about fuel cell technology and its relevance in the future. We can see that it is a very rapidly developing technology holding very high and futuristic promises. It indeed has a large role to play when we are all trying to wean out of the carbon-driven economy to an extremely sustainable hydrogen-driven economy in the near future. Still, we see there are a lot of loopholes to be addressed by the scientific community as soon as possible. All these challenges can be resolved only through very specific understanding, research, development and effective technical solutions. Other energy resources such as batteries, combustion fuels, etc. are putting up stiff competition to fuel cell technology because it is still an immature technology. This is also reducing investment which is injurious to further innovation in this field. Therefore, practically affordable solutions to these issues when obtained will certainly make fuel cells cost-effective, reliable, compact, portable and massively user friendly. This will automatically lead to the large-scale commercialization of this technology for the betterment of mankind.

References

1. R. O'Hayre, S.-W. Cha, W. Colella, B. Fritz, *Fuel Cell Fundamentals*, 3rd edn. (Wiley, 2016)
2. M. Shao, Q. Chang, J. Dodelet, R. Chenitz, Recent advances in electrocatalysts for oxygen reduction reaction. Chem. Rev. **116**, 3594–3657 (2016)
3. R. He, Q. Li, J.O. Jensen, N.J. Bjerrum, *Fuel Cells*, vol 4 (2004), p. 147
4. A.J. Appleby, *Fuel Cell Handbook* (Van Reinhold Co., New York, 1989)
5. B. Leo, M. Mugerwa, *Fuel Cell Systems* (Plenum Press, New York, 1993)
6. P. Breeze, *Power Generation Technologies: Evaluating the Cost of Electricity* (Financial Times Energy, London, 1998)
7. M.N. Eisler, *Overpotential: Fuel Cells, Futurism, and the Making of a Power Panacea* (Rutgers University Press, 2012)
8. Y. Cheng, S. He, S. Lu, J.-P. Veder, B. Johannessen, L. Thomsen, M. Saunders, T. Becker, R. De Marco, Q. Li, S.-Z. Yang, S.P. Jiang, Iron single atoms on graphene as nonprecious metal catalysts for high-temperature polymer electrolyte membrane fuel cells. Adv. Sci. **6**, 1802066 (2019)
9. C. Ahn, E.J. Park, S. Kim, O. Kim, W. Hwang, M. Her, Y.S. Kang, S. Park, O.J. Kwon, S.H. Park, Y. Cho, Y. Sung, Differences in the electrochemical performance of Pt-based catalysts used for polymer electrolyte membrane fuel cells in liquid half- and full-cells. Chem. Rev. **121**, 15075–15140 (2021)
10. A. Bhosale, S.R. Suseendiran, S. Roy, R. Ramya, R. Rengaswamy, Phosphoric acid fuel cells, in *Reference Module in Earth Systems and Environmental Sciences*, (Elsevier, 2020)
11. J. Miyake, Y. Ogawa, T. Tanaka, J. Ahn, K. Oka, K. Oyaizu, K. Miyatake, Rechargeable proton exchange membrane fuel cell containing an intrinsic hydrogen storage polymer. Commun. Chem. **3**, 138 (2020)
12. C. Ni, J. Zhou, Z. Zhang, S. Li, J. Ni, K. Wu, J.T.S. Irvine, Iron-based electrode materials for solid oxide fuel cells and electrolysers. Energy Environ. Sci. **14**, 6287–6319 (2021)

13. H. Dai, X. Xu, C. Liu, C. Ma, Q. Zhang, L. Bi, Tailoring a LaMnO3 cathode for proton-conducting solid oxide fuel cells: integration of high performance and excellent stability. J. Mater. Chem. A **9**, 12553–12559 (2021)
14. D. Linden, *Handbook of Batteries and Fuel Cells* (McGraw-Hill, New York, 1984)
15. FCHEA Homepage. http:// www. https://www.fchea.org/
16. U. Eberle, R. von Helmolt, Sustainable transportation based on electric vehicle concepts: A brief overview. Energy Environ. Sci. **3**, 689–699 (2010)
17. Mr. W. R. Grove on a new voltaic combination. The London and Edinburgh Philosophical Magazine and Journal of Science. 1838
18. Confusion and controversy: Nineteenth-century theories of the Voltaic Pile – Helge Kragh
19. A.M. Haghghi, M. Shamsaiee, G.S. Holagh, A. Chitsaz, A.M. Rosen, Thermodynamic, exergoeconomic, and environmental evaluation of a new multi-generation system driven by a molten carbonate fuel cell for production of cooling, heating, electricity, and freshwater. Energy Convers. Manag. **199**, 112040 (2019)
20. C. Souleymane, J. Zhao, W. Li, Efficient utilization of waste heat from molten carbonate fuel cell in parabolic trough power plant for electricity and hydrogen coproduction. Int. J. Hydrog. Energy **47**, 81–91 (2022)
21. C. Berger (ed.), *Handbook of Fuel Cell Technology* (Prentice-Hall, Englewood Cliffs, NJ, 1968)
22. J.H. Hirschenhofer, D.B. Stauffer, R.R. Engleman, G. Klett M, *Fuel Cell Handbook*, 6th edn. (U S Department of Energy, Morgantown, 2003)
23. G.H.J. Broers, J.A.A. Ketelaar, in *Fuel Cells*, ed. by G. J. Young (Reinhold, New York, 1960)
24. A. Vielstich, W. Lamm, H.A. Gasteiger, *Handbook of Fuel Cells*, vol 2 (Wiley, New York, 2003)
25. E.T. Springer, A.T. Zawodzinski, S. Gottesfeld, Polymer electrolyte fuel cell model. J. Electrochem. Soc. **138**(8), 2334–2342 (1991)
26. P. Adcock, *Development of Cost-Effective, High-Performance PEM Fuel Cells for Automotive Applications* (IQPC, London, 1998)
27. C. Yang, P. Costamagna, S. Srinivasan, J. Benziger, B.A.B. Bocarsly, Approaches and technical challenges to high temperature operation of proton exchange membrane fuel cells. J. Power Sources **103**, 1 (2001)
28. R. He, Q. Li, O.J. Jensen, J.N. Bjerrum, Fuel Cells **4**, 147 (2004)
29. EG&G Technical Services, Inc., Fuel Cell Handbook: Seventh Edition by US DoE
30. Energypedia Fuel cell applications, Homepage. https://energypedia.info/wiki/Fuel_cell_and_its_applications
31. P.V. Aravind, W. de Jong, Evaluation of high temperature gas cleaning options for biomass gasification product gas for solid oxide fuel cells. Prog. Energy Comb Sci (2012)
32. E. Bocci, A. Di Carlo, S.J. McPhail, K. Gallucci, P.U. Foscolo, M. Moneti, M. Villarini, M. Carlini, Biomass to fuel cells state of the art: A review of the most innovative technology solutions. Int. J. Hydr. Energy (2014)
33. P. Odetola, P. Popoola, O. Popoola, D. Delpor, Chapter 11 Electrodeposition of functional coatings on bipolar plates for fuel cell applications – A review, in *IntechOpen*, (2016)
34. Sinha, V., Mondal, S. "Recent development on performance modelling and fault diagnosis of fuel cell systems.", Int. J. Dyn. Contr., 2017
35. M.C. dos Santos, S. Parreira Luanna, F. De Moura Souza, J. Camargo Junior, T. Gentil, *Fuel Cells: Hydrogen and Ethanol Technologies* (Elsevier BV, 2017)
36. G.E. Marnellos, C. Athanasiou, S.S. Makridis, E.S. Kikkinides, Chapter 3 Integration of hydrogen energy technologies in autonomous power systems. Springer, 2008
37. Falcade, T., de Fraga Malfatti, C. Chapter 7 Fuel cell: A review and a new approach about YSZ solid oxide electrolyte deposition direct on LSM porous substrate by spray pyrolysis. (Intech Open, 2012)
38. G. Dhaarini Devi, M. Akther Sabeena, C. Shankar, V. Kirbakaran, Effect of cell temperature on the power output of a PEM fuel cell in a test bed condition, in *International Conference on Energy Efficient Technologies for Sustainability (ICEETS), Nagercoil*, 2016
39. Q. Zhen, S. Bashir, J. Louise Liu, *Nanostructured Materials for Next-Generation Energy Storage and Conversion* (Springer, 2018)

40. L. Duclos, R. Chattot, L. Dubau, X.P. Thivel, G. Mandil, V. Laforest, M. Bolloli, R. Vincent, L. Svecova, Closing the loop: Life cycle assessment and optimization of a PEMFC platinum-based catalyst recycling process. Green Chem. **22**, 1919–1933 (2020)
41. B.T. Ferriday, P.H. Middleton, Alkaline fuel cell technology – A review. Int. J. Hydrog. Energy **46**, 18489–18510 (2021)
42. S. Miyanishi, T. Yamaguchi, Highly durable spirobifluorene-based aromatic anion conducting polymer for a solid ionomer of alkaline fuel cells and water electrolysis cells. J. Mater. Chem. A **7**, 2219–2224 (2019)
43. P.S. Jiang, Q. Li, *Introduction to Fuel Cells* (Springer, 2022)