

Chapter 3. Industrial Gases

Industrial gases perform varied and essential functions in the world. Some are raw materials for the manufacture of other chemicals. This is true for CO₂, O₂, N₂, H₂, CH₄ etc. This chapter will concentrate on the production of O₂, N₂, H₂ gases.

3.1 Oxygen and Nitrogen Gases

Oxygen: Oxygen composed of diatom (O) bind to form O₂ gas, a very pale blue, odorless, tasteless diatomic gas. Oxygen gas constitutes 20.8% of the volume of air. It is necessary to sustain global life. Major uses of O₂:

1. Producing oxyacetylene flame to cutting and welding metals.
2. In open hearth or basic oxygen furnaces for steel production.
3. Applications of artificial respiration and other medical purposes.
4. Chemical manufacture of acetylene, ethylene oxide, and others.

Nitrogen: Nitrogen (N₂) is a colorless, odorless, and mostly inert diatomic gas at standard conditions, constituting 78.09% by volume of Earth's atmosphere. Nitrogen occurs in all living organisms, primarily in amino acids, proteins and in the nucleic acids (DNA and RNA). Major uses of N₂:

1. Manufacture of synthetic ammonia, nitrogen oxide and nitric acid.
2. Manufacture organic nitrates like propellants and explosives.
3. Synthetically produced nitrates are key ingredients of industrial fertilizers.

3.2 Analysis of Air

Air mainly consist of two gases oxygen and nitrogen, which are practically considered to constitute 1/5 and 4/5 of air by volume, respectively. Table 3.1 list of

Table 3.1 shows composition of air

Name of the gas	% by weight in air
Oxygen	20.99
Nitrogen	78.01
Carbon dioxide	0.03 - 0.07
Argon	0.94
Hydrogen	0.01
Neon	0.0015
Helium and Krypton	0.01 - 0.02

various gases present in air. Concentration of all gases present in air, except CO₂ is constant. However water vapors and traces of ozone and iodine are present in air in variable amounts.

Also, composition of air also depends on altitude and distance to sea, in neighborhood of industry, built up urban areas, nearby volcanic phenomena. Other gases such as CO, H₂S and NO₂ are also present in air.

Critical temperature

However, by decreasing the distance the molecules of a gas are brought closer and the gas assumes liquid state provided the repulsive tendency has been diminished beyond a certain point known as critical temperature. Critical temperature is the temperature of a gas in its critical state, below which it can be liquefied by increasing the pressure. Above the critical temperature any gas cannot be liquefied by compression (T_c of air = 132.4 K).

Critical pressure

Since the temperature of a gas in its critical state, above which it cannot be liquefied by pressure alone. Critical pressure is the minimum pressure under which gas liquefies in its critical state (P_c of air = 37 atm.).

Therefore air should be cooled at very high pressure and low temperature for cooling purpose. The liquid form is obtained when the kinetic energy and the potential energy of the substance is approximately equal.

Table 3.2 Critical temperature and critical pressure of some gases

Sr. No.	Gases	Critical temperature (°C)	Critical pressure (atm.)
1.	Ethylene	+9.5	50.65
2.	Methane	-82.85	45.6
3.	Nitrogen	-147.13	33.49
4.	Hydrogen	-239.9	12.8
5.	Oxygen	-118.75	49.7
6.	Acetylene	+35.5	61.55
7.	Ammonia	+132.5	112.3
8.	Carbon monoxide	-138.7	34.6
9.	Carbon dioxide	+31.3	72.9

3.3 Joule-Thomson Effect

Air of free CO₂ is compressed to 200 atm and is cooled by cooling water. The condensed water in air is removed by passing through activated alumina. Then air is passed through inner coil of heat exchanger. Throttle valve (Joule-Thomson valve) is provided at the inlet pipe of a liquid reservoir. Then gas is allowed to suddenly expand by partially opening valve, which result in decrease of temperature of air. After expanding, the cold air goes out through the outer coil of heat exchanger, then recompressed to 200 atm pressure, cooled by water and then again allowed to transverse the inner coil of heat exchanger. Then gas is allowed to suddenly expand by partially opening valve, which result in another decrease of temperature of air. The temperature of the incoming air further falls due to the presence of cold air in the outer coil.

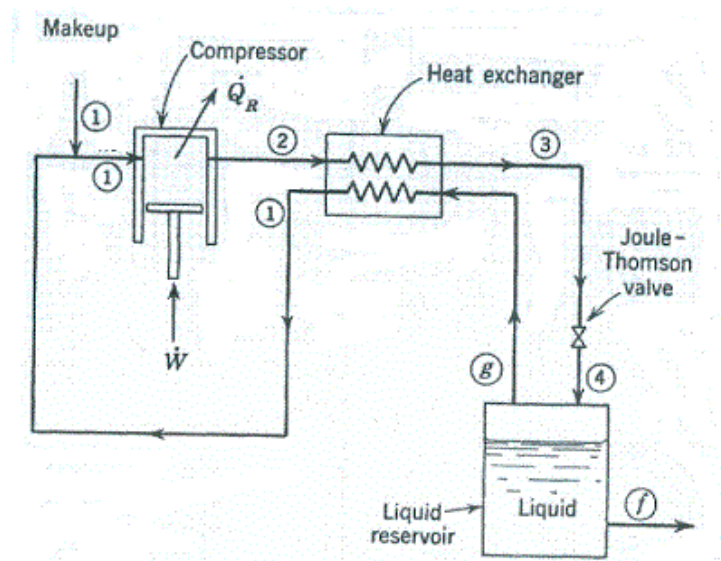


Figure 3.1: Liquefaction of Air by Joule-Thomson effect

3.4 Cryogenic Air Separation

Oxygen and nitrogen are usually separated by rectification of liquid air. The first rectification of N₂ and O₂ using Joule-Thomson effect was carried out by Linde in 1906. After six year Claude rectified them by combined effect of external work and internal work in cooling the air to liquefaction point.

Cryogenic air separation process is one of the most popular air separation process, used frequently in medium to large scale plants. It is the most preferred technology

for producing nitrogen, oxygen, and argon as gases and/or liquid products and supposed to be the most cost effective technology for high production rate plants. In the cryogenic gas processing, various equipment is used like the distillation columns, heat exchangers, cold interconnecting piping etc. which operate at very low temperatures and hence must be well insulated.

3.4.1 Basic steps of cryogenic air separation

The first step in any cryogenic air separation plant is filtering and compressing air.

After filtration the compressed air is cooled to reach approximately ambient temperature by passing through air-cooled or water-cooled heat exchangers. In some cases it is cooled in a mechanical refrigeration system to a much lower temperature.

The second step is removing the remaining CO₂ and H₂O vapor, which must always be removed to satisfy product quality specifications. The portion is that where the very low temperature can make the CO₂ and H₂O to freeze which can be deposited on the surfaces within the process equipment. There are two basic methods molecular sieve units and reversing exchangers.

The third step in the cryogenic air separation is the transfer of additional heat against product and waste gas so as to bring the air feed to cryogenic temperature. The cooling is usually done in brazed aluminum heat exchangers. They let the heat exchange between the incoming air feed and cold product and waste gas streams leave the air separation process.

The fourth step involves the use of distillation columns to separate the air into desired products. For example, the distillation system for oxygen has both "high" and "low" pressure columns. Nitrogen plants can have one or two column. While oxygen leaves from the bottom of the distillation column, nitrogen leaves from the top. Argon has a boiling point similar to that of oxygen and it stays with oxygen. If however high purity oxygen is needed, it is necessary that at an intermediate point argon must be removed from the distillation system. Impure oxygen produced in the higher pressure distillation column is further purified in the lower pressure column.

3.4.2 Cryogenic air separation flow diagram

The cryogenic air separation flow diagram shows general important steps involved in producing oxygen, nitrogen, and argon as both gas and liquid products.

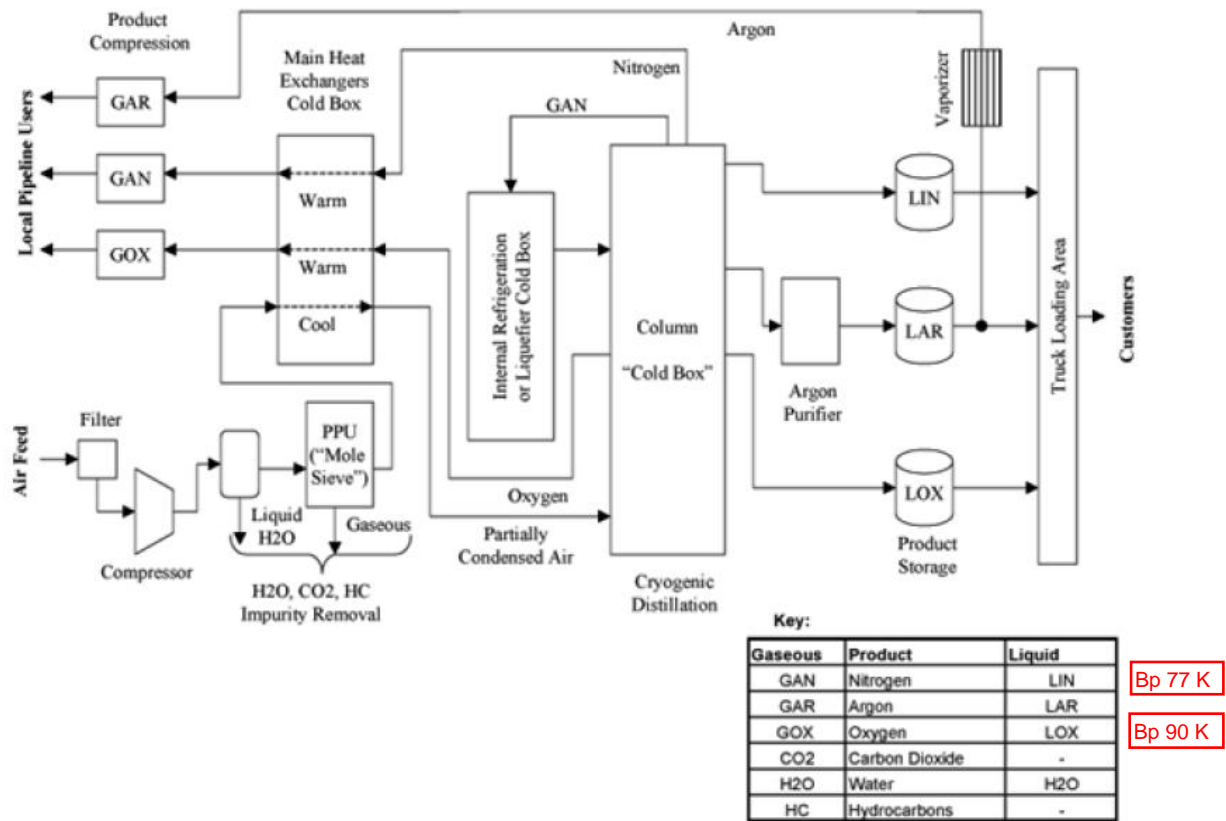


Figure 3.2 Cryogenic air separation flow diagram

3.4.3 Air Distillation Column (Cold Box)

Preventing explosions in oxygen plants requires understanding the distillation column design. Figure 3.3 shows the basic double column. The double column, or two equivalent separate columns, using expansion for cooling and the change of boiling point with pressure for boiling, is the basic unit in all modern oxygen plants.

1. Cooled air enters the high-pressure column near the bottom or at one of the lower plates in the column. Nitrogen boils at a lower temperature than oxygen, so the nitrogen boils and the liquid in the bottom of the high-pressure (lower) column becomes richer in oxygen. The higher the pressure, the higher the temp. at which liquids boil. In the bottom of the low-pressure (upper) column, the boiling oxygen is at a temp. below the boiling point of nitrogen in the high-pressure column.

4. In some oxygen plants, air enters the high-pressure column through an expansion valve. Expansion of a gas causes cooling and results in some liquefaction taking place with the rest of the liquefaction coming from nitrogen reflux. If the expansion valve is in the liquid airline going to the upper column, the same amount of cooling takes place by boiling liquid air at reduced pressure. In such a case, all cooling for liquefaction in the lower column comes from the nitrogen reflux.

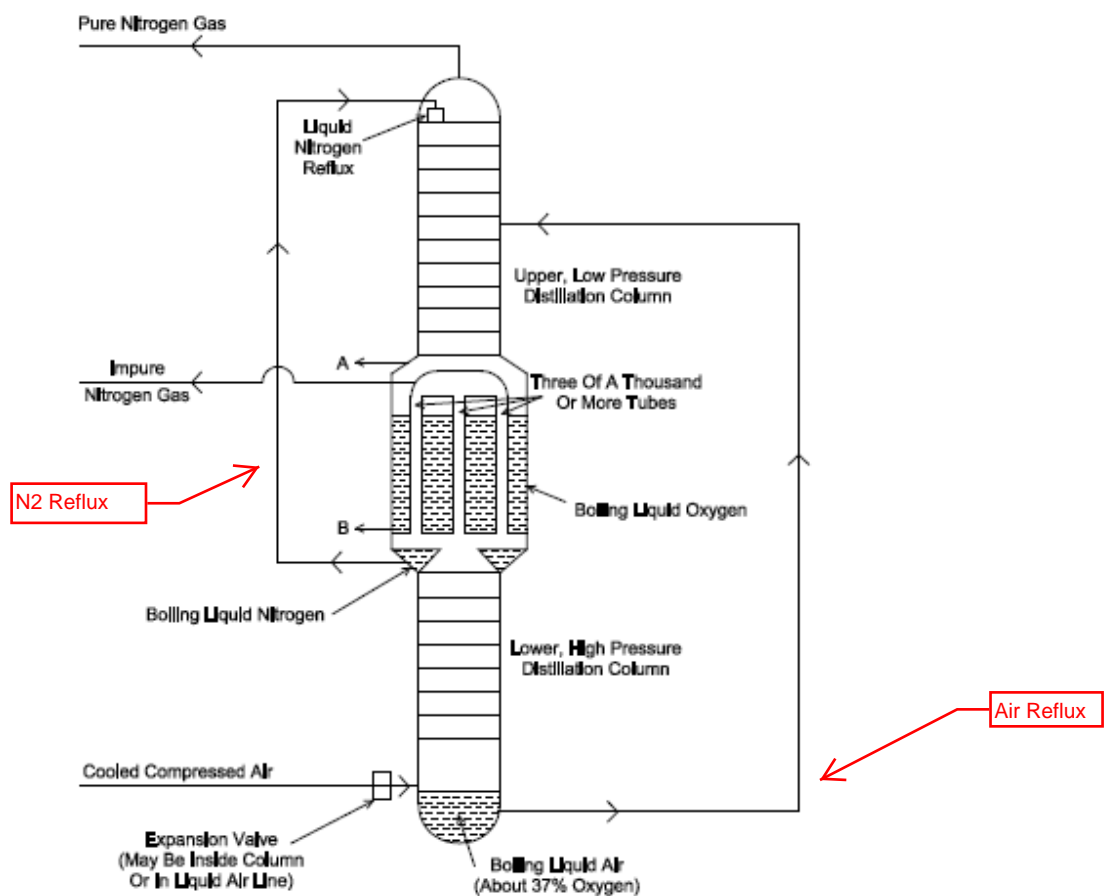


Figure 3.3 Typical liquid air distillation column

3.4.4 Handling and Storage

Oxygen is noncombustible, but will greatly promote combustion if a fuel and ignition source is present. Also, fires in oxygen-rich atmospheres will burn intensely.

Normal operational sequences for an oxygen plant periodically require the disposal of quantities of liquid oxygen, ranging from a large-scale disposal when draining a low-pressure column and condenser of tonnage plants during defrost, to lesser amounts when draining small plants or vessels, cooling down liquid oxygen pumps, draining liquid daily from small plants for acetylene control, etc.

It is important that the hazard involved in operations of this nature be recognized. It is very common to locate small, unattended air liquefaction plants near customer sites. Some larger plants are occupied 24 h/d by only a few operators. Lack of personnel puts a premium on automatic systems for the prevention of losses.

3.5 Hydrogen gas

Uses

Hydrogen has long been an important gaseous raw material for chemical and petroleum industries such as cyclohexanol, ammonia, stearin, isooctane, methanol.

Hydrogen is sold as gas and liquid. Liquid hydrogen is the most profitable, as it is a friend of environment when used as a fuel in fuel cells.

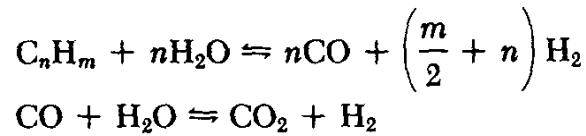
Manufacture

Hydrogen is derived almost exclusively from carbonaceous primarily hydrocarbons or water. These materials are decomposed by the energy, which may be electrical, chemical, or thermal. Examples include electrolysis of water, steam reforming of hydrocarbons, and thermal dissociation of natural gas. Hydrogen is also produced by partial oxidation of hydrocarbons and by water-gas processes.

3.5.1 Steam-Hydrocarbon Reforming Process

This process consists of catalytically reacting a mixture of steam and hydrocarbons at an elevated temperature to form a mixture of H₂ and oxides of carbon.

The following basic reactions occur:



Although the equations are shown for the general case of any hydrocarbon feed, only **light** hydrocarbons have been successfully used in commercial practice. Natural gas (LNG) is most common, and propane and butane (LPG) are also frequently used. With the use of a specially prepared catalyst, naphtha is also a suitable feedstock.

The first reaction is the reforming reaction. It is highly **endothermic**, and the moles of product exceed the moles of reactant so the reaction goes to completion at high temperature and low pressure. Excess steam is normally used, although the basic purpose is to prevent carbon formation, it also helps force the reaction to completion.

The second reaction is the water-gas-shift reaction. It is **mildly exothermic** and is favored by low temperature but unaffected by pressure. Excess steam also forces this reaction to completion with a catalyst is usually employed.

Both reactions occur together in the steam-reforming furnace at temperatures of 760 to 980°C. The composition of the product depends upon the process conditions, including temperature, pressure, and excess steam, which determine equilibrium, and the velocity through the catalyst bed, which determines the approach to equilibrium. A typical product contains approximately 75% H₂, 8% CO, and 15% CO₂; the 2% remainder consists of nitrogen and unconverted hydrocarbon.

The process using propane is shown in Fig. 3.4; this process can be broken down into the following coordinated sequences:

- 1)** Propane is vaporized by steam.
- 2)** Propane vapor is desulfurized by contact with activated carbon to prevent deactivation of the catalyst.
- 3)** Propane vapor mixed with steam is reformed over a **nickel catalyst** at about 815°C in alloy tubes in a combustion furnace (to furnish the heat for this endothermic reaction).

- 4) The gases H_2 , CO , and some CO_2 are cooled to about $370^\circ C$ and the partial pressure of water increased by addition of steam or condensate, and passed over an **iron oxide catalyst** in the first-stage CO converter, where 90 to 95% of the CO is converted to CO_2 with more H_2 . (This is the so called **water-gas-shift reaction**). These hot gases are first cooled ($315^\circ C$) by heat exchange with the gases leaving the first-stage CO_2 absorber before entering the second-stage CO converter, and finally by water to about $38^\circ C$.
- 5) The cooled gases are scrubbed with a monoethanolamine (MEA) solution ($C_2H_5ONH_2$) in absorber to remove essentially all the CO_2 .
- 6) The product gases low in CO_2 are heated to about $315^\circ C$ by exchange with gases from the second-stage CO converter and passed to the methanator over a nickel catalyst to convert essentially all the CO_2 to methane by reaction with H_2 .
- 7) The product H_2 gas from the methanator is cooled to $38^\circ C$ (with water), leaving it pure except for saturation with water vapor.

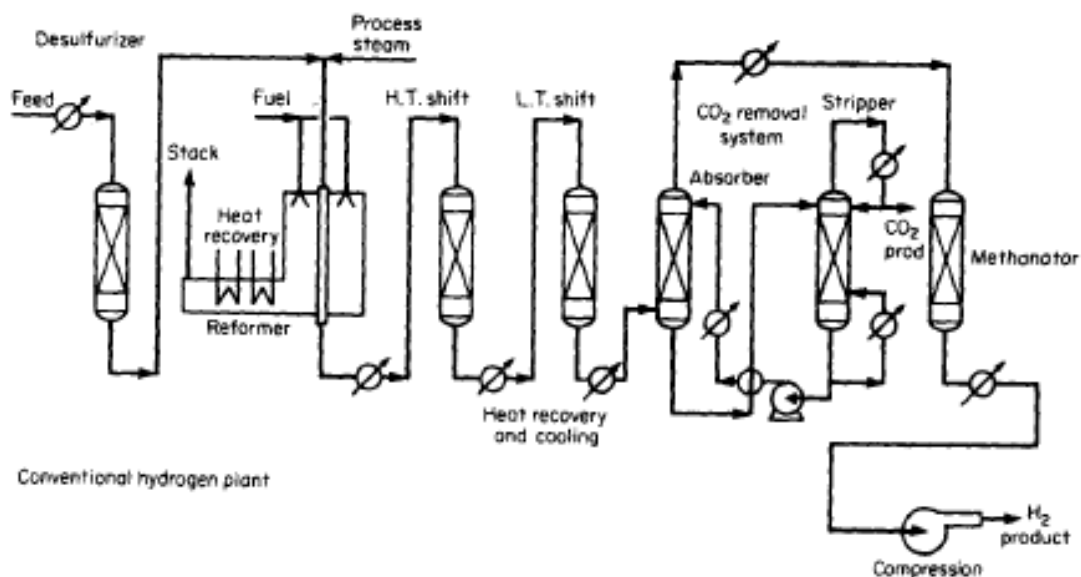
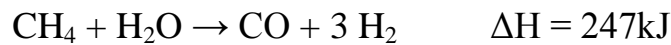
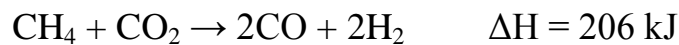
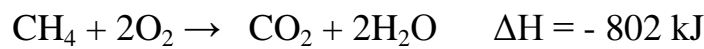


Fig. 3.4 Simplified H_2 Production by HC-Steam Reforming Process.

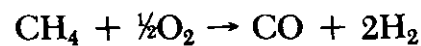
- 8) The MEA rich solution (CO_2 carrier) is returned to the stripper through heat exchangers, and the CO_2 is stripped out by steam. The CO_2 which can be recovered for use about $55 \text{ kg}/100 \text{ m}^3 H_2$. The lean MEA solution from the stripper is pumped through the heat exchanger to the CO_2 absorber to remove the bulk of the CO_2 in the H_2 gas stream.

3.5.2 Partial Oxidation Processes

The starting material can use natural gas, refinery gas, or other hydrocarbon gas mixtures as feedstocks, but their chief advantage is that these processes can also accept liquid hydrocarbon feedstock, such as gas oil, diesel oil, and even heavy fuel oil. There are three commercial versions of the process. All employ **noncatalytic** partial combustion of the hydrocarbon feed with oxygen in the presence of steam in a combustion chamber at flame temperatures between 1300 and 1500°C. When methane is the principal component of the feedstock, the reactions involved are:



The first reaction is highly exothermic and produces enough heat to sustain the other two reactions, which are endothermic. The net reaction is as follows:



This reaction is exothermic, and so the overall process is **a net producer of heat**.

Figure 3.5 shows a flowsheet for H₂ gas production by partial oxidation process of NG with heat recovery using waste heat boiler.

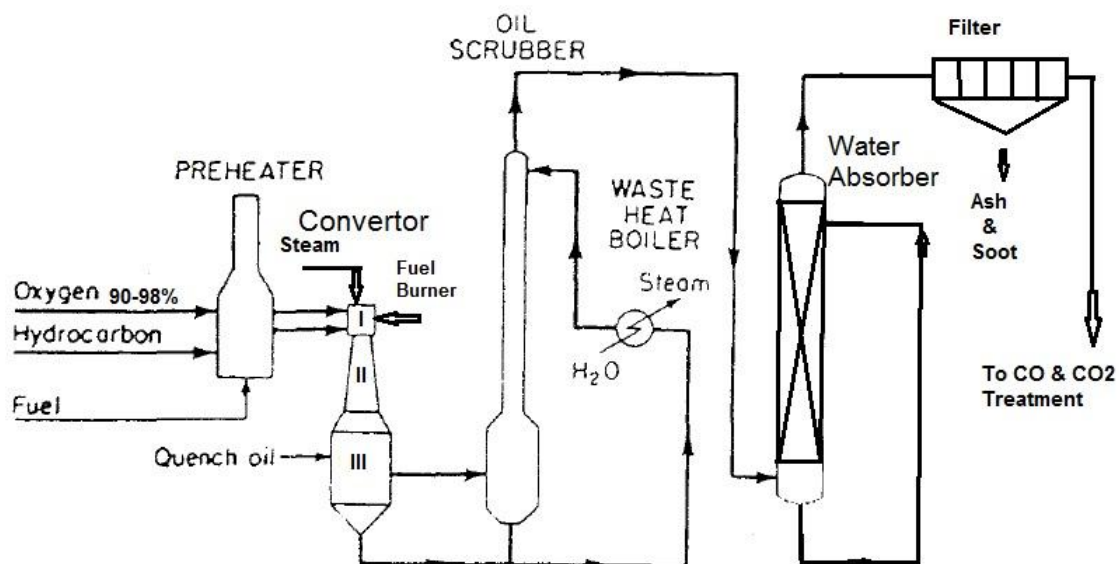


Fig. 3.5 Flowsheet for H₂ gas by partial oxidation process.

3.5.3 The Electrolytic process

Preparation

Water is capable of undergoing both oxidation at anode and reduction at cathode.

Breakdown of water to H₂ and O₂ by electrolysis is usually carried out in dilute solution. A standard apparatus for the electrolysis of water is shown in the figure 3.6

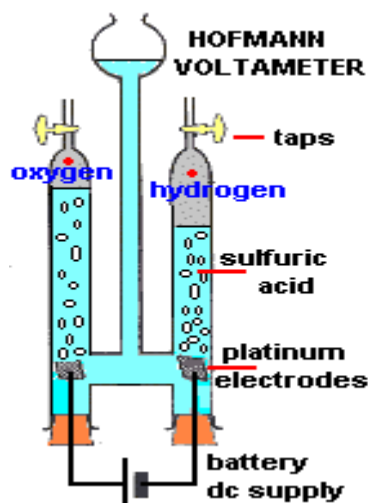
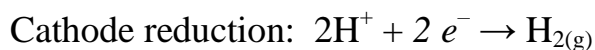
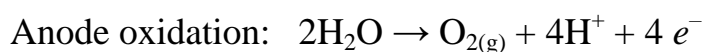


Fig. 3.6 Hofmann electrolysis apparatus used in electrolysis of water

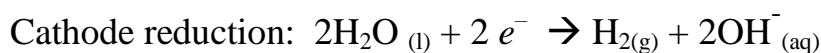
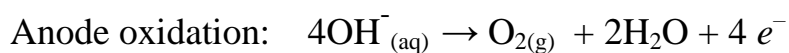
Electrolyte can be an acid, base or a salt. Most soluble acids: sulfuric, nitric and hydrochloric acid and bases are: sodium, potassium, calcium and barium hydroxide are considered strong electrolytes. Potassium hydroxide is the electrolyte of choice for most electrolyzers.

In acid solution:



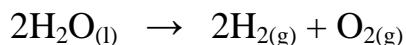
$E^\circ \text{ cell} = -1.23 \text{ v}$

In basic solution:



$E^\circ \text{ cell} = -0.83 \text{ v}$

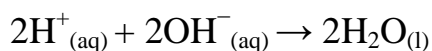
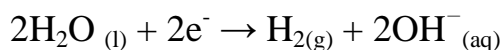
In the two cases the main reaction is:



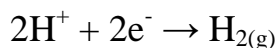
A pair of inert electrodes is sealed in opposite ends of a container designed to collect the H_2 and O_2 gas given off in this reaction. The electrodes are then connected to a source of electric current.

By itself, water is a very poor conductor of electricity. Therefore addition of an electrolyte to water provide ions that can flow through the solution, thereby completing the electric circuit. The electrolyte must be soluble in water. It should also be relatively inexpensive. Most importantly, it must contain ions that are harder to oxidize or reduce than water.

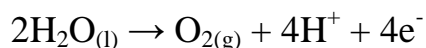
In acidic electrolyte: at the **cathode** water and hydrogen ion compete to be reduced at the cathode but the end results are essentially equivalent since both reductions occur and when added yields essentially hydrogen gas:



Adding these two half reactions together give the net result at the Cathode:



At the **anode** there are two possible options for oxidation, water and the anion. However the oxidation potential of water is -1.23 V and that of sulfate ion for example is -2.05 V. Therefore, it is obvious that the more positive is -1.23 will be the half reaction that occurs:

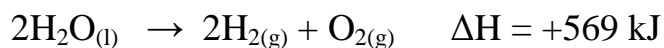


Commercial Water Electrolysis Cells

The scale of industrial water electrolysis is extremely wide, ranging from small portable devices (e.g. 5 kW) through to process installations of 7MW. Three types of water electrolyzer based on **tank cells**, **parallel plate flow cells** and the **solid electrolyte cells** are now becoming familiar. The cells currently available have a

number of common features, largely because each design aims principally to minimize the cell voltage and to avoid problems from corrosion.

This process produces high-purity hydrogen and consists of passing direct current through an aqueous solution of alkali, and decomposing the water to the following equation:



The theoretical decomposition voltage for this electrolysis is 1.23 V at room temperature. However because of the overpotential of hydrogen on the electrodes and also cell resistance itself, a voltage of 2.0 to 2.25 V is usually required. A typical commercial cell electrolyzes a solution, uses anode which is more likely to be **nickel** plated onto steel in conditions to give a high surface area deposit or nickel oxide and cobalt oxide on nickel substrates. The anode coating may also contain precious metals to enhance further the rate of oxygen evolution. The cathodes are also **catalytic coatings** (e.g. high-surface-area nickel alloys, cobalt and sulphided nickel).

Both electrodes are shaped to enhance gas release and to direct the gases away from the current path. The electrolysis is typically conducted at 70-80°C, partly to reduce the electrode overpotentials.

The general specifications of commercial cells are:

- 1) Most types of cells produce about 56 L (74.5 L, theoretically) of hydrogen and half as much oxygen per mega joule. The gas is about 99.7% pure.
- 2) The electrolyte is potassium hydroxide or sodium hydroxide because the alkaline medium causes fewer corrosion problems with the cheaper structural and electrode materials. Their concentration is 20-25 wt% since such values give close to optimum conductivity at the operating temperature. It is also necessary to use very pure water since this is consumed during the electrolysis causing impurities to accumulate.
- 3) The separator has traditionally been **asbestos**, often with a nickel gauze support. It should be remembered that the only role of the separator in a water electrolyzer is to keep the gaseous products apart.

4) The equilibrium potential for the cells is - 1.23V. In fact, no discernible gas evolution is observed until the cell voltage is from -1.65 to -1.79 V, and for the operating current densities of 100-600mA/ cm², the cell voltage is generally from -1.9 to -2.6 V, giving an energy efficiency of 45-65%. The energy requirements usually lie within the range 4.2-4.6 kWhm⁻³.

5) H₂ and O₂ cells are built entirely of steel (with portions made of concrete), insulating materials, and asbestos cloth for diaphragms. All contact voltages are kept to a minimum so as to obtain low cell voltages. Cells are so well designed that almost theoretical yields of the gases are obtained.

Types of Cells

All the important industrial cells are of the separator type but differ in the arrangement of their electrodes, diaphragms, external containers, gas outlets, and assembly in batteries. In most electrolyzers the oxygen is 99% or high and the, hydrogen 99.5% or high at current efficiencies approaching 100%. The voltages on the cells are the summation of the decomposition voltage of water (the oxygen and hydrogen overpotential = 1.23V at 25°C temperature), plus those necessary to overcome the electrolyte resistance and the ohmic resistance of the electrodes, contacts, and terminals. In all cases the raw material is distilled water.

3.5.3. 1. Tank cells

Which are usually operated in a monopolar manner, have the advantages of simplicity, reliability and flexibility. The tank cell is the classical batch or semi-batch (reactants added and products removed at intervals) reactor of electrochemical technology. In most tank cells, however, the electrodes are vertical and made from sheet, gauze or expanded metal. The cell is arranged with parallel lines of alternate anodes and cathodes, the electrodes extending across and to the full depth of the tank. The anode-cathode gap is made as small as possible to maximize the space-time yield and to reduce the energy consumption. The asbestos diaphragm in a water electrolyzer is only to prevent mixing of the oxygen and hydrogen while allowing the interelectrode gap to be quite small.

Stuart Cell: A rectangular tank (e.g. nickel plated steel) contains alternate anodes and cathodes, which are made of rigid metal, closely spaced and parallel. Fig 3.7 shows a typical version of Stuart monopolar tank cell. All electrodes having the same polarity are connected in parallel, such that the cell voltage (equivalent to that of cathode-anode pair) is from -1.7 to -2.0V. Cells are connected in series in order to provide a total voltage drop suitable to the rectifier output (from -100 to -500 V). Higher currents (hence a greater H₂ output) can be achieved by increasing the number of electrodes per tank or the number of tanks.

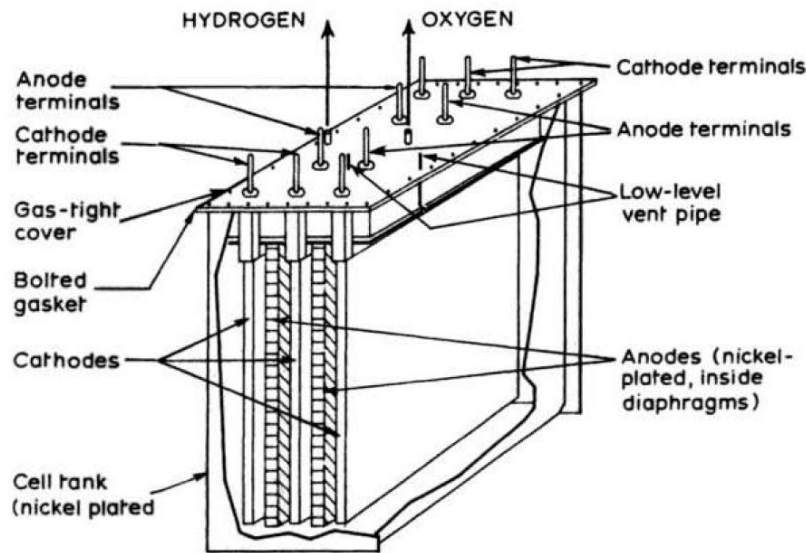


Fig. 3.7 Components and construction of monopolar water electrolysis cell.

The simple construction of many monopolar Tank cells is illustrated by the use of a single gasket to seal the electrolyzer tank. The Stuart cell typically has a nominal power rating of 200kW, with the specifications listed in Table 3.3.

Table 3.3 Specifications of modern 200 kW monopolar water electrolyzer.

Cell current	10 kA
Cell voltage	-1.85 V
Energy efficiency	≥ 80%
Energy consumption	4.4 kWh/m ³ H ₂
Current density	0.25 A cm ⁻²
Temperature	70° C
Hydrogen output	42 m ³ h ⁻¹
Oxygen output	21 m ³ h ⁻¹
Specific plant area	0.15 m ² /m ³ h ⁻¹ H ₂

3.5.3.2. Solid Polymer Electrolyte (SPE) Cells

The first solid polymer electrolyzers were developed by the General Electric Company as fuel cells for the NASA space program. Subsequently, small scale solid polymer water electrolyzers were used for military and space applications in the early 1970s. SPE are also used in chlor-alkali cells, water electrolyzers, and electro-organic synthesis cells, where an ion exchanger membrane, for example, Nafion®, serves as the electrolyte. Nafion® is the most known trademark among ionic membranes and is patented by Du Pont Company in 1966.

Pure water is supplied to the anode where it is oxidized to oxygen and protons; the latter pass through the polymer electrolyte to the cathode where hydrogen gas evolves. In fact excess water is circulated through the anode compartment to remove waste heat. In solid polymer electrolyte cells, the electrolyte is a thin perfluorinated sulphonic acid (Nafion) membrane (0.25 mm thick) having a structure which promotes conduction of hydrated protons.

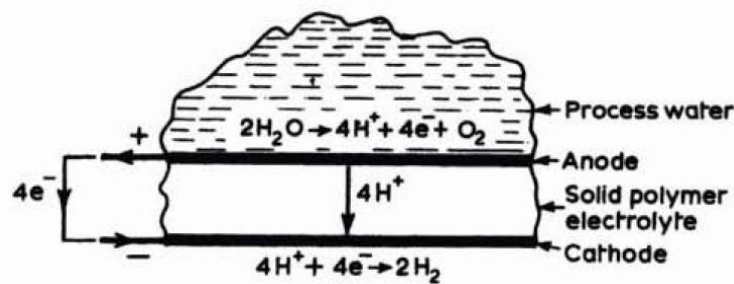
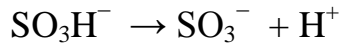


Fig. 3.8 the schematic cell reactions of SPE

SPE membranes have excellent chemical stability, high ionic conductivity and excellent mechanical strength. Water electrolysis using Nafion® as an electrolyte is a promising technology for large-scale hydrogen production.

The solid polymer electrolyte (SPE) is a membrane which acts as a proton conductor in electrolyzer cell. Usually, the ionic membrane consists of a solid polytetrafluoroethylene (PTFE) backbone, which is chemically altered and contains sulfonic ionic functional groups thus the pendant side chains terminated with $-\text{SO}^3^-$.

The acid dissociates and release protons by the following mechanism:



Nafion® allow water molecules to penetrate into its structure, while remaining not permeable to molecular H_2 and O_2 . The sulfonic groups are responsible for the transfer of protons during electrolysis, where a hydrated proton H_3O^+ can freely move within the polymer matrix, while a sulfonate ion SO_3^- is fixed to the side chain of polymer. When electric current flows across the membrane, the hydrated protons are attracted to the cathode, where they are combined into hydrogen.

However, SPE electrolyzer has a number of important advantages compared to other water electrolyzers;

1. The electrolyte is stable and the cell design is simple.
2. The absence of a corrosive electrolyte promotes a high reliability with low maintenance.
3. The membrane prevents mixing of the product gases, facilitating safety and high gas purities.

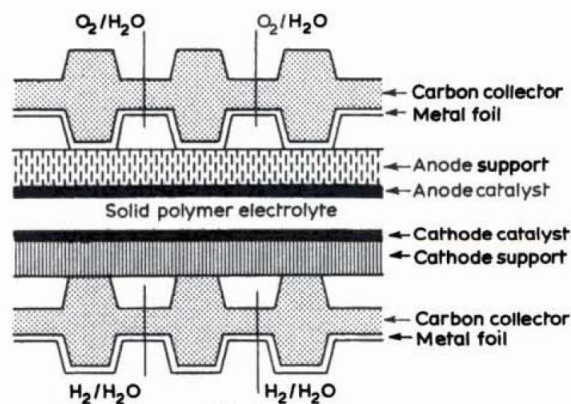


Fig. 3.9 The solid polymer cell design

As shown in Fig. 3.9 the solid polymer electrolyte cell comprises:

- 1) Solid polymer electrolyte SPE membrane
- 2) Porous electrodes with catalyst
- 3) Anode support made from porous platinized titanium
- 4) Cathode support made from carbon-fiber paper
- 5) Platinized titanium foil
- 6) Carbon collector

The collector is molded in graphite with a fluorocarbon polymer binder. A metal foil of 25 μ m thick platinized titanium is molded to the anode side to prevent oxidation. The purposes of the collector are:

1. to ensure even fluid distribution over the active electrode area.
2. to act as the main structural component of the cell.
3. to provide sealing of fluid ports and the reactor.
4. to carry current from one cell to the next.

Demineralized water is carried across the cell via a number of channels molded into the collector. These channels terminate in recessed manifold areas each of which is fed from six drilled ports. The anode support is a porous conducting sheet of platinized titanium having a thickness of approximately 250 μ m, with purposes of:

1. distribute current uniformly over the active electrode area.
2. distribute fluid uniformly over the active electrode area.
3. prevents masking of those parts of the electrode area which would be covered by the carbon collector.

The cathode support comprises a layer of carbon-fiber paper having a thickness of 300-330 μ m. The cathode electrode composition is PTFE/graphite-based porous structure with precious metal (probably Pt) catalyst of loading 0.1-0.25 mg/ cm², and the anode has a similar base but with ruthenium dioxide mixed with transition-metal additives as the catalyst. Fig. 3.10 indicates the cell voltage-time relationship both for module of fourteen 0.093 m² cells.

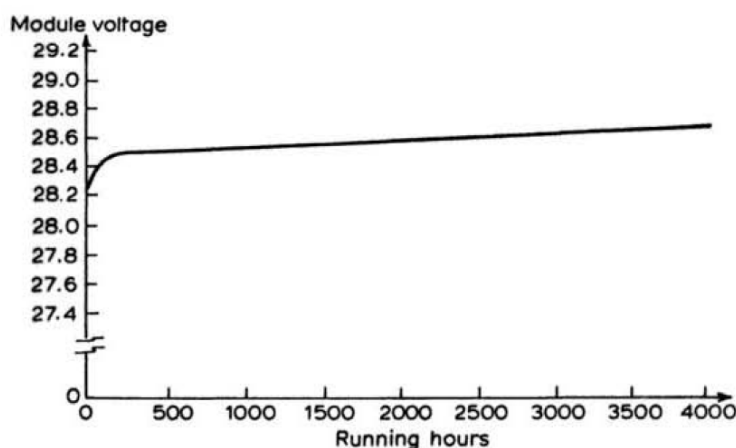


Fig 3.10 Module voltage as a function of time for SPE cell Stack.

Each module consists of 14 cathodes, each of area 0.093 m² operating at 1.075 A/cm² and 55°C. Typical operating characteristics of the cell stack are given in Table 3.4

Table 3.4 Typical performance of a solid polymer electrolyzer

Parameter	Value
Cell module:	
Cell active area	0.093 m ²
Number of cells	> 7-51
Current density	1.075 A cm ⁻²
Maximum current	1000 A
Initial cell voltage	- 2 V/cell
Gas production:	
Hydrogen gas flow rate	0.42 m ³ h ⁻¹ /cell
Oxygen gas flow rate	0.21 m ³ h ⁻¹ /cell
Hydrogen gas purity	H ₂ > 99.995% by volume O ₂ < 0.005% by volume Halogens and halides < 4 v.p.m.* Total impurities < 50 v.p.m.
Oxygen gas purity	O ₂ > 99% by volume H ₂ < 1% by volume Total impurities < 500 v.p.m.
Maximum differential pressure (H ₂ over O ₂)	7 bar
Process water:	
Demineralized water conductivity	< 0.25 μS cm ⁻¹
Inlet temperature	50° C
Outlet temperature	65° C

*Volumes per million (volumes)