People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research
Echahid Hama Lakhdar El-Oued University
Faculty of Technology
MECHANICAL ENGINEERING DEPARTMENT
Field: Science and Technology
Sector: Mechanical Engineering
2nd year Master, Specialization in Renewable Energy in Mechanics

Course Handout for Teaching the Module:

Fuel Cells and Hydrogen Production

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COURSE INFORMATION

University: Echahid Hamma Lakhdar'EL-OUED

Faculty: science of technology

Department: Mechanical Engineering

Target audience: 2ed year Master, specialty renewable energies in mechanics

Course title: Fuel cell and hydrogen production

Semester: 03

Teaching unit: Fundamental TUF

Credit: 04

Coefficient: 02

Duration: 15 weeks

Teacher:

Courses and TD: Dr. Horr Sabrina

MODULE OBJECTIVES AND PERQUISITES

Module Objectives

The competency targeted by this course, as a whole, is:

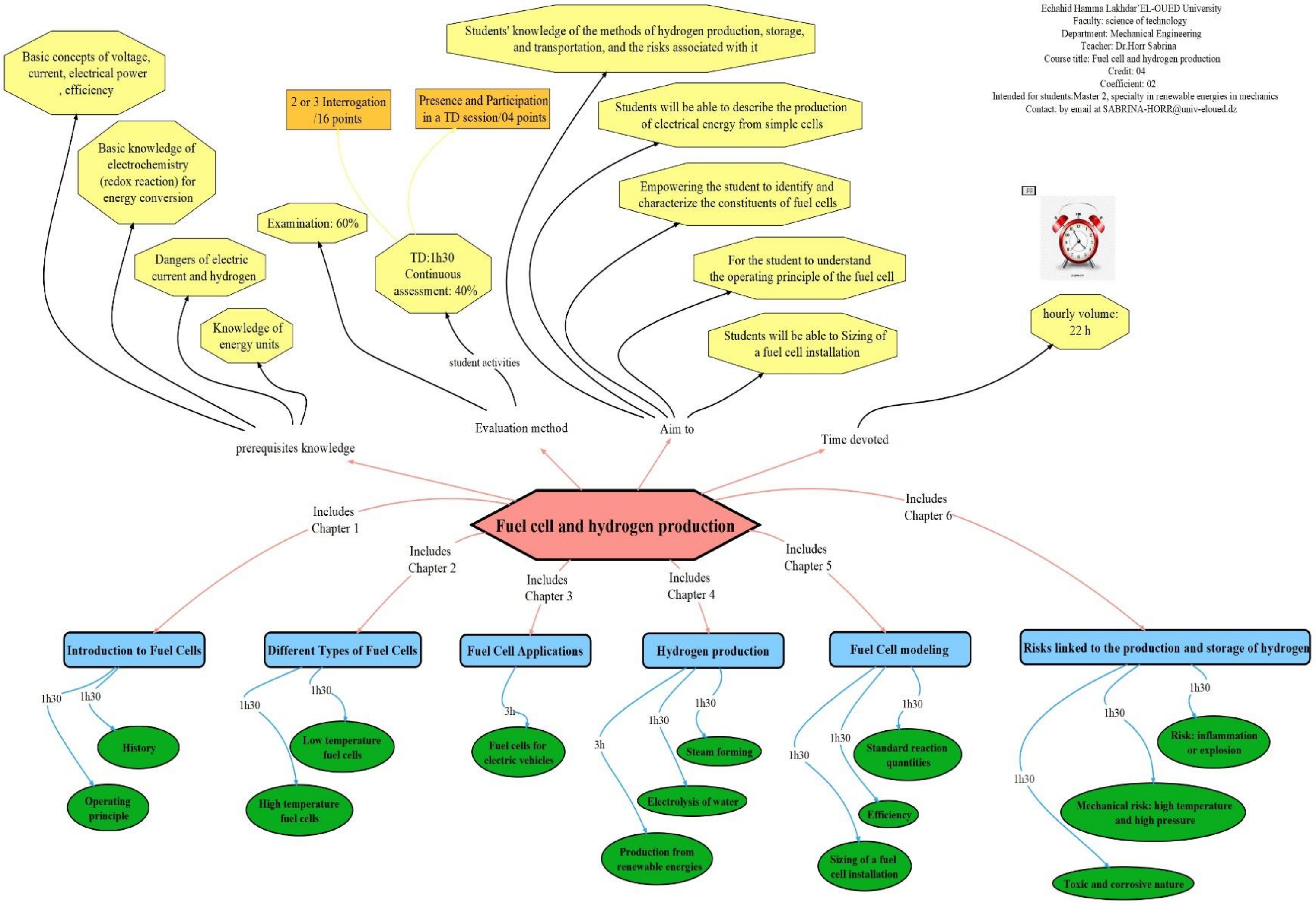
1. **Knowledge** some concepts related to the topic of fuel cells. The student is given multiple test questions and is asked to answer them. The goal is to recall his prior knowledge
2. **Explain** the student how to produce electrical energy from fuel cells during its chemical reaction and what are the products of this reaction
3. **To identify** and characterize the constituents of fuel cells
4. **To design** and create a simple fuel cell, This depends on the type of fuel cell and its scope of application
5. **Differentiates** the student between the various parts of the fuel cell and the work of each of them
6. **Evaluated** the production of electrical energy from simple cell

Perquisites

To be able to successfully complete this course, it is recommended that learners know:

1. Basic concepts of voltage, current, electrical power, efficiency
2. Dangers of electric current and hydrogen
3. Basic knowledge of electrochemistry (redox reaction) for energy conversion
4. Basic knowledge of thermodynamics, particularly energy conversion principles and efficiencies, will provide a foundation for understanding fuel cell performance.
5. A general understanding of different energy generation and storage technologies would provide a good context for learning about fuel cells and hydrogen within the broader energy landscape.

TECHNICAL CARD FOR THE MODULE



Conceptual Map of Fuel cell and hydrogen production module

FOREWORD

This course module, ***Fuel Cells and Hydrogen Production***, is designed for Master 2 students specializing in Renewable Energy at the University of El Oued. It provides a comprehensive introduction to the scientific, technological, and practical aspects of hydrogen as an energy carrier and fuel cells as efficient energy conversion systems.

The content is structured to cover the fundamental principles of electrochemistry and thermodynamics, the different families of fuel cells, hydrogen production methods, storage and safety considerations, as well as applications in stationary, mobile, and hybrid systems. Special emphasis is given to the integration of hydrogen technologies with renewable energy sources, particularly solar energy in Saharan regions.

The aim of this module is not only to provide theoretical knowledge but also to develop practical skills through tutorials, and problem-solving sessions. Students are encouraged to engage critically with the material, analyze real-world case studies, and explore innovative solutions adapted to the Algerian and global energy context.

This handout lecture material is intended as both a teaching tool and a reference guide. It reflects current developments in hydrogen and fuel cell research and highlights their potential role in the transition towards sustainable and clean energy systems.

The handout is divided into **six chapters**, organized and summarized as follows:

Chapter 1: Introduction to Fuel Cells

Chapter 2: Different Types of Fuel Cells

Chapter 3: Fuel Cell Applications

Chapter 4: Hydrogen production

Chapter 5: Fuel Cell modeling

Chapter 6: Risks linked to the production and storage of hydrogen

TABLE OF CONTENTS

Chapter 1: Introduction to Fuel Cells

Chapter 1: Introduction to Fuel Cells

Course objective

At the end of this chapter, the student will be able to:

1. **Understand** the history of fuel cells and identify their main areas of application.
2. **Explain** how fuel cells produce electrical energy through chemical reactions and recognize the resulting products.
3. **Differentiate** between the various parts of a fuel cell and describe the function of each component, thereby preparing to study in the next chapter the different types of fuel cells and their specific characteristics.

1.1 Introduction

Alternative sources to fossil fuels (oil, gas, and coal) have become one of the most pressing challenges of the modern era, attracting the attention of many scientists and researchers and inspiring numerous innovations across various fields. Despite extensive efforts to reduce global dependence on petroleum and its derivatives, the world has not yet found a definitive solution to replace fossil fuels entirely.

Fuel cells, however, have emerged as one of the most promising alternatives. Although their development has faced several scientific and technological challenges, significant progress has been achieved in recent years. Today, fuel cells are increasingly regarded as a realistic and sustainable substitute for fossil fuels.

They have been successfully implemented in many sectors of modern life, offering numerous advantages such as high efficiency, low emissions, and flexibility of application. As one of the most important technologies based on hydrogen, fuel cells represent a cornerstone in the ongoing transition towards cleaner and more sustainable energy systems.

1.2 History of fuel cell

Fuel cells have been known in the scientific community for about 150 years. They began to be explored in the 1800s, and have been extensively researched during the second half of the twentieth and early twenty-first century. A summary of fuel cell history is:

- **1839: William Grove** invented the first fuel cell is produced what he called a ‘gas voltaic battery’, a device that combined hydrogen and oxygen to produce electricity.
- **1895:** American electrical engineer William Jacques built the first carbon battery with a power of 1.5 kW. However, due to the expensiveness of carbonates and difficulty to regenerate it, Jacques was not able to go very far with his work.

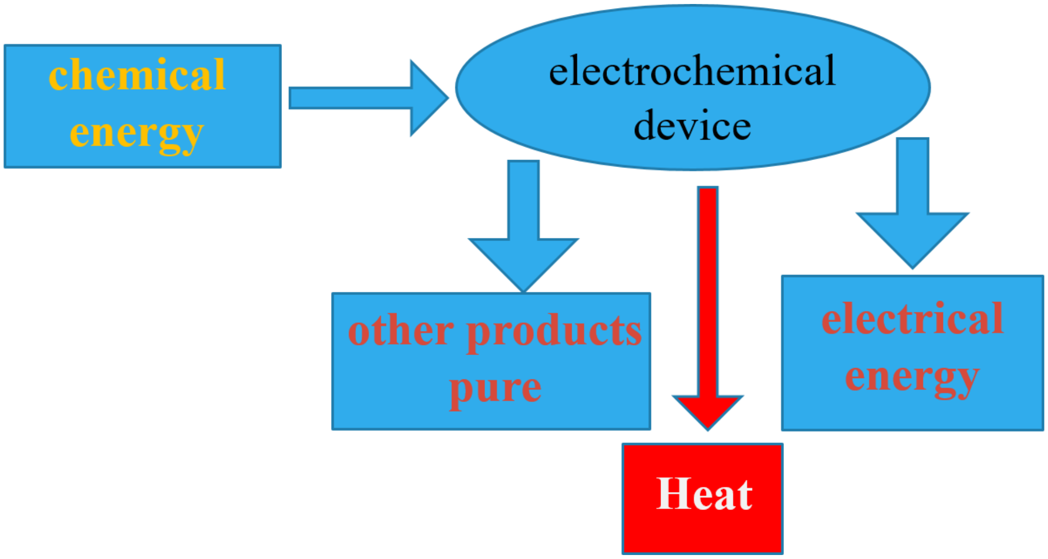
- **1960:** Fuel cells have been rediscovered by NASA and Apollo Missions
- **1977:** A fuel cell is designed to produce electrical power of about 1Mw
- **1983:** A fuel cell is designed to produce electrical power of about 4.5Mw (PAFC)
- **1987:** Development of PEMFC fuel cells type
- **1990:** 1st fuel-cell electric vehicle prototypes were released

1.3 Fuel cells

A fuel cell is an **electrochemical device** that converts the chemical energy of a fuel such as hydrogen, natural gas, methanol, or gasoline and an oxidant such as air or pure oxygen directly into electrical energy.

In principle, a fuel cell operates similarly to a **battery**. However, unlike a battery, it does not discharge or require recharging. Instead, it continuously generates both **electricity and heat** as long as it is supplied with fuel and an oxidant.

Fuel cells combine fuel and oxidant molecules without combustion, thereby avoiding the pollutants and inefficiencies associated with conventional thermal power generation systems.



Fuel used in fuel cells:

Hydrogen is the fuel currently used in fuel cells, and there are also some other gases such as:

- **Nitrogen (N_2)** from the air is generally inert and has only a minor influence on fuel cell performance.

- **Carbon monoxide (CO) and methane (CH_4):** Their influence on fuel cells varies depending on the type of cell. For example, carbon monoxide acts as a poison for low-temperature fuel cells, such as proton exchange membrane fuel cells (PEMFCs), by blocking catalytic sites and reducing efficiency.

On the other hand, carbon monoxide (CO) can be used as a direct fuel for high temperature fuel cells, such as solid oxide fuel cells (SOFCs).

Each fuel cell, depending on its electrolyte and catalyst, can accept certain gases as fuel while others may act as contaminants that negatively affect its performance. Therefore, the fuel supply system must be carefully designed and tailored to the specific type of fuel cell.

A typical fuel cell consists of the following main components:

1.3.1 Anode (Negative Electrode)

- Function: The anode is the site where the fuel (e.g., hydrogen) is introduced and undergoes **oxidation**.
- Reaction: At the anode, hydrogen molecules (H_2) are split into protons (H^+) and electrons (e^-).
- Role:
  - Conducts electrons released during the oxidation reaction to the external circuit, creating an electric current.
  - Allows protons to migrate through the electrolyte toward the cathode.
- Material: Usually made of porous conductive materials (e.g., carbon-based supports with catalysts such as platinum).

1.3.2 Cathode (Positive Electrode)

- Function: The cathode is where the **oxidant** (usually oxygen from air) is supplied.
- Reaction: Oxygen molecules (O_2) combine with electrons (from the external circuit) and protons (from the electrolyte) to form water (H_2O).
- Role:
  - Completes the electrochemical reaction.
  - Ensures efficient reduction of oxygen with the help of a catalyst.
- Material: Typically porous carbon structures with catalysts (e.g., platinum, nickel, or perovskite materials in high-temperature cells).

1.3.3 Electrolyte

- Function: The electrolyte is the medium that **conducts ions** (protons, oxygen ions, or carbonate ions depending on the type of fuel cell) from the anode to the cathode.
- Role:

  - Ensures ionic conductivity while being electronically insulating (prevents electrons from passing through).
  - Maintains separation between hydrogen and oxygen to avoid direct combustion.
- Examples:
  - **PEMFC (Proton Exchange Membrane Fuel Cell):** Polymer electrolyte membrane that conducts protons (H^+).
  - **SOFC (Solid Oxide Fuel Cell):** Solid ceramic electrolyte that conducts oxygen ions (O^{2-}).
  - **MCFC (Molten Carbonate Fuel Cell):** Molten carbonate salts that conduct carbonate ions (CO_3^{2-}).

1.3.4 Catalyst

- Function: Catalysts accelerate the electrochemical reactions at both the anode and cathode.
- Role:
  - At the **anode**, the catalyst helps split hydrogen into protons and electrons.
  - At the **cathode**, it assists in the reduction of oxygen.
- Material:
  - Platinum is widely used in PEM fuel cells due to its high activity, but alternatives (nickel, cobalt, perovskites) are explored to reduce costs.

1.3.5 Bipolar Plates (or Flow Plates)

- Function: Bipolar plates are conductive plates placed between individual cells in a fuel cell stack.
- Role:
  - Distribute fuel and oxidant gases uniformly across the electrodes.
  - Collect and conduct electrons between adjacent cells.
  - Remove heat and water generated during operation.
- Material: Graphite composites, metal alloys, or coated stainless steel.

1.3.6 Gas Diffusion Layer (GDL)

- Function: A porous layer located between the catalyst layer and the bipolar plates.
- Role:
  - Facilitates uniform distribution of gases to the catalyst sites.
  - Removes water produced at the cathode to prevent flooding.
  - Provides electrical conductivity.
- Material: Porous carbon paper or carbon cloth.

1.3.7 Sealing and End Plates

- Seals: Prevent leakage of hydrogen and oxygen gases.

- End Plates: Provide mechanical strength, compress the cell stack, and maintain good contact between layers.

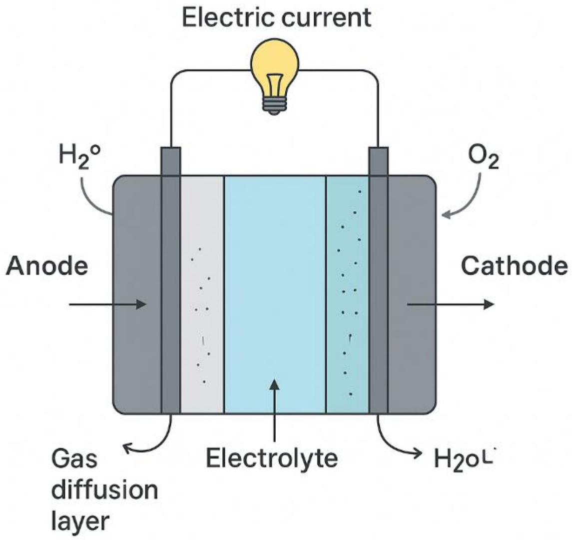


Figure 1.1: The components of fuel cells

1.4 Operating principle of fuel cells

Fuel cells are electrochemical generators that convert the chemical energy of a fuel, such as a hydrogen, into electrical energy. A fuel cell consists of a negatively charged electrode (anode), a positively charged electrode (cathode), and an electrolyte membrane. Hydrogen is oxidized at the anode, i.e., it is decomposed into protons and electrons. The protons then cross the electrolyte and end up at the cathode. The imbalance in electrons creates a positive pole and a negative pole between which the electrons circulate, thus producing electricity. Simultaneously at the cathode, the protons react with the electrons and oxygen to produce water, as expressed in Eqs.:

At cathode:

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{1.1}$$

At anode $$H_2 + \rightarrow 2H^+ + 2e^-$$ **(1.2)**

Overall $$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + \text{Heat}$$ **(1.3)**

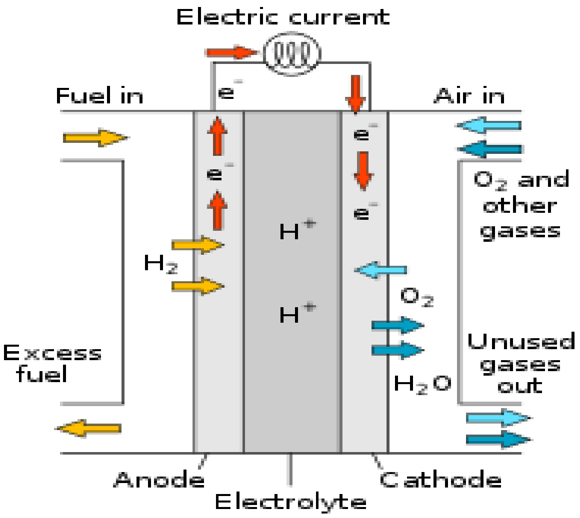


Figure 1.2: Operating principle fuel cells

EXERCISES

Exercise 1.1:

Describe the differences between a fuel cell and a battery.

Exercise 1.2:

William Grove is usually credited with the invention of the fuel cell. In what way does his gaseous voltaic battery represent the first fuel cell?

Exercise 1.3:

Describe the functions of each layer in a fuel cell.

Exercise 1.4:

Describe the operating principles of a fuel cell. (With schema)

1.5 Conclusion

In this chapter, we introduced the fundamental principles of fuel cells, highlighting their origin, historical development, and the reasons behind the growing interest in this clean and efficient energy technology. We examined how fuel cells operate as electrochemical devices, converting chemical energy directly into electrical energy without combustion, and producing water and heat as byproducts. Furthermore, we explored the essential components of a typical fuel cell and clarified their respective functions in ensuring the system’s overall performance.

Chapter 2: Different Types of Fuel Cells

Chapter 2: Different Types of Fuel Cells

Course objective

At the end of this chapter, the student will be able to:

1. **Knowledge** about the various types of fuel cells, the fuels they employ, and their operating temperatures.
2. **Classify** fuel cells into low-temperature and high-temperature categories based on their applications.
3. **Predict** the most appropriate type of fuel cell for different applications, such as stationary power generation or transportation.

2.1 Introduction

With the increase in energy consumption and declining reserves of fossil fuels, it is important to find new alternative solutions. In this context, we often talk about fuel cells appearing as one of the interesting solutions for the future because of the absence of polluting discharge when used. Several types of fuel cells can be distinguished, each type having its own characteristics.

2.2 The different types of fuel cells and how they work

There are six major types of fuel cells, differentiated from one another by their electrolyte. Further, the second characteristic used to classify fuel cells is their operating temperature:

1. Phosphoric acid fuel cell (PAFC).
2. Polymer electrolyte membrane fuel cell (PEMFC).
3. Alkaline fuel cell (AFC).
4. Molten carbonate fuel cell (MCFC).
5. Direct methanol cells (DMFC).
6. Solid-oxide fuel cell (SOFC).

2.2.1 Phosphoric acid fuel cell (PAFC)

Phosphoric acid fuel cells use an electrolyte that conducts hydrogen ions (H^+) from the anode to the cathode to combine with oxygen and electrons, producing water and heat. Phosphoric acid fuel cells use liquid phosphoric acid as an electrolyte

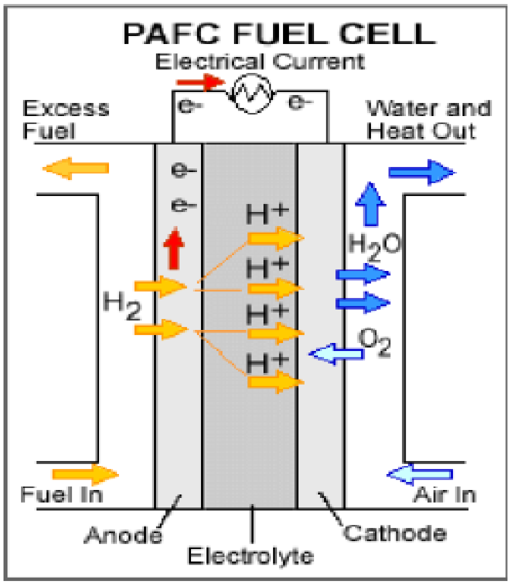


Figure 2.1: **Phosphoric Acid Fuel Cell**

Reaction

Phosphoric acid fuel cells react hydrogen with oxygen.

At cathode: $$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad (2.1)$$

At anode $$H_2 + \rightarrow 2H^+ + 2e^- \quad (2.2)$$

Overall $$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + \text{Heat} \quad (2.3)$$

2.2.2 Polymer electrolyte membrane fuel cell (PEMFC)

In polymer electrolyte membrane (PEM) fuel cells, protons move through the electrolyte to the cathode to combine with oxygen and electrons, producing water and heat. Polymer electrolyte membrane (PEM) fuel cell uses a polymeric membrane as the electrolyte, with platinum electrodes.

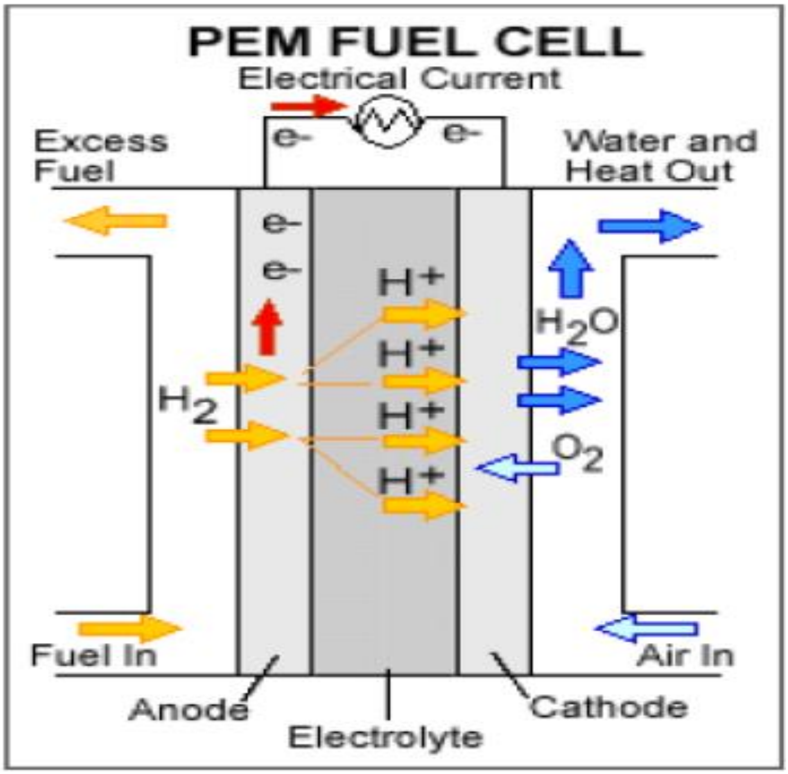


Figure 2.2: Polymer Electrolyte Membrane (PEM) Fuel Cell

Reaction

At cathode: $\frac{1}{2}O_2 + 2H^+ + \ 2e^- \rightarrow \ H_2O$ **(2.4)**

At anode $H_2 + \ \rightarrow \ 2H^+ + 2e^-$ **(2.5)**

Overall $H_2 + \frac{1}{2}O_2 \rightarrow \ H_2O + \text{Heat}$ **(2.6)**

2.2.3 Alkaline fuel cell (AFC)

In alkaline fuel cells, negative ions (OH^-) travel through the electrolyte to the anode where they combine with hydrogen to generate water and electrons. This is opposite to many other types of fuel cells that conduct hydrogen ions from the anode to the cathode. The electrolyte is typically composed of a molten alkaline mixture such as potassium hydroxide (KOH).

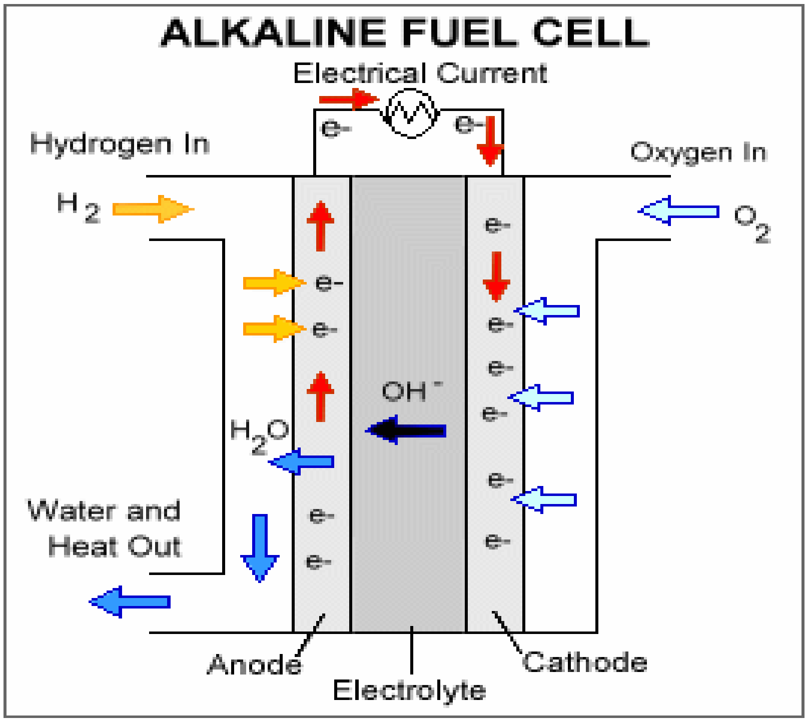


Figure 2.3: Alkaline Fuel Cell

Reaction

At cathode:	$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$	**(2.7)**
At anode	$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$	**(2.8)**
Overall	$2H_2 + O_2 \rightarrow 2H_2O + \text{Heat}$	**(2.9)**

2.2.4 Molten carbonate fuel cell (MCFC)

Molten carbonate fuel cells use an electrolyte that conducts carbonate (CO_3^{2-}) ions from the cathode to the anode where they combine with hydrogen to generate water and electrons. The molten carbonate fuel cell uses a **molten carbonate salt as the electrolyte.**

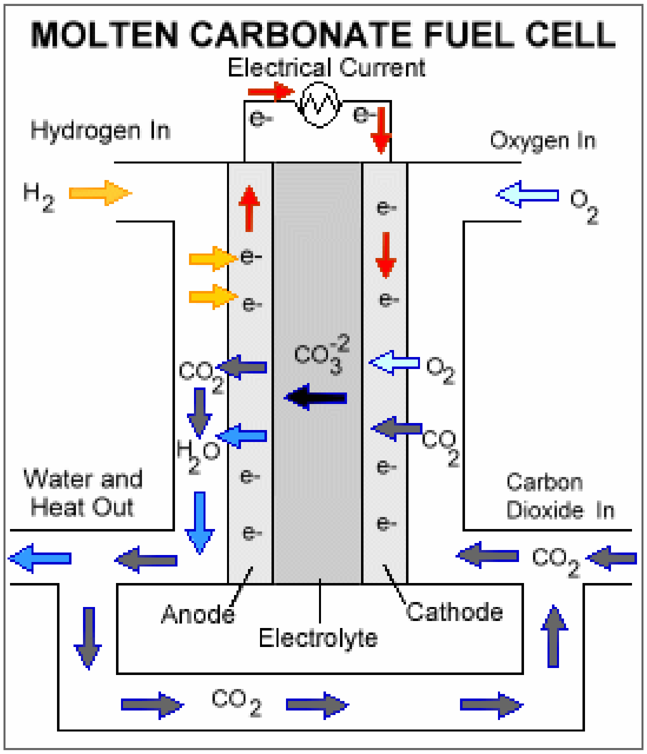


Figure 2.4: Molten Carbonate Fuel Cell

Reaction

At cathode: $$\frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3^{-2} \qquad (2.10)$$

At anode $$CO_3^{-2} + H_2 \rightarrow H_2O + CO_2 + 2e^- \qquad (2.11)$$

Overall $$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + \text{Heat} \qquad (2.12)$$

2.2.5 Direct methanol cells (DMFC)

Methanol and water react electrochemically (the methanol is oxidised) at the anode to form carbon dioxide, protons and electrons. Protons are generated at the anode flow through the polymer electrolyte to the cathode, where they react with oxygen to produce water.

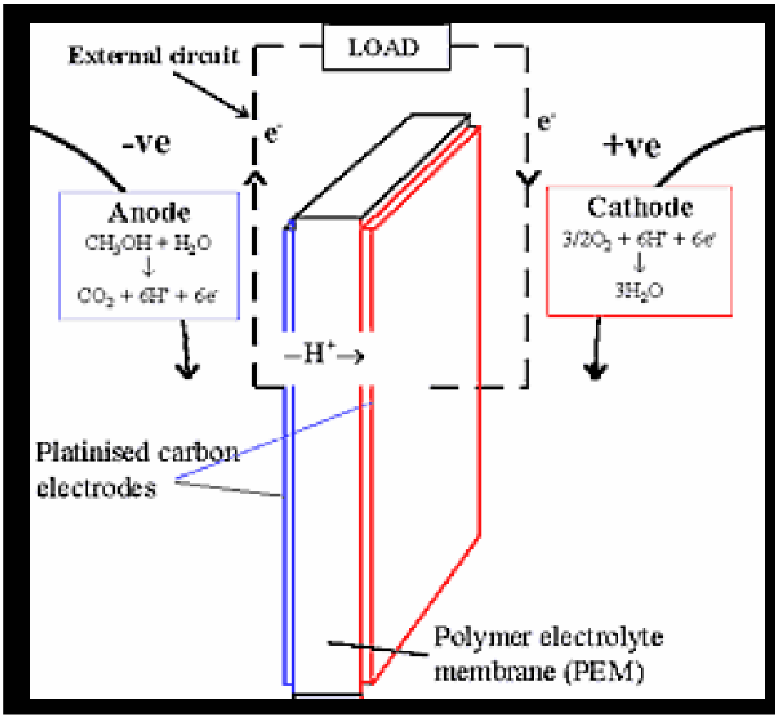


Figure 2.5: Direct Methanol Fuel Cell

Reaction

At cathode: $$\frac{3}{2}\mathrm{O_2} + 6H^+ + 6\mathrm{e}^- \rightarrow 3\mathrm{H_2O} \quad (2.13)$$

At anode $$\mathrm{CH_3OH} + \mathrm{H_2O} \rightarrow 6H^+ + \mathrm{CO_2} + 6\mathrm{e}^- \quad (2.14)$$

Overall $$\frac{3}{2}\mathrm{O_2} + \mathrm{CH_3OH} \rightarrow 2\mathrm{H_2O} + \mathrm{CO_2} \quad (2.15)$$

2.2.6 Solid-oxide fuel cell (SOFC)

In solid oxide fuel cells, negative ions travel through the electrolyte to the anode where they combine with hydrogen to generate water and electrons. The electrolyte is composed of a solid oxide, usually zirconia (stabilized with other rare earth element oxides like yttrium), and takes the form of a ceramic.

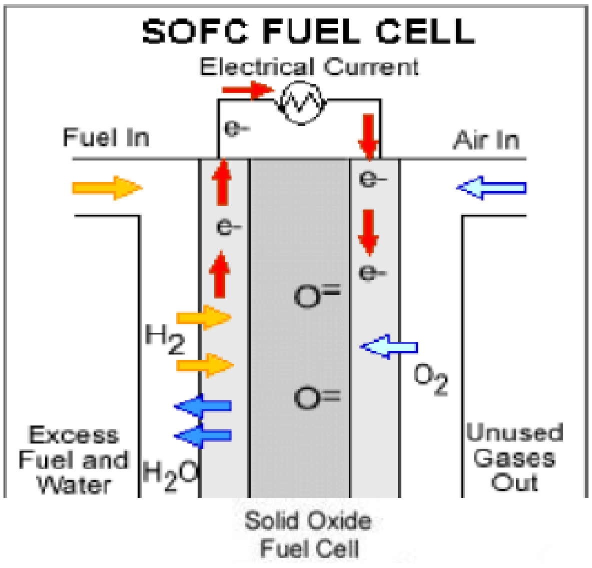


Figure 2.6: Solid Oxide Fuel Cell

Reaction

At cathode: $\frac{1}{2}O_2 + 2e^- \rightarrow O^{-2}$ **(2.16)**

At anode $H_2 + O^{-2} \rightarrow H_2O + 2e^-$ **(2.17)**

Overall $$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$ **(4)**

Table 2.1: Fuel Cells Types.

Fuel cell type	**Electrolyte**	**Mobile ion**	**Fuel**	**oxidant**	**Operating Temperature**	**Efficiency (%)**
Alkaline Fuel Cell (AFC)	Mobilized or Immobilized Potassium Hydroxide in asbestos matrix	OH^-	H_2	O_2(pure)	50-200°C	60%

Proton electrolyte membrane) fuel cells (PEMFC)	Hydrated Polymeric Ion Exchange Membranes	H^+	H_2(pure or reformed)	Air	40-100°C	40-60%
Direct Methanol Fuel Cell (DMFC)	Polymeric membrane Proton conductor	H^+	Methanol	Air	60-100°C	20-40%
Phosphoric Acid Fuel Cell (PAFC)	Immobilized Liquid Phosphoric Acid in SiC	H^+	H_2(pure or reformed)	Air	205°C	40%
Molten Carbonate Fuel Cell (MCFC)	Immobilized Liquid Molten Carbonate in LiAlO2 Nickel	CO_3^{2-}	H_2(pure or reformed)	Air	650°C	50-60%
Solid Oxide Fuel Cell (SOFC)	Perovskites (Ceramics)	O^{2-}	H_2(pure or reformed)	Air	500-1000°C	60-80%

2.3 Classification of Fuel Cells

Fuel cells can be classified into two classes:

- High-temperature Fuel Cells (for stationary power applications)
- Low-temperature Fuel Cells (for transportation applications)

The low-temperature fuel cells are ideally suited to transportation applications and high temperature fuel cells are suited to power generation. It is important to distinguish between the low-temperature and high temperature variants because it places a different demand on the fuel cell stack and system.

2.3.1 Low temperature fuel cells

Proton exchange membrane cells (PEMFC), alkaline fuel cells (AFC), and direct methanol cells (DMFC) are distinguished by their low operating temperature. Which makes it different from other cells in that they can be run directly after start-up and at low-temperature conditions.

2.3.1.1 Characteristics of Low-temperature Fuel Cells

The low-temperature fuel cells can be distinguished by the following common characteristics:

a. Primary application – Transportation and portable devices

b. They require a relatively pure supply of hydrogen as a fuel.

c. They generally incorporate precious metal electrocatalysts to improve performance.

d. They exhibit fast dynamic response and quick startup.

2.3.2 High temperature fuel cells

High-temperature fuel cells are essentially solid oxide cells (SOFC), phosphoric acid cells (PAFC), and molten carbonate cells (MCFC). These kinds of fuel cells are commonly applied for fixed applications where constant power generation is required. This is due to its large temperature changes which need a long time to start up.

2.3.2.1 Characteristics of High Temperature Fuel Cells

The high temperature fuel cells can be classed as having the following general features:

a. Primary application – Stationary Power Generation

b. Fuel flexibility: they can be operated on a range of hydrocarbon fuels.

c. They don’t require platinum as a catalyst.

d. They can generate useful high-grade waste heat and are therefore well suited in downstream processes for cogeneration purposes.

e. They exhibit long start-up times and are sensitive to thermal transients.

f. They suffer from severe materials problems to withstand the operating temperature, particularly in the balance of plant (piping, heat exchangers, etc.). Few materials can work for extended periods without degradation within a chemical environment at high temperatures.

g. Reliability and durability is a concern, again due to the operating temperature.

h. They can be integrated with a gas turbine, offering high efficiency combined cycles.

EXERCISES

Exercise 2.1:

1. What are the six main types of fuel cells?

2. What are the advantages and disadvantages of each type of fuel cell?

Exercise 2.2:

Which type of fuel cell is best suited for each of the following applications?

- Portable electronics
- Transportation
- Stationary power generation
- Spacecraft

Exercise 2.3:

Compare and contrast the different types of fuel cells.

Exercise 2.4:

Classify the following fuel cells into high-temperature and low-temperature fuel cells:

- Alkaline fuel cell (AFC)
- Phosphoric acid fuel cell (PAFC)
- Proton exchange membrane fuel cell (PEMFC)
- Solid oxide fuel cell (SOFC)
- Molten carbonate fuel cell (MCFC)
- Direct methanol fuel cell (DMFC)

2.4 Conclusion

In this chapter, we explored the different types of fuel cells and the criteria that distinguish them, including their electrolytes, operating temperatures, and fuel requirements. Fuel cells were broadly classified into low-temperature systems (such as PEMFCs and AFCs) and high-temperature systems (such as SOFCs and MCFCs). Each category has specific advantages and limitations, making them more suitable for particular applications ranging from portable devices and transportation to large-scale stationary power generation.

Chapter 3: Fuel Cell Applications

Chapter 3: Fuel Cell Applications

Course objective

At the end of this chapter, the student will be able to:

1. **Identify** the main advantages and disadvantages of fuel cell technology.
2. **Understand** the operating principle of fuel cell electric vehicles (FCEVs) and how they produce energy to drive an electric motor.
3. **Evaluate** the potential of fuel cells in the transportation sector compared with conventional vehicles and battery-electric cars.

3.1 Introduction

Fuel cells have the potential to play a major role in the transportation sector in the future. They offer a number of advantages over traditional battery-powered vehicles, including high efficiency, zero emissions, and fast refueling. As the challenges associated with fuel cells are addressed, FCEVs are likely to become more widely adopted**.**

3.2 The advantages of fuel cells

Fuel cells are usually offered as the solution of the future in the domains of electric power generation, automotive sectors. This attraction is justified by heir many advantages:

- **Clean:** Fuel cells produce no emissions other than water vapor and heat, making them a clean and environmentally friendly source of energy.
- **Efficient:** Fuel cells are more efficient than traditional power generation technologies, such as internal combustion engines. This means that fuel cells can produce more electricity from the same amount of fuel.
- **Versatile:** Fuel cells can be used to power a wide range of applications, from portable electronic devices to transportation vehicles to stationary power plants.
- **Reliable:** Fuel cells are reliable and have a long lifetime

3.3 The disadvantages of fuel cells

However there are also disadvantages which are as follows:

- **Cost:** Fuel cells are currently more expensive than traditional power generation technologies.
- **Durability:** Some types of fuel cells are not as durable as traditional power generation technologies.
- **Fuel infrastructure:** Hydrogen, the most common fuel used in fuel cells, is not as widely available as other fuels, such as gasoline and natural gas.Moerover, Transporting and storing hydrogen is much more complex than transporting and storing natural gas and coal.
- Fuel cells require complex control and support systems
- **Delicate technology:** corrosion problems, catalyst lifespan problems, electrode humidification problems, heat dissipation problems**(**Fuel cells can generate a lot of heat)

3.4 Fuel cells for electric vehicles

How do fuel cells work?

Fuel cells generate electricity by combining hydrogen and oxygen. The hydrogen is stored in a tank on the vehicle, and the oxygen is taken from the air. The fuel cell stack converts the hydrogen and oxygen into electricity, water, and heat. The electricity is used to power the vehicle's electric motor, and the water is released through the tailpipe.

1. **Fuel Cell Stack** – An aggregate of numerous fuel cells that combine oxygen and hydrogen to generate electricity and power the electric motor
2. **Fuel Tank** – Hydrogen gas is stored in carbon-fiber reinforced tanks to provide fuel to the fuel-cell stack
3. **Electric Motor** – Powers the car using energy produced in the fuel cell stack
4. **Battery** – Captures energy from regenerative braking and provides additional power to the electric motor

5. **Exhaust** – The byproduct of the reaction occurring in the fuel cell stack is water vapor, which is emitted through the exhaust

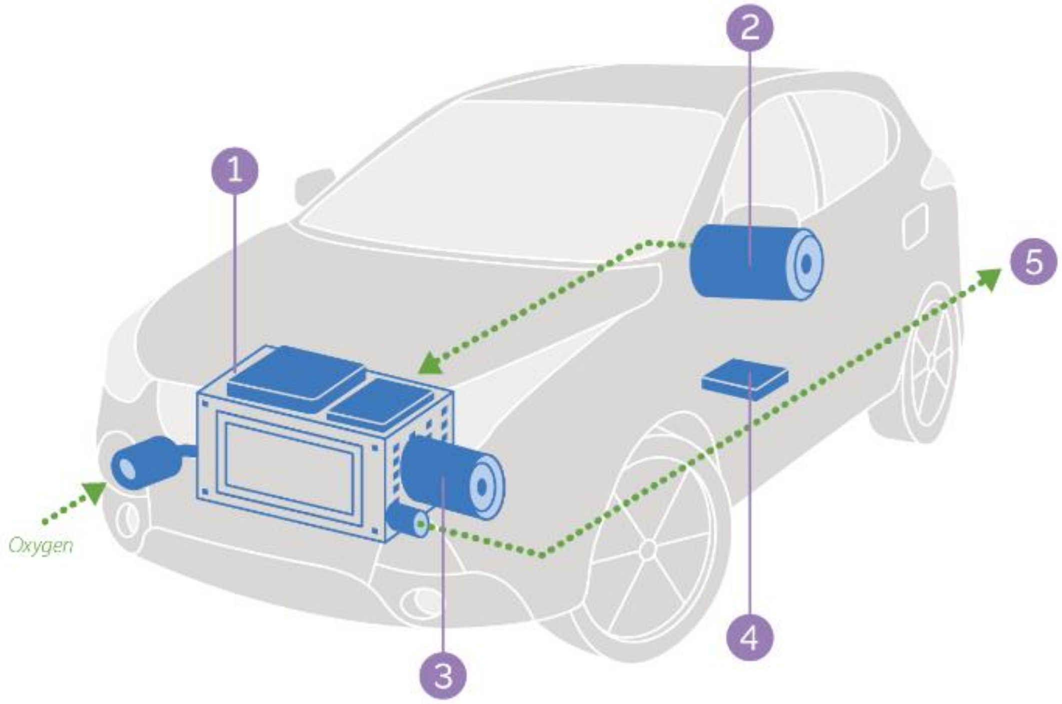


Figure 3.1: **Electric vehicles**

3.4.1 Types of fuel cells for electric vehicles

There are several different types of fuel cells that can be used in electric vehicles, but the most common type is the proton exchange membrane (PEM) fuel cell.

The following are the reasons why PEM fuel cells are the most common type of fuel cell used in electric vehicles:

- **Power density:** PEM fuel cells have a high power density, meaning that they can generate a lot of power in a small space. This is important for electric vehicles, which need to be able to generate enough power to propel a vehicle of a given size.
- **Operating temperature:** PEM fuel cells operate at a relatively low temperature, which makes them easier to start and stop than other types of fuel cells. This is also important for electric vehicles, which need to be able to be refueled quickly.
- **Solid structure:** PEM fuel cells are composed of solid elements, which makes them more durable than other types of fuel cells. This is important for electric vehicles, which are subjected to a lot of vibration and shock.

In addition to these reasons, PEM fuel cells are also relatively inexpensive to produce. This makes them a more cost-effective option for electric vehicles than other types of fuel cells.

EXERCISES

Exercise 3.1:

List the advantages and disadvantages of fuel cells.

Exercise 3.2:

Discuss the advantages and disadvantages of using fuel cells to power electric vehicles

3.5 Conclusion

In this chapter, we examined the advantages and disadvantages of fuel cells**,** highlighting both their potential and their challenges. Fuel cells offer many benefits, including high efficiency, low emissions, silent operation, and flexibility in applications ranging from portable devices to transportation and stationary power generation. However, they also face obstacles such as high production costs, durability issues, and the need for advanced hydrogen storage and distribution infrastructures.

We also explored how **fuel cell electric vehicles (FCEVs)** work, showing how hydrogen is converted into electricity through the electrochemical reaction inside the fuel cell stack. This electricity powers the electric motor, with water vapor as the only emission, making fuel cell cars a promising alternative for clean mobility.

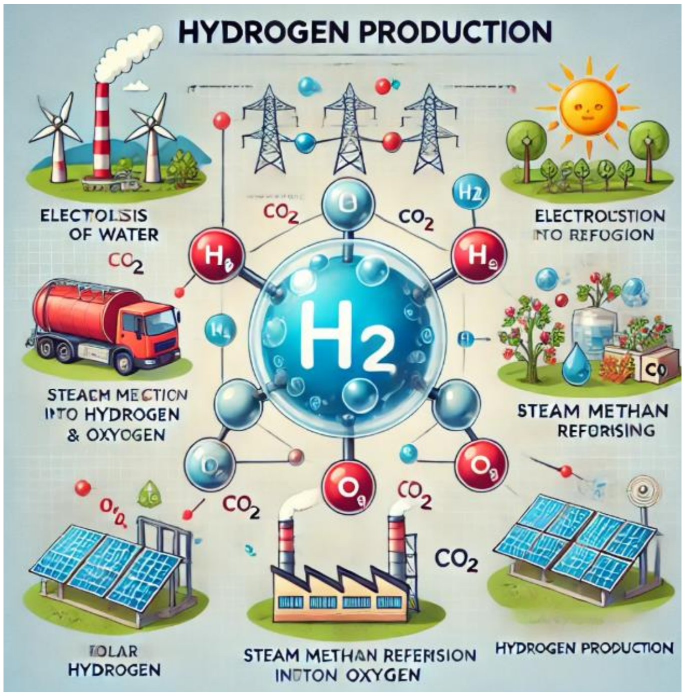
Chapter 4: Hydrogen production

Chapter 4: Hydrogen production

Course objective

At the end of this chapter, the student will be able to:

1. **Describe** the main hydrogen production methods and the principles behind them.
2. **Distinguish** between fossil-based and renewable-based hydrogen production technologies.
3. **Evaluate** the advantages, limitations, and environmental impacts of each production method.
4. **Appreciate** the role of hydrogen as a clean energy carrier and its potential contribution to the global energy transition.



4.1 Introduction

Hydrogen is a versatile energy carrier that has the potential to play a major role in the transition to a clean and sustainable energy future. Hydrogen is a clean-burning fuel that produces no emissions when it is burned, only water vapor. Hydrogen can be produced from a variety of sources, including fossil fuels, water electrolysis, and renewable energy sources.

4.2 Hydrogen Production from fossil fuels

1. Steam methane reforming
2. Coal gasification
3. Partial oxidation of methane

4.2.1 Steam Methane Reforming (SMR) for Hydrogen Production

Steam methane reforming (SMR) is a thermochemical process for producing hydrogen from natural gas (methane). It is the most common method for producing hydrogen, accounting for about 80% of global hydrogen production.

4.2.1.1 Principles of SMR

- SMR is based on the reaction between methane (**CH_4**) and steam (**H_2O**). This reaction is endothermic, meaning that it requires heat to proceed. The reaction occurs in a reactor at high temperatures (700-1100°C) and pressures (3-25 bar) in the presence of a catalyst to produce hydrogen (**H_2**) and carbon monoxide (**CO**) :

$$\mathbf{CH_4 + H_2O \rightarrow CO + 3H_2} \qquad \mathbf{(4.1)}$$

- The steam and methane are preheated before entering the reactor. The preheating is necessary to increase the rate of the reaction and to prevent the formation of unwanted byproducts.
- The reaction products, hydrogen and carbon monoxide, are then separated from each other. The hydrogen is then purified to remove any impurities.
- Subsequently, in what is called the "water-gas shift reaction," the carbon monoxide and steam are reacted using a catalyst to produce carbon dioxide and more hydrogen

$$\mathbf{CO + H_2O \rightarrow CO_2 + H_2} \qquad \mathbf{(4.2)}$$

4.2.1.2 SMR process diagram

- **Preheat:** Steam and methane are preheated to a high temperature.
- **Reactor:** The preheated steam and methane enter the reactor, where they react to form hydrogen and carbon monoxide.
- **Shift Conversion:** The reaction products exit the reactor and enter the shift converter. The shift converter converts some of the carbon monoxide to carbon dioxide and additional hydrogen.
- **CO_2 Removal:** The carbon dioxide is removed from the gas stream.
- **Purification:** The hydrogen is purified to remove any impurities.
- **Hydrogen Product:** The purified hydrogen is the final product of the SMR process.

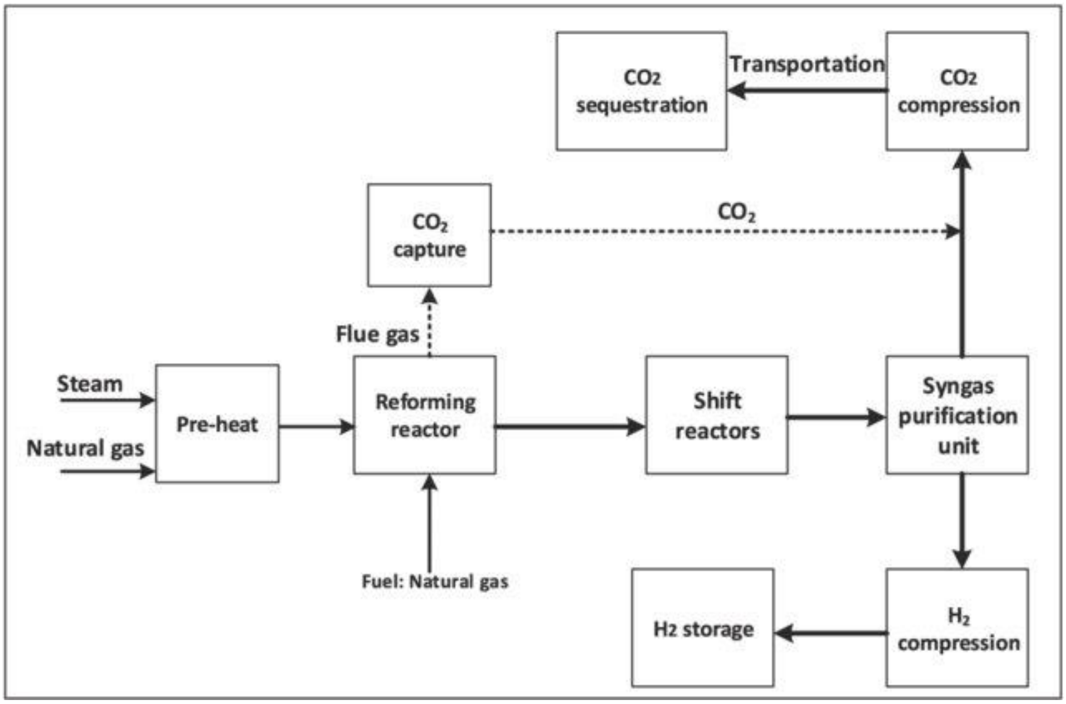


Figure 4.1: SMR process diagram

4.3 Hydrogen Production by Water Electrolysis

Water electrolysis is the process of using electricity to split water into hydrogen and oxygen. The overall reaction for water electrolysis is:

$$2H_2O\ (l) + \text{electrical energy} \rightarrow 2H_2\ (g) + O_2\ (g) \qquad (4.3)$$

This reaction takes place in a unit called an electrolyzer.

4.3.1 The components of an electrolyzer

The electrolyzer (electrolysis cell) consists of two electrodes called cathode and anode. A cathode is a negatively charged electrode, while the anode is positively charged. Both cathodes are separated by a membrane called electrolyte and surrounded by water.

4.3.2 Types of electrolyzers

There are three main types of electrolyzers: alkaline electrolyzers, proton exchange membrane (PEM) electrolyzers, and solid oxide electrolyzers (SOEs)

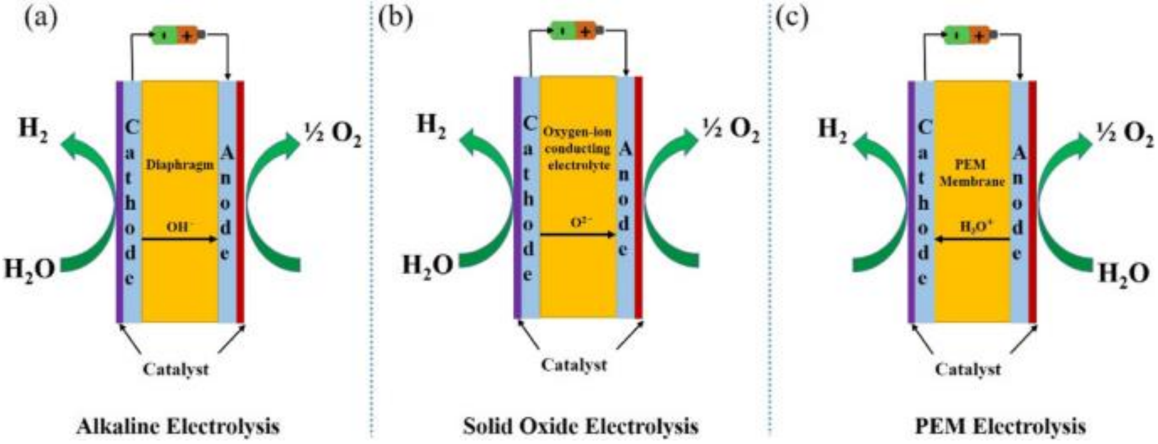


Figure 4.2: Type of electrolyzers

4.3.2.1 Alkaline electrolyzers (AEL)

Alkaline electrolyzers are the oldest and most mature type of water electrolysis. They use an alkaline electrolyte, typically potassium hydroxide (KOH) or sodium hydroxide (NaOH), the electrodes are made of metal. Between the two electrodes is a diaphragm that is non-permeable to hydrogen and oxygen. They operate at temperatures of around 80-90°C.

5.1 The basic principle of alkaline electrolysis

The basic principle of alkaline electrolysis is to pass an electric current through water in the presence of an alkaline electrolyte. The electrolyte is a substance that allows the hydroxide ions (OH^-) to move freely, but does not conduct electricity itself. The electric current causes the water molecules to split into hydrogen ions (H^+) and hydroxide ions (OH^-). The hydrogen ions then move to the negative electrode, where they are reduced to hydrogen gas (H_2). The hydroxide ions move to the positive electrode, where they are oxidized to oxygen gas (O_2).

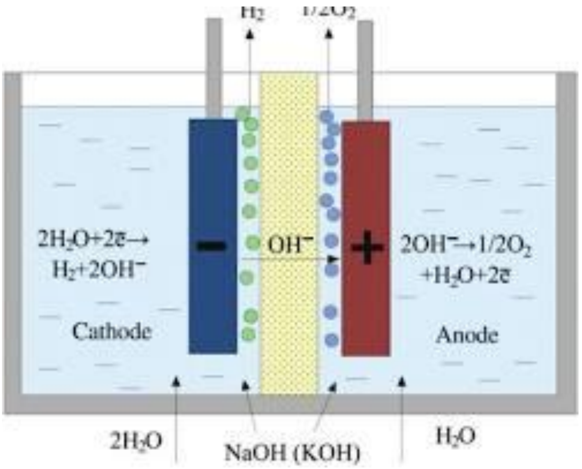


Figure 4.3: The basic principle of alkaline electrolysis

At cathode: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$ **(4.4)**

At anode: the hydroxide ions (OH-) in the electrolyte lose electrons and are oxidized to oxygen gas (O2) and water:

$$2OH^- \rightarrow 1/2O_2 + H_2O + 2e^- \qquad (4.5)$$

Overall: $$H_2O(\mathrm{L}) + electrical\ energy \rightarrow H_{2(\mathrm{g})} + \frac{1}{2}O_{2(\mathrm{g})} \qquad (4.6)$$

4.3.2.2 Proton exchange membrane (PEM) electrolyzers

In a polymer electrolyte membrane (PEM) electrolyzer, the electrolyte is a solid specialty plastic material.

5.1 The basic principle of PEM electrolysis

- Water reacts at the anode to form oxygen and positively charged hydrogen ions (protons).
- The electrons flow through an external circuit and the hydrogen ions selectively move across the PEM to the cathode.
- At the cathode, hydrogen ions combine with electrons from the external circuit to form hydrogen gas.

Anode Reaction: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$ **(4.7)**
Cathode Reaction: $4H^+ + 4e^- \rightarrow 2H_2$ **(4.8)**
Overall: $2H_2O \rightarrow O_2 + 2H_2$ **(4.9)**

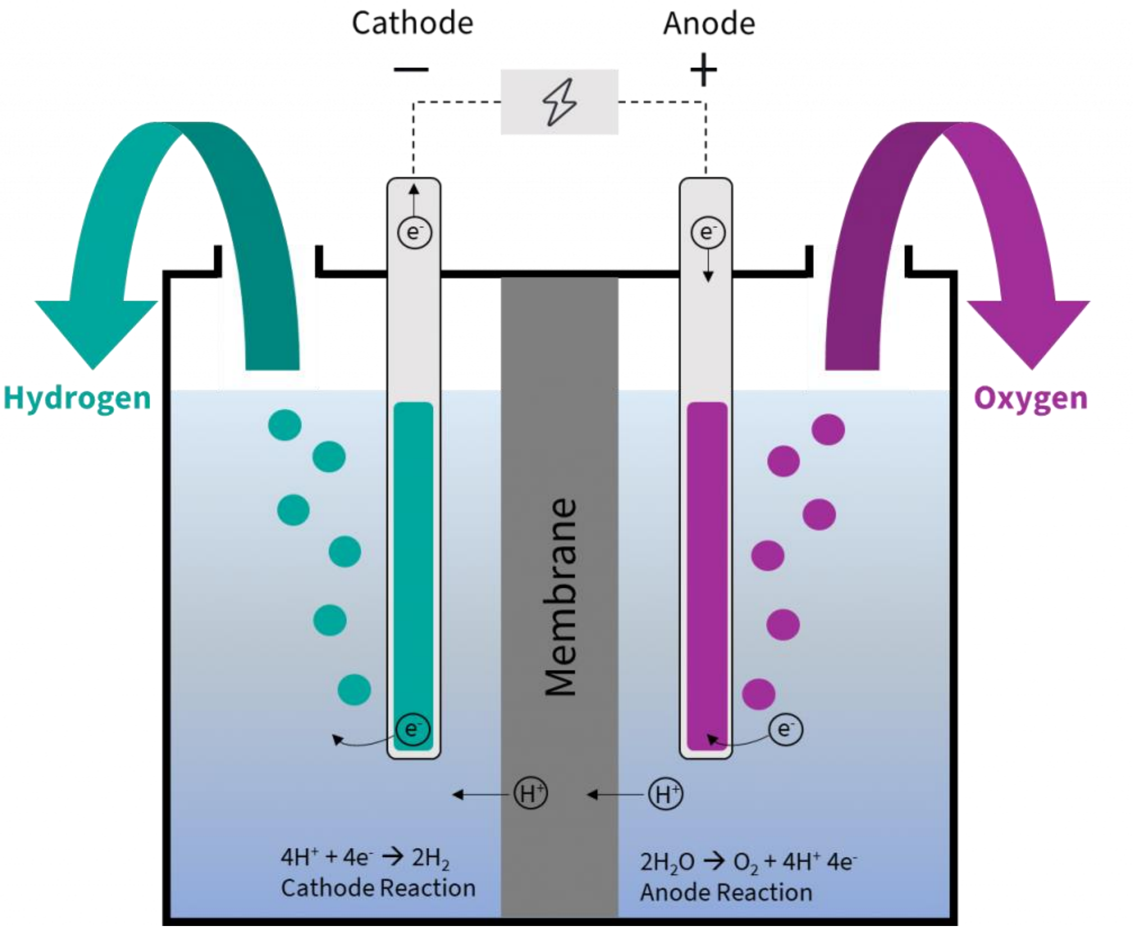


Figure 4.4: Polymer electrolyte membrane (PEM) electrolyzer

4.3.2.3 Solid oxide electrolyzers (SOEC)

Solid oxide electrolyzers, which use a solid ceramic material as the electrolyte that selectively conducts negatively charged oxygen ions (O^{2-}) at elevated temperatures (700-800°C), generate hydrogen in a slightly different way.

5.1 The basic principle of SOEC electrolysis

- Steam at the cathode combines with electrons from the external circuit to form hydrogen gas and negatively charged oxygen ions.
- The oxygen ions pass through the solid ceramic membrane and react at the anode to form oxygen gas and generate electrons for the external circuit.

At cathode: $\mathbf{H_2O + 2e^- \rightarrow H_2 + O^{2-}}$ **(4.10)**

At anode: $\mathbf{O^{2-} \rightarrow 1/2O_2 + 2e^-}$ **(4.11)**

4.3.3 Water electrolysis process diagram

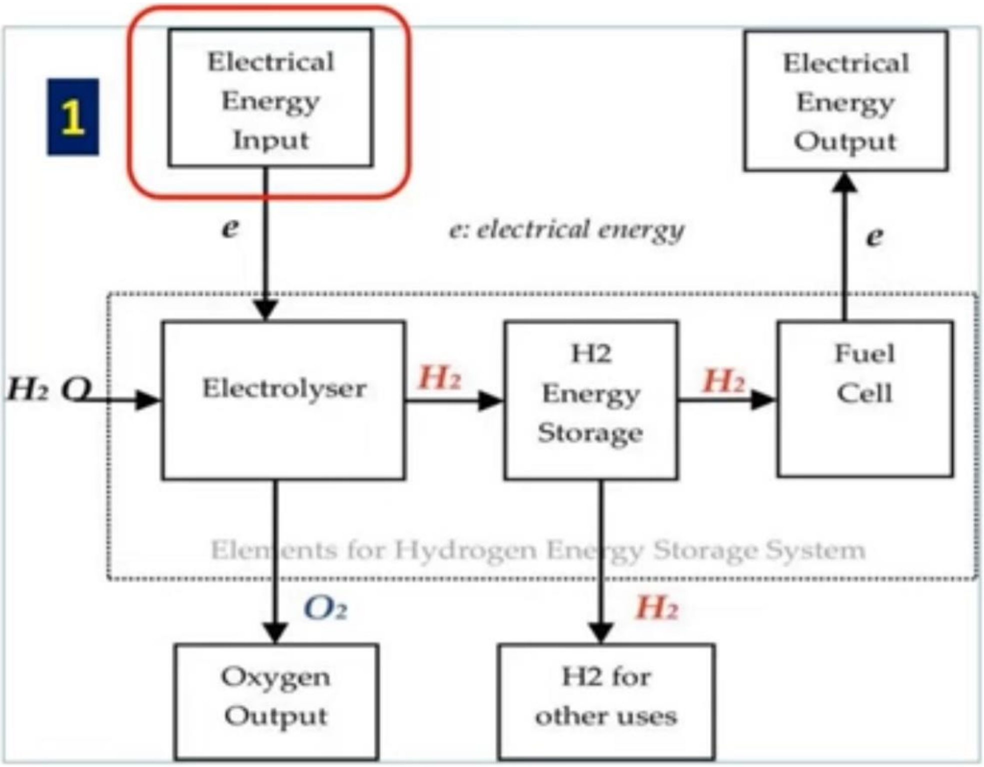


Figure 4.5: Water electrolysis process diagram

4.4 Production from renewable energies

Several renewable energy sources can be utilized to produce hydrogen:

- ✓ Thermal solar (high temperature)
- ✓ Photovoltaic (Photo-electrolysis)
- ✓ Production from biomass

4.4.1 Production from Thermal solar

This technique utilizes concentrated solar energy to drive thermochemical reactions that split water molecules into hydrogen and oxygen. These high-temperature solar thermochemical processes, typically operating between 500°C and 1500°C, offer efficient hydrogen production from solar energy.

Thermochemical Cycles for Hydrogen Production

Sulfur-Iodine (SI) cycle: This cycle involves a series of reactions between sulfur dioxide (SO_2), iodine (I_2), and water (H_2O) to produce hydrogen (H_2) and sulfuric acid (H_2SO_4). The sulfuric acid is then decomposed back into sulfur dioxide and water using thermal energy, completing the cycle.

4.4.1.1 Steps of the Sulfur-Iodine (SI) Cycle

Here's a step-by-step explanation of how heat from solar thermal concentrators is utilized in the SI cycle:

1. **Solar Energy Collection:** Solar radiation is captured by a concentrating solar collector, such as a parabolic trough or heliostat field, and concentrated onto a central receiver.

2. **Heat Transfer to Reactor:** The concentrated solar energy is transferred from the receiver to a reactor through a heat transfer fluid, such as molten salt or liquid metal.

3. **Bunsen Reaction:** The heated fluid enters the reactor, where it provides the thermal energy required for the first step of the SI cycle, the Bunsen reaction. In this reaction, sulfur dioxide (SO_2), iodine (I_2), and water (H_2O) react to produce sulfuric acid (H_2SO_4) and hydrogen iodide (HI) at 120°C (an exothermic reaction).

$$SO_2 + I_2 + 2H_2O \rightarrow H_2SO_4 + 2HI \qquad (120°C) \qquad \textbf{(4.12)}$$

4. **Intermediate Heat Transfer:** The heat from the Bunsen reaction is transferred to another heat transfer fluid loop, which circulates through the reactor and absorbs the heat generated by the exothermic reaction.
5. **Hydrogen Iodide Decomposition:** The heated fluid from the Bunsen reaction loop is then directed to a separate reactor, where it provides the thermal energy for the second step of the SI cycle, the hydrogen iodide decomposition. In this reaction, HI decomposes into hydrogen (H_2) and iodine (I_2) at around 500°C (endothermic reaction).

$$2HI \rightarrow H_2 + I_2 \qquad (200\text{-}500°C) \qquad \textbf{(4.13)}$$

6. **Sulfuric Acid Decomposition:** The heat from the hydrogen iodide decomposition reaction is also transferred to the intermediate heat transfer fluid loop. The heated fluid is then circulated to a third reactor, where it provides the thermal energy for the third step of the SI cycle, the sulfuric acid decomposition. In this reaction, H_2SO_4 decomposes back into SO_2, water (H_2O), and oxygen (O_2) at around 850°C(endothermic reaction).

$$H_2SO_4 \rightarrow SO_2 + H_2O + 1/2\ O_2 \qquad (850°C) \qquad \textbf{(4.14)}$$

7. **Hydrogen Separation:** The hydrogen produced in the hydrogen iodide decomposition step is separated from the iodine and other reaction products. The separated hydrogen is then collected and stored for use.

8. **Regeneration of Reactants:** The SO_2 and I_2 recovered from the sulfuric acid decomposition reaction are recycled back to the Bunsen reaction, completing the cycle.

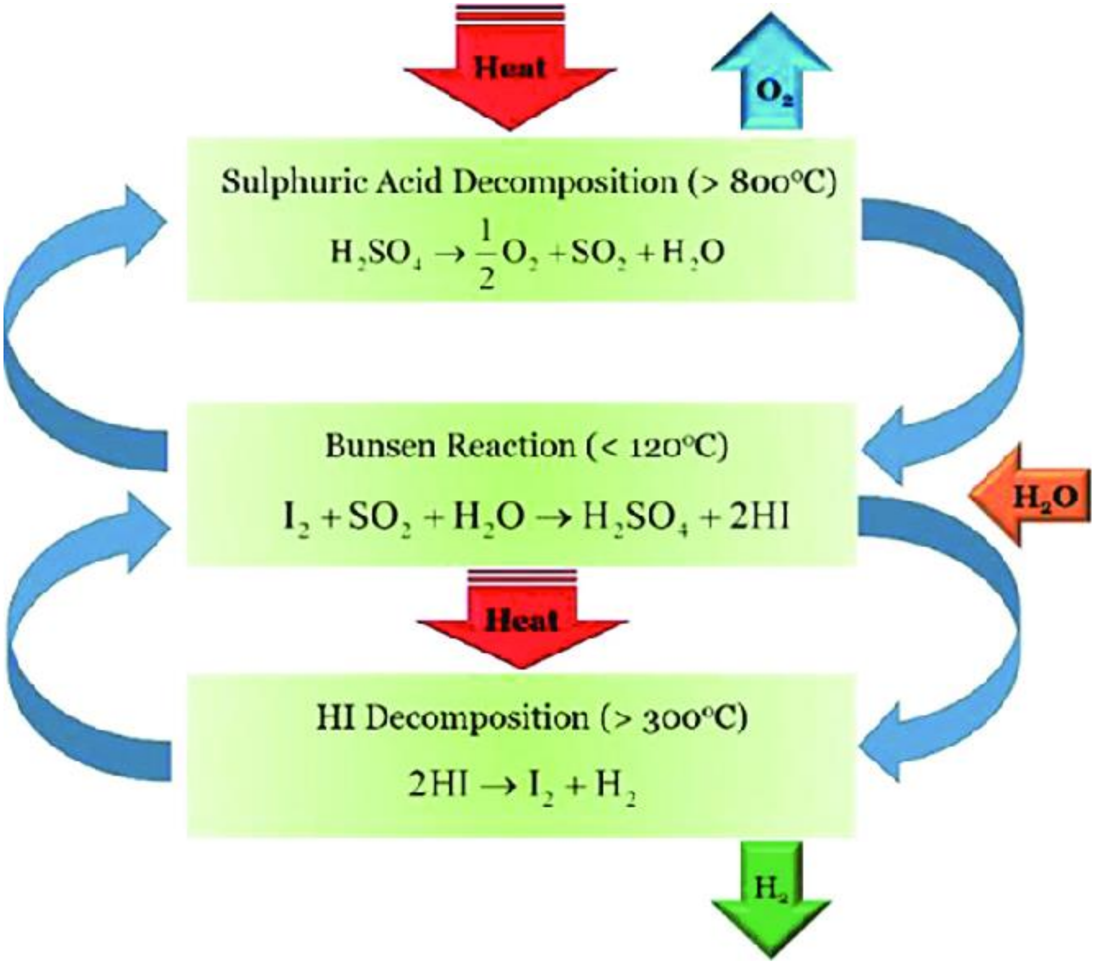
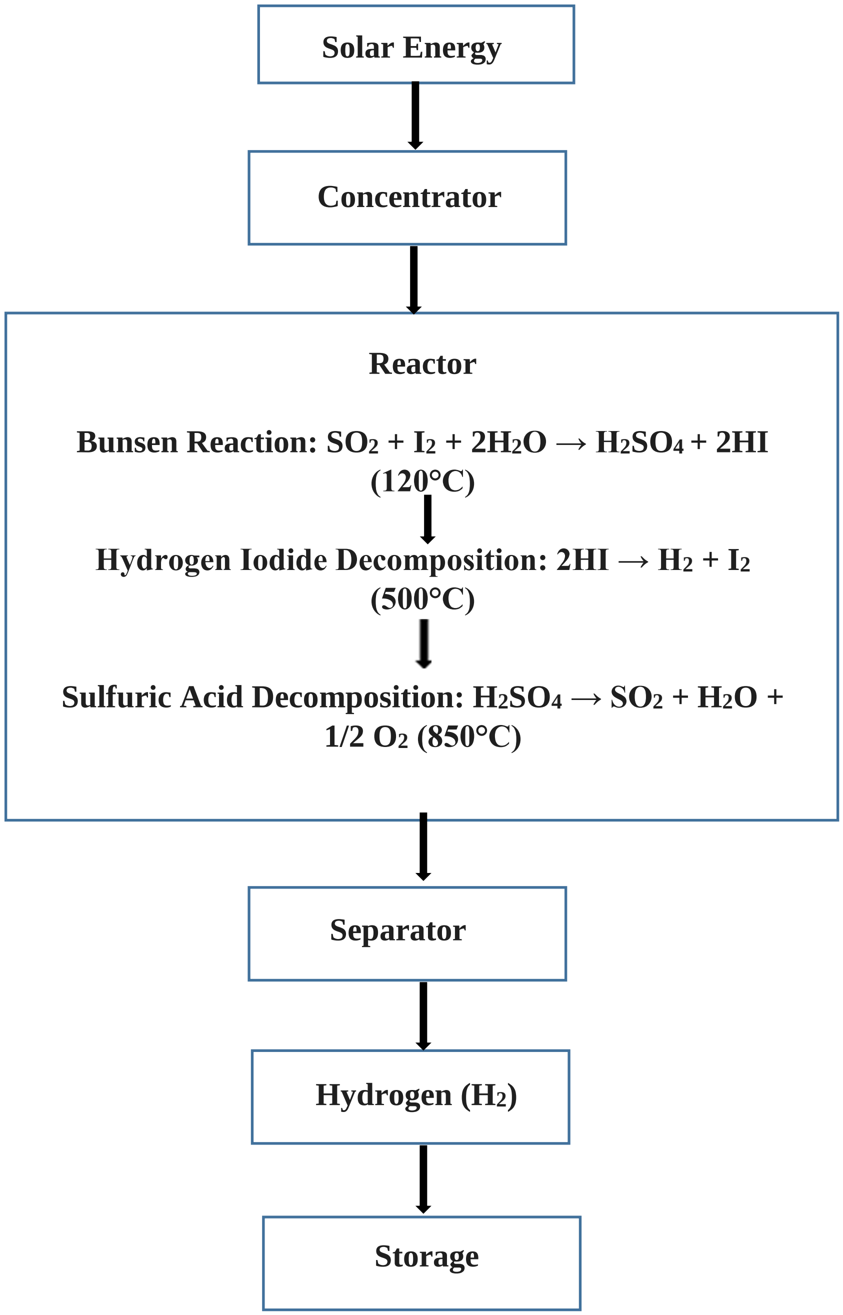


Figure 4.6: Sulfur-Iodine Cycle

4.4.1.2 Diagram of the sulfur-iodine (SI) cycle for hydrogen production



4.4.2 Production from Photovoltaic (Photo-electrolysis)

Producing hydrogen through photoelectrochemical (PEC) water splitting involves utilizing sunlight to generate electricity from a photovoltaic (PV) cell and then using that electricity to split water molecules into hydrogen and oxygen. PECs consist of a photoanode (**Barium titanate** $BaTiO_3$) and a photocathode (pt), typically made from semiconductor materials. The photoanode absorbs sunlight and generates electron-hole pairs. The electrons are transferred to the external circuit, generating an electric current. The holes at the photoanode oxidize water molecules, releasing oxygen and protons. These protons travel through the electrolyte to the photocathode, where they combine with electrons to produce hydrogen gas

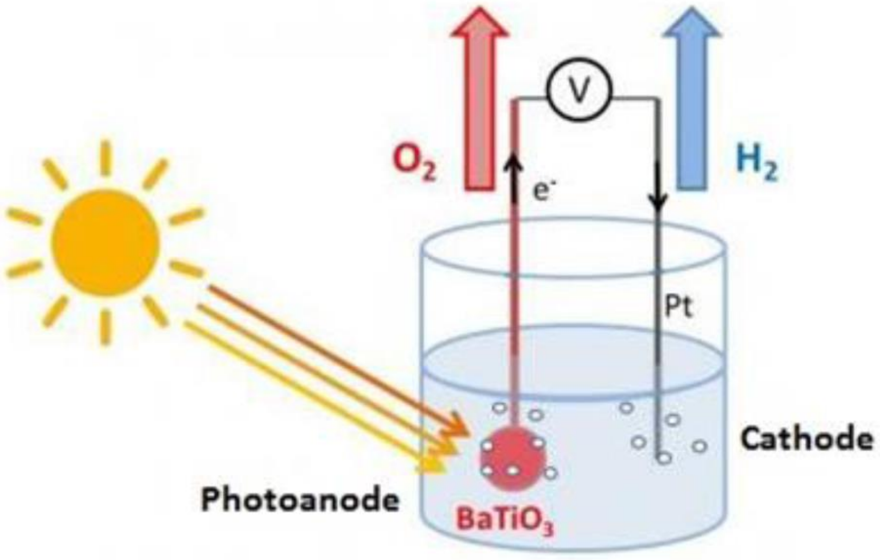


Figure 4.7: Producing hydrogen through photoelectrochemical (PEC) water

4.4.2.1 Steps of Photoelectrochemical Water Splitting

1. Light Absorption: Sunlight strikes a semiconductor photo electrode, typically composed of materials like titanium dioxide (TiO_2), hematite (Fe_2O_3), or silicon (Si).
2. Excitation of Electrons: The absorbed light energy excites electrons in the semiconductor, promoting them to a higher energy state, creating electron-hole pairs.
3. Charge Separation: The excited electrons move to the cathode, while the holes remain at the anode. This separation of charges creates an electric potential difference.
4. Oxygen Evolution Reaction (OER): At the anode, the holes react with water molecules to produce oxygen gas and release protons (H^+).

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \qquad (4.15)$$

5. Hydrogen Evolution Reaction (HER): At the cathode, the electrons react with protons (H^+) from water to produce hydrogen gas.

$$4H^+ + 4e^- \rightarrow 2H_2 \qquad (4.16)$$

4.5 Production hydrogen from biomass

Producing hydrogen from biomass, also known as biomass gasification, is a promising method for generating clean hydrogen using renewable energy sources. This process involves converting organic materials, such as agricultural residues, wood waste, or municipal solid waste, into hydrogen and other products through a thermochemical process.

Steps of Biomass Gasification for Hydrogen Production:

1. Feedstock Preparation: Biomass feedstock is first prepared by drying, grinding, and sieving to ensure uniform particle size and moisture content. Consistent feedstock properties are crucial for efficient gasification
2. Gasification Reactor: The prepared biomass is fed into a gasification reactor, where it is heated under controlled conditions in the presence of a gasification agent, typically air, steam, or a mixture of both.
3. Thermal Decomposition: The high temperatures in the reactor cause the biomass to decompose into its constituent elements, primarily carbon, hydrogen, and oxygen.
4. Syngas Formation: The decomposition process produces a mixture of gases called syngas, composed primarily of carbon monoxide (CO), hydrogen (H_2), and carbon dioxide (CO_2).
5. Water-Gas Shift Reaction: The syngas is then passed through a water-gas shift reactor, where a catalytic reaction occurs between CO and steam, converting CO into additional hydrogen and CO_2.
6. Hydrogen Purification: The resulting gas mixture is purified to remove impurities, such as CO_2, sulfur compounds, and particulates, leaving a stream of pure hydrogen gas.

EXERCISES

Exercise 4.1:

1-Provide the methods of hydrogen production from renewable energies.

2- Each of these methods has its own advantages and disadvantages. Explain

Exercise 4.2:

1- What mean SMR.

2- Explain this process.

Exercise 4.3:

1- Provide the methods of hydrogen production from water electrolysis.

2- Explain the basic principle of one method of water electrolysis with diagram.

Exercise 4.4:

1- Explain the methods of hydrogen production from Sulfur-Iodine (SI) cycle.

2- Draw Sulfur-Iodine Cycle.

4.6 Conclusion

In this chapter, we explored the different methods of hydrogen production, emphasizing both conventional and renewable pathways. Conventional techniques such as steam methane reforming (SMR) and coal gasification remain dominant due to their maturity and cost-effectiveness, but they are associated with significant carbon emissions. On the other hand, water electrolysis**,** biological processes, and thermochemical cycles provide cleaner alternatives, especially when powered by renewable energy sources like solar, wind, or biomass.

We highlighted the key challenges of hydrogen production, including energy efficiency, cost reduction, and the need for sustainable large-scale infrastructure. Addressing these issues is crucial for positioning hydrogen as a cornerstone of the future low-carbon energy system.

Chapter 5: Fuel Cell Modeling

Chapter 5: Fuel Cell Modeling

Course objective

At the end of this chapter, the student will be able to:

1. **Apply** the Nernst equation to calculate the reversible voltage of a fuel cell.
2. **Identify** and **quantif**y the different losses that reduce the cell voltage.
3. **Calculate** power output and reactant flow requirements from current–voltage data.
4. **Evaluate** the efficiency of a fuel cell under different operating conditions.
5. **Perform** a basic sizing of a fuel cell system to meet a given power demand.

5.1 Introduction

Fuel cell modeling is an essential tool for understanding, optimizing, and designing fuel cell systems. It involves creating mathematical models that capture the complex electrochemical and physical processes occurring within fuel cells.

5.2 Standard Reaction Quantities

A fuel cell is based on the electrochemical reaction between hydrogen and oxygen:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + \textbf{electricity} + \textbf{heat} \qquad \textbf{(5.1)}$$

- **Standard Gibbs free energy (ΔG°):** Determines the maximum useful work (electrical energy) obtainable.
- **Standard enthalpy (ΔH°):** Represents the total energy released (both electricity + heat).

5.2.1 Gibbs energy

Gibbs energy is basically free energy available for conversion into usable work. The change in Gibbs free energy is given by:

$$\Delta G = \Delta H - T\Delta S$$

Where:

- ΔG is the Gibbs free energy (J)
- ΔH is the enthalpy change (J)

- T is the temperature (K)
- ΔS is the entropy change (J/K)

The Gibbs free energy of formation G_f can also be expressed in terms of products and reactants as follows:

$$\Delta G_f = \Delta G_f(Product) - \Delta G_f(reactants)$$

We can demonstrate the Gibbs energy of formation with the help of the following reaction:

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O \qquad \textbf{(5.2)}$$

$$\Delta G_f = (G_f)_{H_2O} - \left[(G_f)_{H_2} + \frac{1}{2}\,(G_f)_{O_2}\right]$$

5.3 Electromotive force (EMF)

The electromotive force (EMF) of a fuel cell is the maximum potential difference that can be produced by the fuel cell reaction. It is measured in volts (V). The electromotive force (EMF) is given by the change in Gibbs free energy of the reaction:

$$emf = E^{\circ} = -\frac{\Delta G}{nF}$$

Where:

n: The number of electrons participating in the reaction
F: (96485 C mol^{-1}) is Faraday constant
E°: The ideal potential of the cell (V).

For example, for DMFC the cell reaction is given by:

$$CH_3OH + 3/2\ O_2 \rightarrow 2H_2O + CO_2 \qquad \textbf{(5.3)}$$

- 6e− are passing through the external circuit for each methanol molecule. The change in Gibbs free energy for is **−698 kJ/mol**. By using Eq., we obtain

$$E = \frac{698 \times 10^3}{6 \times 96485} = 1.21\,V$$

- For a hydrogen fuel cell, the Gibbs free energy is -237 kJ/mol. At standard conditions (298 K and 1 atm), the EMF of a hydrogen fuel cell is 1.23 V

5.3.1 The Nernst equation

The Nernst equation is used to calculate the voltage of a fuel cell under operating conditions. It is relates the electromotive force (EMF) of a cell to the concentrations of the reactants and products involved in the electrochemical reaction. It is expressed as:

$$\mathrm{E}_{\mathrm{Nernst}} = -\frac{\Delta \mathrm{G}}{\mathrm{nF}} - \frac{\mathrm{RT}}{\mathrm{nF}} \ln(\mathrm{Q})$$

$$\mathrm{E} = E^{\circ} - \frac{\mathrm{RT}}{\mathrm{nF}} \ln(\mathrm{Q})$$

Where,
R: is the gas constant (8.314 J/mol·K)
T: is the temperature in Kelvin (K)
Q: is the reaction quotient, which is the product of the concentrations of the reactants raised to their stoichiometric coefficients

- The reaction quotient is a measure of the concentration of reactants and products. It is given by the equation:

$$\mathbf{Q = [H_2][O_2]/(H_2O)^2}$$

Where:

- $[H_2]$ is the concentration of hydrogen (mol/L)
- $[O_2]$ is the concentration of oxygen (mol/L)
- $[H_2O]$ is the concentration of water (mol/L)

5.4 Voltage

The voltage of a fuel cell is the potential difference between the anode and cathode of the cell. It is typically lower than the EMF due to various losses, such as activation losses, Ohmic losses, and concentration losses. the cell voltage is given by the expression:

$$\mathrm{V}_{\mathrm{cell}} = \mathrm{E}_{\mathrm{Nernst}} - \eta_{\mathrm{Ohm}} - \eta_{\mathrm{act}} - \eta_{\mathrm{con}}$$

$\mathrm{V}_{\mathrm{cell}}$: Actual voltage of a single cell;

E_{Nernst}: Thermodynamic (ideal) potential of each cell and represents the reversible voltage;

η_{Ohm}: Ohmic polarization of the anode and the cathode;

η_{act}: Activation polarization of the anode and cathode,

η_{con}: Concentration polarization of the anode and cathode.

5.5 Power

The power of a fuel cell is the rate at which it generates electrical energy. It is measured in watts (W). The power of a fuel cell is determined by the product of the voltage and current:

$$P = V \times I$$

Where:

P is the power of the fuel cell in watts (W)
I is the current flowing through the fuel cell in amperes (A)
V is the voltage of the fuel cell in volts (V)

5.6 Efficiency

The efficiency of a fuel cell is the ratio of the electrical energy it generates to the chemical energy of the fuel consumed. It is typically expressed as a percentage.

$$\eta_{actual} = \frac{P_{electrical}}{P_{chemical}} \times 100$$

$$\eta_{actual} = \frac{\Delta G}{\Delta H * \text{flow rate}} \times 100$$

Where ΔH is the enthalpy change.

5.7 Sizing of a fuel cell stack installation

A fuel cell stack is a series of fuel cells that are connected together to increase the voltage and power output. The sizing of a fuel cell stack installation involves determining the appropriate number and size of fuel cells needed to meet a specific energy demand. This sizing must take into account the peak power of the fuel cell.

The peak power of stack is calculated by the following relationship:

$$P_{peak} = N_{cell} \times V_{cell} \times I \times A_{cell}$$

P_{peak}: The peak power of stack (W)

N_{cell}: Number of cells

A_{cell}: cell size (m^2)

EXERCISES

Exercise 5.1:

Consider a hydrogen-oxygen fuel cell operating at standard temperature (25°C) and pressure (1 atm). The standard enthalpy change (ΔH) for the reaction is -285.8 kJ/mol, and the standard entropy change (ΔS) is 114.3 J/mol·K.

1. Calculate the standard Gibbs free energy change (ΔG) for the reaction.

2. Calculate the Gibbs free energy change (ΔG) for the reaction at a temperature of 50°C.

Exercise 5.2:

Calculate the Gibbs free energy change (ΔG) for the following hydrogen fuel cell reaction:

$$\mathbf{H_2 + \frac{1}{2}O_2 \rightarrow\ H_2O}$$

Given:

- $\Delta H = -285.8$ kJ/mol
- $T = 298$ K (standard temperature)
- $S\_H_2O(l)$ is the standard entropy of liquid water (69.91 J/mol·K)
- $S\_H_2(g)$ is the standard entropy of hydrogen gas (130.68 J/mol·K)
- $S\_O_2(g)$ is the standard entropy of oxygen gas (205.19 J/mol·K)

Exercise 5.3:

A hydrogen fuel cell operates at a temperature of 353 K and a pressure of 1 atm. The standard cell potential for the hydrogen fuel cell is 1.23 V. The reaction quotient for the hydrogen fuel cell is 0.1.

1. Calculate the EMF of the hydrogen fuel cell using the Nernst equation.

2. Calculate the power of the hydrogen fuel cell if the current is 10 A.

3. Calculate the peak power of the hydrogen fuel cell if the maximum current density is 2 A/cm^2 and the active area of the cell is 100 cm^2.

Exercise 5.4:

A hydrogen fuel cell stack is being designed to provide a peak power of 10 kW. The operating voltage of each cell is 1.23 V and the maximum current density is 1 A/cm^2. The active area of each cell is 100 cm^2.

1. Calculate the number of cells required in the stack.

Exercise 5.5:

A fuel cell is operating at a temperature of 30°C (303 K) and the partial pressures of hydrogen and oxygen are 1.0 atm and 0.2 atm, respectively. The fuel cell is consuming hydrogen at a rate of 1.0 mol/s and producing electrical power at a rate of 10.0 W.

Given:
- For H_2O, the standard enthalpy of formation is -286 kJ/mol.
- The standard entropy change is -88.3 J/mol·K

1. Calculate the theoretical maximum efficiency of the fuel cell.

2. Calculate the actual efficiency of the fuel cell

5.8 Conclusion

In this chapter, we studied the theoretical and practical modeling of fuel cells. We began by examining the standard thermodynamic quantities that define the maximum possible efficiency of the electrochemical reaction. We then introduced the Nernst equation to calculate the electromotive force and discussed how real performance is affected by different types of losses (activation, ohmic, and concentration)**.**

We also analyzed the relationships between voltage, current, and power, and showed how the reactant flow rate can be directly calculated using Faraday's law. Finally, we addressed the methods of efficiency evaluation and the sizing of fuel cell systems, which are essential for real-world applications in transportation, stationary power, and portable devices.

Chapter 6: Risks linked to the production and storage of hydrogen

Chapter 6: Risks linked to the production and storage of hydrogen

Course objective

At the end of this chapter, the student will be able to:

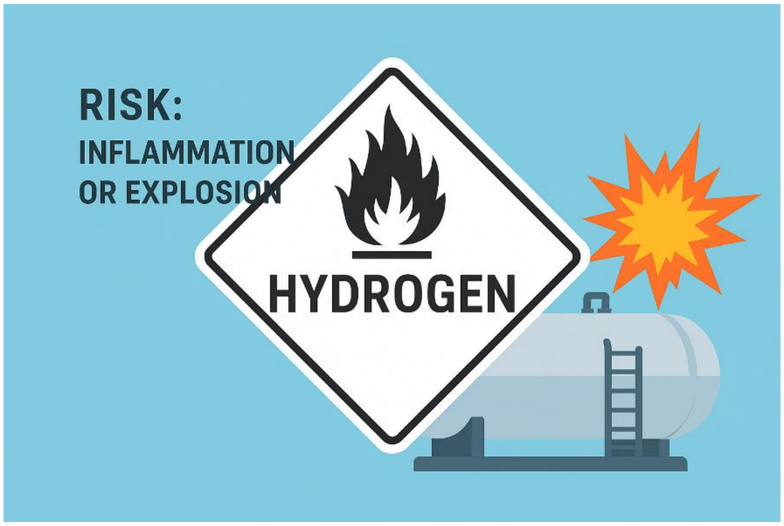
1. **Identify** the main risks associated with hydrogen production, storage, and transport.
2. **Recognize** the safety techniques and protective measures needed when handling hydrogen.
3. **Appreciate** the importance of safety standards in ensuring the secure and widespread use of hydrogen technologies.

6.1 Introduction

Hydrogen is a highly flammable gas and, if not handled properly, it can pose a significant risk to workers' safety during production, transportation, and storage.

6.2 Risk: inflammation or explosion

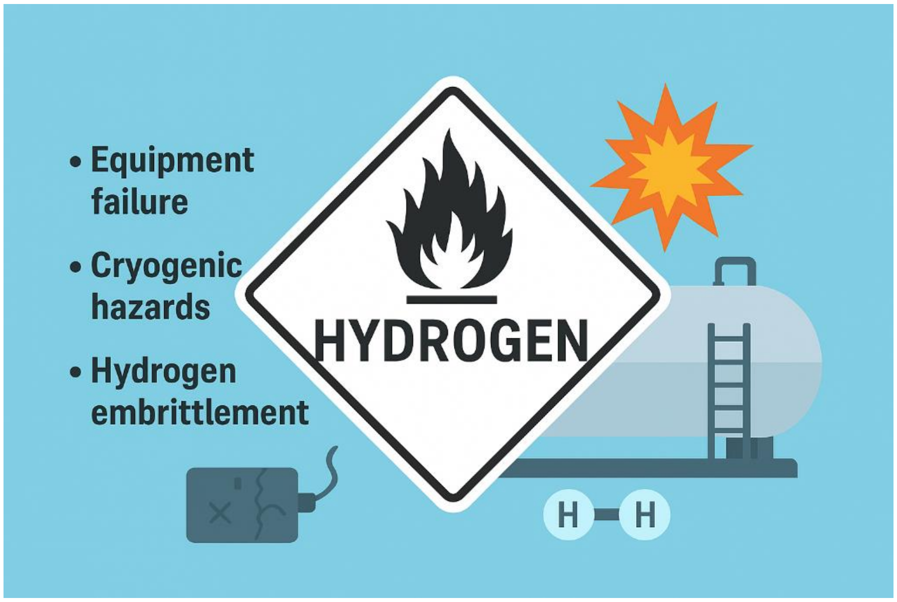
Hydrogen's main risk is its high flammability and wide explosive range. This risk arises in several situations:



- **Flammability range:** Hydrogen has an extremely wide flammability range in air (4–75% by volume).
- **Ignition energy:** Very low (~0.02 mJ), meaning even small sparks can ignite hydrogen–air mixtures.
- **Flame:** Almost invisible, burns with a pale blue flame, making detection difficult.
- **Explosion risk:** When mixed with oxygen in confined spaces, hydrogen can create violent explosions.

6.3 Mechanical risk: high temperature and high pressure

Hydrogen production and storage often involve high temperatures and pressures, which pose mechanical risks:



- **Equipment failure:** High temperatures and pressures can cause equipment to malfunction or fail, potentially leading to accidents.
- **Cryogenic hazards:** Liquid hydrogen is stored at extremely low temperatures (-253°C), posing risks of frostbite and burns on contact.
- **Hydrogen embrittlement**: Hydrogen can embrittle certain metals, making them more susceptible to cracking and failure.

6.4 Toxic and corrosive nature

While hydrogen itself is not toxic, some of the chemicals involved in its production and storage can be:

- **Acidic electrolytes:** Electrolysis, a common hydrogen production method, uses acidic electrolytes that can be corrosive to equipment and hazardous if released.
- **Byproducts of production:** Steam methane reforming, a traditional hydrogen production method, releases carbon dioxide as a byproduct, contributing to greenhouse gas emissions.

These risks highlight the need for stringent safety measures throughout the hydrogen lifecycle, including:

- Implementing strong safety regulations and standards.
- Utilizing leak detection and prevention technologies.
- Investing in research and development for safer hydrogen production methods.
- Developing and implementing proper training for personnel handling hydrogen.
- Designing and maintaining equipment to withstand high temperatures and pressures.
- Choosing materials resistant to hydrogen embrittlement.
- Managing and disposing of hazardous chemicals safely.

6.5 Techniques of Hydrogen Transport and Storage

6.5.1 Introduction

Hydrogen is the lightest and most abundant element in the universe, accounting for nearly 75% of all matter. On Earth, however, it rarely exists in its pure molecular form (H_2); instead, it is commonly found combined with other elements, such as oxygen in water (H_2O) and carbon in hydrocarbons.

As an energy carrier, hydrogen has gained increasing attention because it is clean, versatile, and highly efficient. When used in fuel cells, hydrogen reacts with oxygen to produce electricity, heat, and water as the only by-product—making it an environmentally friendly alternative to fossil fuels.

Hydrogen can be produced from a wide variety of resources, including natural gas, biomass, and water (through electrolysis). This flexibility allows it to be integrated into both renewable and conventional energy systems. Moreover, hydrogen can be stored, transported, and used in diverse applications, ranging from stationary power generation to fuel for vehicles.

Despite its many advantages, hydrogen also presents challenges. Issues such as production cost, storage, transportation, and safety risks (flammability, high-pressure requirements, and material embrittlement) must be carefully managed for large-scale deployment.

Today, hydrogen is seen as a cornerstone of the transition toward a sustainable energy future. It plays a vital role in decarbonizing hard-to-electrify sectors, such as heavy industry and long-distance transport, and supports the global effort to reduce greenhouse gas emissions.

6.5.2 Hydrogen Storage Options

1. Liquid Hydrogen

Hydrogen can be stored in liquid form in special containers and tanks capable of withstanding very low temperatures. However, converting hydrogen from gas to liquid requires a significant amount of energy because of its extremely low boiling point, which is **20.271 K (–252.879 °C)**.

2. Gaseous Hydrogen

One drawback of hydrogen is its **low energy density by volume** compared to hydrocarbon gases. This means that, to obtain the same amount of energy as from a hydrocarbon gas, a much larger storage tank is required. To store hydrogen as a gas, it must be compressed to **very high pressures (550 bar – 700 bar)**. Such compressed hydrogen tanks are currently used in vehicles.

3. Solid-State Storage in Materials

Hydrogen can also be stored by binding it with different materials, from which it can later be released. Some examples of these methods are:

- **Adsorption**: This refers to the accumulation of hydrogen molecules on the surface of a solid material called an adsorbent, forming a dense layer of hydrogen.
- **Interstitial Hydrides**: Hydrides are compounds that contain hydrogen atoms in their chemical bonds. Interstitial hydrides, such as **palladium hydride**, are characterized by metallic bonding, where hydrogen atoms occupy spaces within the metal lattice.

- **Complex Hydrides**: These are chemical compounds that contain hydrogen in more complex bonding structures. An example is **sodium alanate ($NaAlH_4$)**, which can release hydrogen under specific conditions.

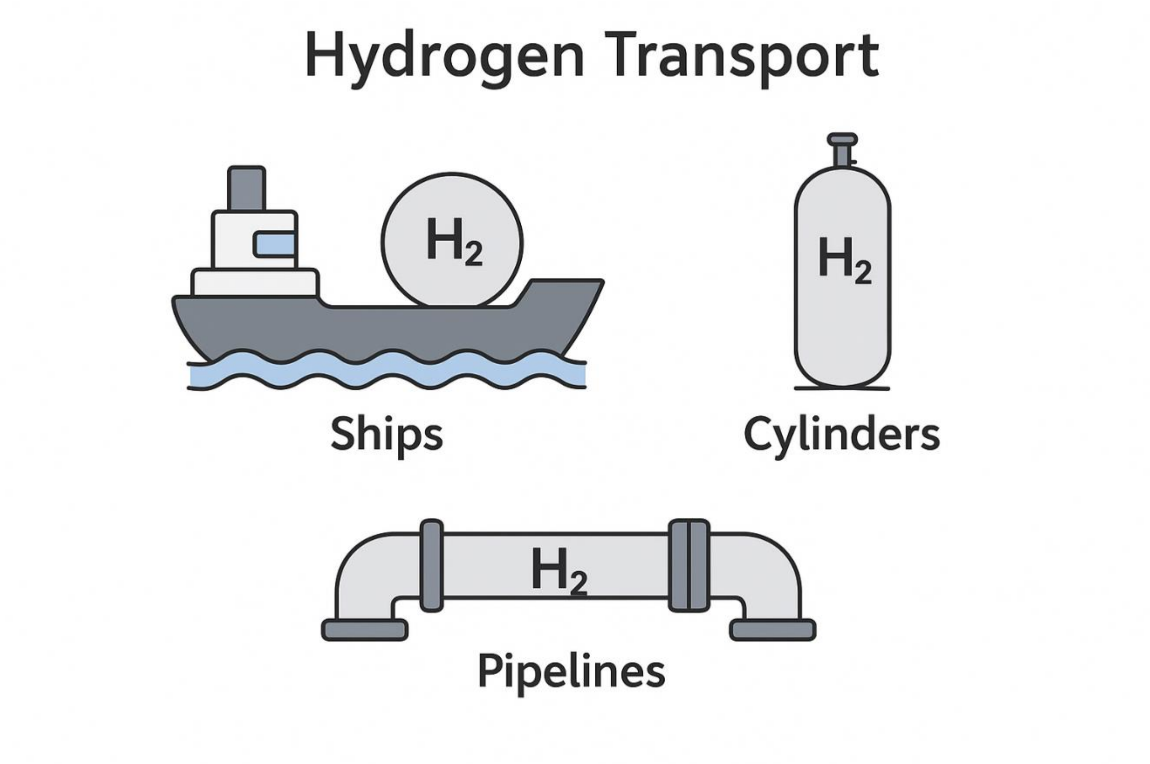
6.5.3 Hydrogen Transport

The most significant safety challenge in storing or transporting hydrogen gas is the high pressure or temperature involved. For maritime transport, hydrogen is stored in spherical containers that can absorb pressure. These containers are coated with white paint to reflect heat and are equipped with water spray cooling systems that activate before safety valves open, in order to avoid losses. As is well known, when temperature decreases, pressure also decreases.

For transportation on specialized ships, hydrogen must be cooled down to **–253 °C** to remain in liquid form at around **1 bar pressure**. This requires ships to be equipped with a complete refrigeration system and spherical tanks. However, excessive cooling and pressurization demand significant amounts of energy.

Hydrogen can also be transported in steel tanks or cylinders that can be carried. These are manufactured to withstand very high pressures, are leak-proof, and are designed with strict safety standards. Additionally, hydrogen can be transported via special pipelines that are cooled and engineered specifically for this purpose.

Nevertheless, hydrogen must always be handled with extreme caution, as it can leak through the smallest cracks and is highly flammable.



6.5.4 Risks of Handling Hydrogen

Hydrogen is considered very dangerous, as evidenced by the famous accident that occurred in 1937 in New Jersey, USA: the burning of the *Hindenburg* airship. It was filled with hydrogen because of its light weight, but the accident led to the death of 35 people in a massive fire. Safety instructions issued by NASA—the largest organization in the world that uses hydrogen—serve as the main reference for preventing its risks:

1. Hydrogen burns with an invisible flame at very high temperatures. Therefore, extreme caution must be taken to avoid skin contact. The simplest way to detect a suspected leak is by using a straw broom with a long handle to check for the presence of hydrogen.
2. Liquid hydrogen, due to its extremely low temperature, can cause what is known as *cold burns*, which are more severe than ordinary burns. These can lead to significant and rapid swelling (edema). Treatment is simple for physicians, but the affected area must never be touched directly.
3. Hydrogen is one of the most penetrating elements. For this reason, it is necessary to always wear protective clothing, gloves, and face shields during filling, emptying, network or valve maintenance, or when dismantling any equipment through which hydrogen flows.
4. Inhalation of hydrogen leaks is dangerous and can cause burns to the respiratory system. Therefore, great care must be taken when handling hydrogen. It is important to note that strict adherence to safety instructions ensures complete

protection, as hydrogen can be a safe element once we fully understand how to handle it.

EXERCISES

Exercise 6.1:

1. Explain why hydrogen is painted in white-coated spherical tanks when transported on ships.
2. Describe two risks associated with liquid hydrogen.
3. Why is strict leak detection important when dealing with hydrogen pipelines?

Exercise 6.2:

A research team at a university is setting up a hydrogen storage laboratory. They plan to use both compressed gas cylinders (700 bar) and liquid hydrogen tanks (–253 °C)**.**

- Identify the main risks linked to each storage method.
- Suggest at least three safety precautions the team must adopt to ensure safe operation.
- Explain how improper handling could lead to serious accidents.

6.6 Conclusion

Hydrogen, while being a promising clean energy carrier, presents several safety challenges during its production, storage, and transport. Its flammability, the possibility of invisible flames, cryogenic hazards, and mechanical risks linked to high pressure and extreme temperatures require special attention. Additionally, issues such as hydrogen embrittlement, equipment failure, and the potential for toxic or corrosive effects highlight the importance of adopting strict safety protocols.

By understanding these risks and implementing appropriate preventive measures—such as protective equipment, safe storage systems, effective cooling methods, and careful leak detection—hydrogen can be handled and used safely. Ensuring safety is not only a technical requirement but also a vital step toward building trust in hydrogen as a sustainable energy solution.

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ANNEXES

- Uploading the courses on the platform "E-learning" of Echahid Hama Lakhdar University of El Oued;
  Uploading: https://e-learning.univ-eloued.dz/course/view.php?id=2147

Fuel cell and hydrogen production

Dr.Horr Sabrina

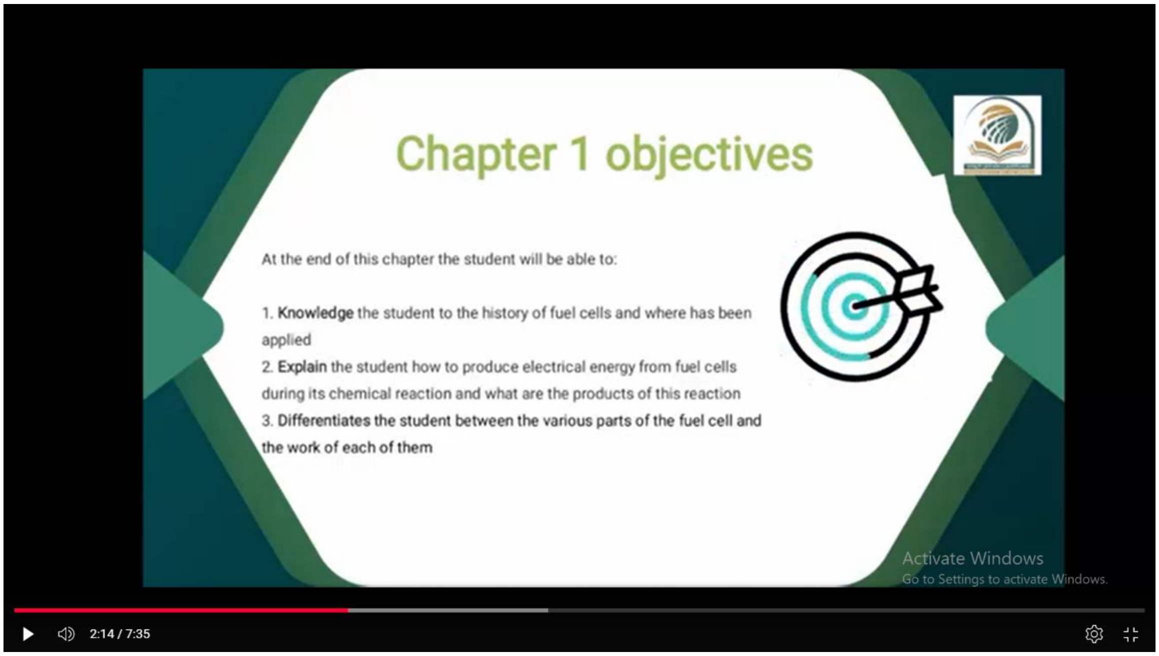
1.0 29/02/2024

- Educational Support Materials – To facilitate deeper understanding of the lessons, students are invited to consult my YouTube channel, which provides pedagogical videos with comprehensive audio-visual explanations of the course content.
  Uploading: https://youtu.be/pX6zFHl7gd8

Course Information

Course title: Fuel cell and hydrogen production
Semester: 03
Teaching unit: Fundamental TUF
Credit: 04
Coefficient: 02
Duration: 15 weeks

- To gain further insight into Chapters 1 and 2, students are encouraged to consult the pedagogical video prepared for this purpose, available on my YouTube channel: https://youtu.be/uB14a3_WFFs



Chapter 1 objectives

At the end of this chapter the student will be able to:

1. **Knowledge** the student to the history of fuel cells and where has been applied
2. **Explain** the student how to produce electrical energy from fuel cells during its chemical reaction and what are the products of this reaction
3. **Differentiates the student between the various parts of the fuel cell and the work of each of them**

Abstract

This module provides a comprehensive introduction to hydrogen as a clean energy carrier and to fuel cell technologies as efficient energy conversion devices. It explores hydrogen properties, production methods, storage and transport options, as well as the associated safety considerations. Particular emphasis is placed on the role of hydrogen and fuel cells in the global transition towards sustainable energy systems. The course also examines recent technological advancements, applications in various sectors, and future perspectives for large-scale deployment. Designed as both a teaching resource and a reference guide, the module equips students with theoretical foundations insights into one of the most promising solutions for decarbonizing energy.

Keywords: Hydrogen, Fuel Cells, Energy Transition, Clean Energy, Hydrogen Storage, Safety, Renewable Energy

الملخص

يقدّم هذا المقياس مدخلًا شاملًا للهيدروجين بوصفه ناقلًا نظيفًا للطاقة، ولتقنيات خلايا الوقود باعتبارها أجهزة فعّالة لتحويل الطاقة. ويتناول خصائص الهيدروجين، وطرق إنتاجه، وخيارات تخزينه ونقله، إضافةً إلى اعتبارات السلامة المرتبطة به. كما يركّز المقياس بشكل خاص على دور الهيدروجين وخلايا الوقود في الانتقال العالمي نحو أنظمة طاقة مستدامة.

ويستعرض المقياس كذلك أحدث التطورات التكنولوجية، وتطبيقات هذه التقنيات في مختلف القطاعات، إلى جانب الآفاق المستقبلية لاعتمادها على نطاق واسع. وقد صُمّم هذا المقياس ليكون موردًا تعليميًا ودليلًا مرجعيًا في آنٍ واحد، حيث يزوّد الطلبة بالأسس النظرية والرؤى العلمية المتعلقة بإحدى أكثر الحلول الواعدة لإزالة الكربون من قطاع الطاقة.

الكلمات المفتاحية:
الهيدروجين، خلايا الوقود، الانتقال الطاقوي، الطاقة النظيفة، تخزين الهيدروجين، السلامة، الطاقات المتجددة.

"I sincerely hope that I have succeeded in preparing this Module in a clear and useful way. Any comments, suggestions, or corrections are most welcome and can be shared through the provided feedback link: (https://e-learning.univ-eloued.dz/mod/feedback/view.php?id=22475 *).*

Your feedback will be highly appreciated, as it will help improve the quality of future materials."