4. Industrial Gases (H₂ & O₂ Production)

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

4.1 Hydrogen and Oxygen 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.

A major use of **oxygen** is the production of steel in open hearth or basic oxygen furnaces. The steel industry also uses oxygen as well as the chemical industry which is the consumer of oxygen in such applications as acetylene, ethylene oxide, hydrocarbons and medical purposes.

4.2 Hydrogen 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 steam-hydrocarbon reforming process.

4.2.1 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:

\[ C_nH_m + nH_2O \rightleftharpoons nCO + \left( \frac{m}{2} + n \right) \text{H}_2 \]

\[ \text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{CO}_2 + \text{H}_2 \]

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
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 these 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.

For the production of additional H₂, the reformer is followed by a separate stage of water gas-shift conversion. The process using propane is shown in Fig. 4.1; 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 H₂, CO, and some CO₂ are cooled to about 370°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 CO₂ with more H₂. (This is the so called water-gas-shift reaction). These hot gases are first cooled by heat exchange with the gases leaving the first-stage CO₂
absorber before entering the second-stage CO converter, and finally by water to about 38°C.

5) The cooled gases are scrubbed with a monoethanolamine (MEA) solution (C₂H₅ONH₂) in absorber to remove essentially all the CO₂.

6) The product gases low in CO₂ are heated to about 315°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 CO₂ to methane by reaction with H₂.

7) The product H₂ gas from the methanator is cooled to 38°C (with water), leaving it pure except for saturation with water vapor.

8) The MEA rich solution (CO₂ carrier) is returned to the stripper through heat exchangers, and the CO₂ is stripped out by steam. The CO₂ which can be recovered for use about 55 kg/100 m³ H₂. The lean amine solution from the stripper is pumped through the heat exchanger to the CO₂ absorber to remove the bulk of the CO₂ in the H₂ gas stream.

Fig. 4.1 Simplified Hydrogen Production Processing
4.2.2 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. Feedstocks 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:

\[
\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} \quad \Delta H = -802 \text{ kJ}
\]

\[
\text{CH}_4 + \text{CO}_2 \rightarrow 2\text{CO} + 2\text{H}_2 \quad \Delta H = 206 \text{ kJ}
\]

\[
\text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2 \quad \Delta H = 247\text{kJ}
\]

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:

\[
\text{CH}_4 + \%\text{O}_2 \rightarrow \text{CO} + 2\text{H}_2
\]

This reaction is exothermic, and so the overall process is a net producer of heat. For efficient operation, heat recovery (using waste heat boilers) is important. The product gas has a composition that depends upon the carbon/hydrogen ratio in the feed and the amount of steam added. Pressure does not have a significant effect on composition, and the process is usually conducted at 2-4 MPa, permitting the use of more compact equipment and reducing compression costs.

*Table 4.1 The typical composition for a fuel oil feedstock.*

<table>
<thead>
<tr>
<th>Component</th>
<th>Mole Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>48.0</td>
</tr>
<tr>
<td>CO</td>
<td>46.1</td>
</tr>
<tr>
<td>CO₂</td>
<td>4.3</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.4</td>
</tr>
<tr>
<td>N₂, etc</td>
<td>0.3</td>
</tr>
<tr>
<td>H₂S</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100.0</strong></td>
</tr>
</tbody>
</table>

In this process much higher carbon oxides/hydrogen ratio than steam reformer gas. The remaining process steps for conversion of the partial oxidation product gas to hydrogen are the same as for the steam-hydrocarbon reforming process.
4.2.3 Coal Gasification Processes

Coal as a source of hydrogen will assume increasing importance in the future as reserves of gaseous and liquid hydrocarbon feedstock decrease. Although coal was used in early water-gas and producer-gas plants for the manufacture of a H₂-CO mixture, these plants cannot compete with more modern processes. The gases produced require the water-gas-shift reaction and subsequent purification to produce high-purity hydrogen.

4.2.4 Thermal Decomposition

A mixture of nitrogen, 1 volume, and hydrogen, 3 volumes, may be prepared from the cracking or dissociation of ammonia. This mixed gas can be used for hydrogenation because the nitrogen is inert. The process consists of vaporizing the liquid, ammonia from cylinders, heating it to 870°C, passing it over an active catalyst, and then cooling it in heat exchangers where the incoming gas may be vaporized. A single 68-kg cylinder of anhydrous ammonia will produce 190 m³ of cracked ammonia. This is equivalent to the contents of about 33 hydrogen cylinders. Table 4.2 shows a comparison of the four main processes for the production of hydrogen.

Table 4.2 Comparison of Hydrogen Production Alternatives
4.2.5 The Electrolytic process

4.2.5.1 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 4.2

![Hofmann Electrolysis Apparatus](image)

**Fig. 4.2 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:**

Anode oxidation: \(2 \text{H}_2\text{O} \rightarrow \text{O}_2(g) + 4\text{H}^+ + 4 \text{e}^- \)

Cathode reduction: \(2\text{H}^+ + 2 \text{e}^- \rightarrow \text{H}_2(g) \)

\(E^\circ\) cell = -1.23 v

**In basic solution:**

Anode oxidation: \(4\text{OH}^- (aq) \rightarrow \text{O}_2(g) + 2\text{H}_2\text{O} + 4 \text{e}^- \)
Cathode reduction: \( 2\text{H}_2\text{O} \text{(l)} + 2e^- \rightarrow \text{H}_2\text{(g)} + 2\text{OH}^-\text{(aq)} \)

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

In the two cases the main reaction is:

\[ 2\text{H}_2\text{O}(\text{l}) \rightarrow 2\text{H}_2(\text{g}) + \text{O}_2(\text{g}) \]

A pair of inert electrodes is sealed in opposite ends of a container designed to collect the \( \text{H}_2 \) and \( \text{O}_2 \) 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. We therefore add an electrolyte to water to 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:

\[ 2\text{H}_2\text{O} \text{(l)} + 2e^- \rightarrow \text{H}_2\text{(g)} + 2\text{OH}^-\text{(aq)} \]

\[ 2\text{H}^+(\text{aq}) + 2\text{OH}^-\text{(aq)} \rightarrow 2\text{H}_2\text{O(l)} \]

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

\[ 2\text{H}^+ + 2e^- \rightarrow \text{H}_2(\text{g}) \]

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:

\[ 2\text{H}_2\text{O}\text{(l)} \rightarrow \text{O}_2\text{(g)} + 4\text{H}^+ + 4e^- \]

4.2.5.2 **Electrical Connection to Cells**

The arrangement of cells is also important and the plant must be electrically and chemically safe, although it is common for each cell to have a number of pipes for electrolyte feed and effluent and for gaseous products, the connections must be made
so that individual cells may be isolated for cleaning, maintenance and the replacement of cell components. The high currents in larger plants create substantial magnetic fields and it is therefore necessary to layout the cells to minimize these fields. When a cell contains more than two electrodes, there are two ways of making the electrical connection:

1) monopolar cell connection Fig. 4.3(a)

In the monopolar cell there is an external electrical contact to each electrode and the cell voltage is applied between each cathode and anode, where the anodes and the cathodes alternate and both faces of each central electrode are active, with the same polarity. Monopolar connection requires a low-voltage, high current supply.

2) bipolar cell connection Fig. 4.3(b)

Bipolar connection requires only two external electrical contacts to the two end electrodes and it recognizes that the cell reaction will occur wherever there is an appropriate potential difference. In the bipolar cell the opposite face of each electrode will have different polarities. The bipolar cell, in addition to simplicity of electrical connection, has the advantage that it produces the equivalent amount of product to monopolar cells using a lower current and a higher voltage.

The voltage field caused by the bipolar connection of the six electrodes of the cell can lead to five electrolysis cells. The voltage distributes itself between the end electrodes with the electrical contacts.

Fig. 4.3 Electrical connections in multielectrode cells. 1) Monopolar connections(b) Bipolar connections showing the possibility of 'bypass' or leakage currents.
4.2.5.3 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 electrolyser based on tank cells, filterpress 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:

\[ 2\text{H}_2\text{O}(l) \rightarrow 2\text{H}_2(g) + \text{O}_2(g) \quad \Delta H = +569 \text{kJ} \]

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 70-800 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 100-600 mA/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). Hydrogen and oxygen 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.

4.2.5.4 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.

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 or 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.

*Figure 4.4 A monopolar plate-in-tank reactor for water electrolysis.*

Fig 4.5 shows a typical version of the monopolar tank cell (the 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. 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. 4.5 the components and construction of a monopolar water electrolysis cell (the Stuart cell)

Table 4.3 Specifications of modern 200 kW monopolar water electrolyzer

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell current</td>
<td>10 kA</td>
</tr>
<tr>
<td>Cell voltage</td>
<td>−1.85 V</td>
</tr>
<tr>
<td>Energy efficiency</td>
<td>≥80%</td>
</tr>
<tr>
<td>Energy consumption</td>
<td>4.4 kWh/m³ H₂</td>
</tr>
<tr>
<td>Current density</td>
<td>0.25 A cm⁻²</td>
</tr>
<tr>
<td>Temperature</td>
<td>70° C</td>
</tr>
<tr>
<td>Hydrogen output</td>
<td>42 m³ h⁻¹</td>
</tr>
<tr>
<td>Oxygen output</td>
<td>21 m³ h⁻¹</td>
</tr>
<tr>
<td>Specific plant area</td>
<td>0.15 m²/m³ H₂⁻¹</td>
</tr>
</tbody>
</table>

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 200 kW, with the specifications listed in Table 4.4.

2. Parallel-Plate Flow Cells
Most industrial flow cells are based on the parallel-plate electrode configuration. The cell is usually constructed in a plate-and-frame arrangement and mounted on a filterpress. Each cell stack is assembled from a number of monopolar or bipolar cells comprising an electrode assembly and a cell frame which contains the asbestos diaphragm. The electrodes, electrolyte chambers, insulating plates to separate cells
The filterpress is then used to seal the cells with up to 100 cells in each unit using applied compression via a screw-press or hydraulic press. The electrical connection may be monopolar or bipolar and in a series of cells, the electrolyte feeds to the cells may be connected so that the cells are in series or parallel so far as the electrolyte is concerned.

Typically, bipolar filter press units with various sizes give hydrogen delivery rates between 3-50 m$^3$/hr. A modern bipolar filterpress unit operates at a current of 2.5 kA and a power consumption of 4.6kWhm$^3$, the total electrolysis capacity being 250kW. The increase in hydrogen delivery rate may be achieved by increasing both the area of the diaphragm and electrodes and the number of cells in the filterpress stack.
Fig. 4.8 Plate-and-frame cells with bipolar electrodes & internal manifolding

The parallel-plate geometry is a popular and convenient choice of reactor for a diverse range of processes. Reasons for this include:

1. Simplicity of construction with regard to features such as cell frames, electrode connections and membrane sealing.
2. Wide availability of electrode materials and separators in a suitable form.
3. The potential distribution is reasonably uniform.
4. Mass transport may be enhanced and adjusted using a variety of turbulence promoters and control of the linear electrolyte velocity.
5. Scale-up readily achieved by a suitable combination of:
   (a) increased electrode size.
   (b) using more electrodes.
   (c) duplicating the cell Stack.
6. Versatility, with respect to monopolar or bipolar operation and the possibility of modifying the fundamental unit cell.
3. Solid polymer Cells

The first solid polymer electrolysers 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.

Cells with an active cathode area of 0.093 m\(^3\) were developed and 0.23 m\(^2\) cells (involving a 200 kW module capable of producing 55 m\(^3/\)hr H\(_2\)) are now in operation.

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. 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.

The solid polymer electrolyte cell tends to be slightly larger than corresponding high-pressure cells and requires a compressor to remove the hydrogen gas. However, it 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.
As shown in Fig. 4.10 the solid polymer electrolyte cell comprises a membrane, fuel cell type, porous electrodes and three further components:

1) carbon collector
2) platinized titanium anode support
3) cathode support made from carbon-fiber paper

The collector is molded in graphite with a fluorocarbon polymer binder. A 25μm thick platnized titanium foil 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 μm. The purpose of the support is to distribute current and fluid uniformly over the active electrode area. It also 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 μm. 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. 4.11 indicates the cell voltage-time relationship both for module of fourteen 0.093 m² cells.

![Graph](image)

Fig 4.11  Module voltage as a function of time for a solid-polymer electrolyte cell Stack. Each module consist 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 4.4

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cell module:</strong></td>
<td></td>
</tr>
<tr>
<td>Cell active area</td>
<td>0.093 m²</td>
</tr>
<tr>
<td>Number of cells</td>
<td>&gt; 7−51</td>
</tr>
<tr>
<td>Current density</td>
<td>1.075 A cm⁻²</td>
</tr>
<tr>
<td>Maximum current</td>
<td>1000 A</td>
</tr>
<tr>
<td>Initial cell voltage</td>
<td>−2 V/cell</td>
</tr>
<tr>
<td><strong>Gas production:</strong></td>
<td></td>
</tr>
<tr>
<td>Hydrogen gas flow rate</td>
<td>0.42 m³ h⁻¹/cell</td>
</tr>
<tr>
<td>Oxygen gas flow rate</td>
<td>0.21 m³ h⁻¹/cell</td>
</tr>
<tr>
<td>Hydrogen gas purity</td>
<td>H₂ &gt; 99.995% by volume</td>
</tr>
<tr>
<td></td>
<td>O₂ &lt; 0.005% by volume</td>
</tr>
<tr>
<td></td>
<td>Halogens and halides &lt; 4 v.p.m.*</td>
</tr>
<tr>
<td></td>
<td>Total impurities &lt; 50 v.p.m.</td>
</tr>
<tr>
<td>Oxygen gas purity</td>
<td>O₂ &gt; 99% by volume</td>
</tr>
<tr>
<td></td>
<td>H₂ &lt; 1% by volume</td>
</tr>
<tr>
<td></td>
<td>Total impurities &lt; 500 v.p.m.</td>
</tr>
<tr>
<td>Maximum differential pressure (H₂ over O₂)</td>
<td>7 bar</td>
</tr>
<tr>
<td><strong>Process water:</strong></td>
<td></td>
</tr>
<tr>
<td>Demineralized water conductivity</td>
<td>&lt; 0.25 μS cm⁻¹</td>
</tr>
<tr>
<td>Inlet temperature</td>
<td>50°C</td>
</tr>
<tr>
<td>Outlet temperature</td>
<td>65°C</td>
</tr>
</tbody>
</table>

*Volumes per million (volumes)

Table 4.4 Typical performance of a solid polymer electrolyzer