Lecture Note #10 (Spring, 2022)

# Fuel cell stack and system

1. System analysis
2. Basic stack design concepts
3. Cell stack configurations
4. Components
5. Utilization of oxidant and fuel
6. Flow-field design
7. Water and thermal management
8. Structural-mechanical considerations
9. Case study

Fuller & Harb (textbook), ch.10

# System analysis

-Fuel cell system: fuel processor, cell stack, power conditioning section
-the oxidant (air): compressor or blower needed
-Fuel processor
e.g.
$CH_4 + H_2O \rightarrow CO + 3H_2$ reformation
$CO + H_2O \rightarrow CO_2 + H_2$ water-gas shift reaction
$CO + 0.5O_2 \rightarrow CO_2$ selective oxidation

-Design consideration factors:
efficiency, system size, cost, durability

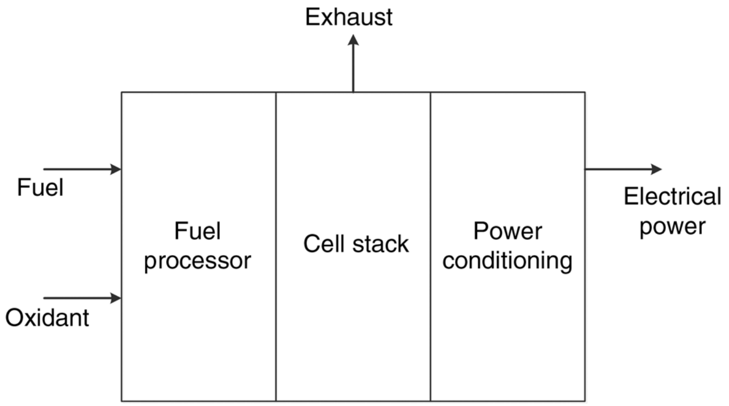

**Figure 10.1** Generic fuel-cell system operating on fuel and oxidant. There are three main subsystems: fuel processor, the cell stack, and the power conditioning subsystem.

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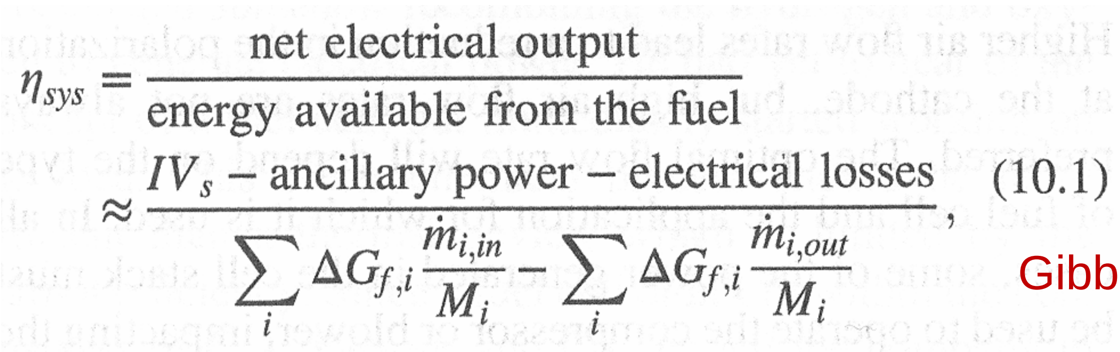
- ✓ Efficiency of the fuel cell (based on the free energy change)

= the net electrical work produced / the energy available from the reactants

fuel cell system efficiency



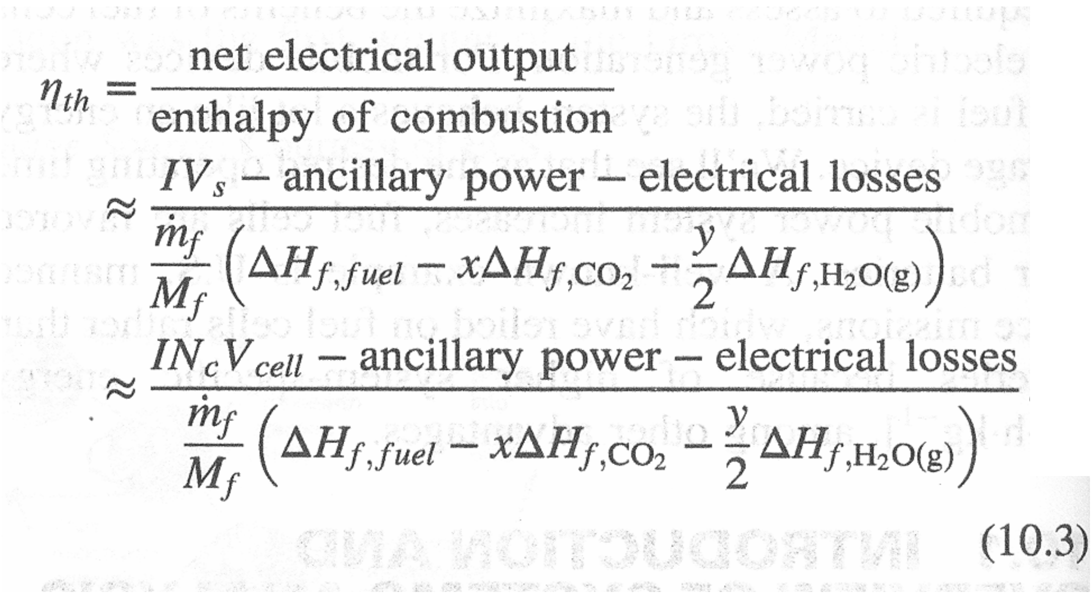
$$\eta_{sys} = \frac{\text{net electrical output}}{\text{energy available from the fuel}} \approx \frac{IV_s - \text{ancillary power} - \text{electrical losses}}{\sum_i \Delta G_{f,i} \frac{\dot{m}_{i,in}}{M_i} - \sum_i \Delta G_{f,i} \frac{\dot{m}_{i,out}}{M_i}}, \qquad (10.1)$$

Gibbs free energy

High cell potential needed → minimization of ohmic, kinetic, mass-transfer polarization is desired

✓ System thermal efficiency (more, common, based on the change of enthalpy)

For $C_xH_yO_z + (x + 4/y - z/2)O_2 \rightarrow xCO_2 + (y/2)H_2O$ (10.2)



$$
\begin{aligned}
\eta_{th} &= \frac{\text{net electrical output}}{\text{enthalpy of combustion}} \\
&\approx \frac{IV_s - \text{ancillary power} - \text{electrical losses}}{\frac{\dot{m}_f}{M_f}\left(\Delta H_{f,fuel} - x\Delta H_{f,\mathrm{CO_2}} - \frac{y}{2}\Delta H_{f,\mathrm{H_2O(g)}}\right)} \\
&\approx \frac{IN_cV_{cell} - \text{ancillary power} - \text{electrical losses}}{\frac{\dot{m}_f}{M_f}\left(\Delta H_{f,fuel} - x\Delta H_{f,\mathrm{CO_2}} - \frac{y}{2}\Delta H_{f,\mathrm{H_2O(g)}}\right)}
\end{aligned}
\qquad (10.3)
$$

enthalpy

-The enthalpy of reaction depends strongly on the phase of the product of water
(i) HHV (the higher heating value) assumes that the product water is liquid phase
(ii) LHV (the lower heating value) assumes the vapor phase
→ usually LHV is used

Illustration 10.1

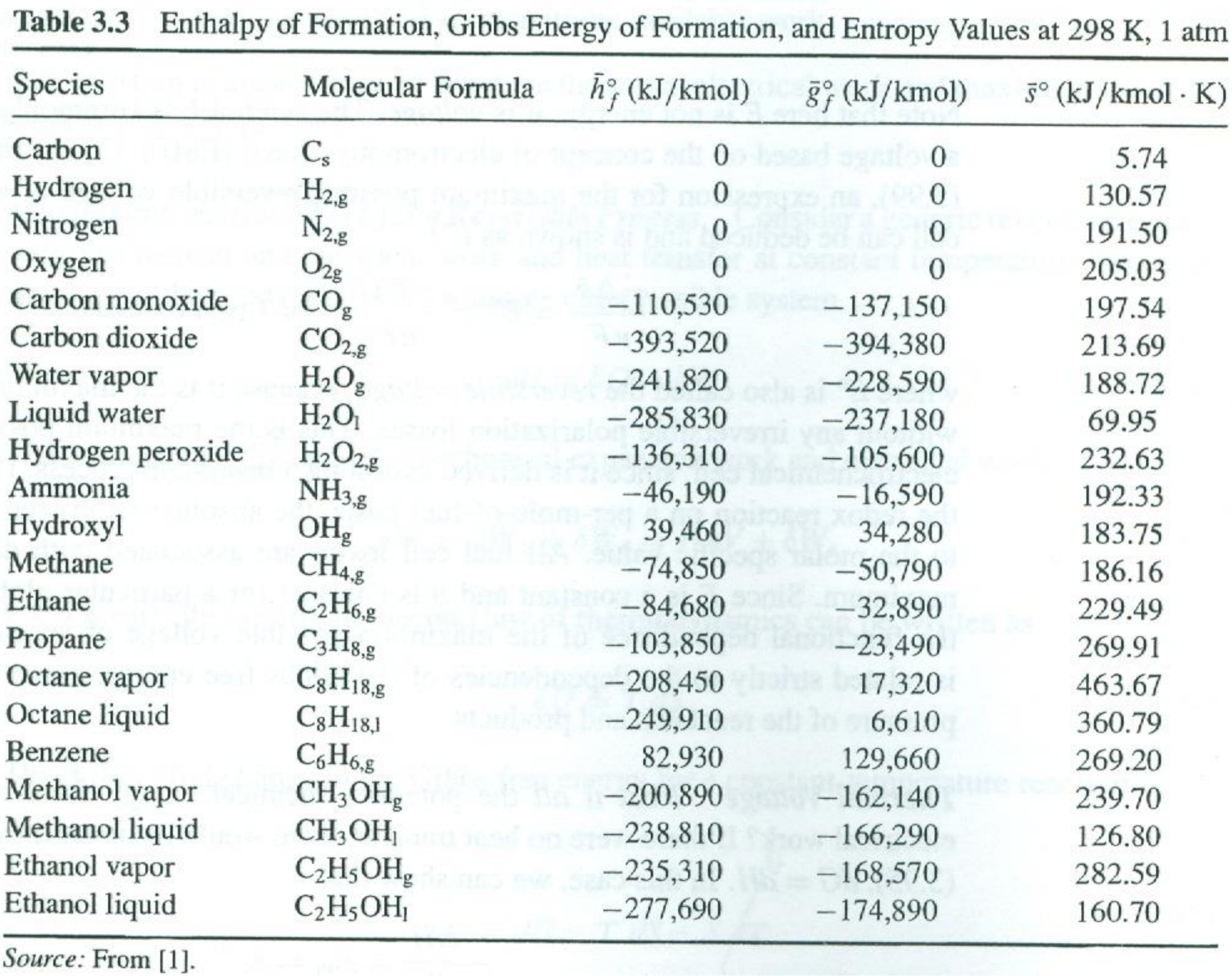


**Table 3.3** Enthalpy of Formation, Gibbs Energy of Formation, and Entropy Values at 298 K, 1 atm

| Species | Molecular Formula | $\bar{h}_f^\circ$ (kJ/kmol) | $\bar{g}_f^\circ$ (kJ/kmol) | $\bar{s}^\circ$ (kJ/kmol · K) |
|---|---|---|---|---|
| Carbon | $C_s$ | 0 | 0 | 5.74 |
| Hydrogen | $H_{2,g}$ | 0 | 0 | 130.57 |
| Nitrogen | $N_{2,g}$ | 0 | 0 | 191.50 |
| Oxygen | $O_{2g}$ | 0 | 0 | 205.03 |
| Carbon monoxide | $CO_g$ | −110,530 | −137,150 | 197.54 |
| Carbon dioxide | $CO_{2,g}$ | −393,520 | −394,380 | 213.69 |
| Water vapor | $H_2O_g$ | −241,820 | −228,590 | 188.72 |
| Liquid water | $H_2O_l$ | −285,830 | −237,180 | 69.95 |
| Hydrogen peroxide | $H_2O_{2,g}$ | −136,310 | −105,600 | 232.63 |
| Ammonia | $NH_{3,g}$ | −46,190 | −16,590 | 192.33 |
| Hydroxyl | $OH_g$ | 39,460 | 34,280 | 183.75 |
| Methane | $CH_{4,g}$ | −74,850 | −50,790 | 186.16 |
| Ethane | $C_2H_{6,g}$ | −84,680 | −32,890 | 229.49 |
| Propane | $C_3H_{8,g}$ | −103,850 | −23,490 | 269.91 |
| Octane vapor | $C_8H_{18,g}$ | −208,450 | 17,320 | 463.67 |
| Octane liquid | $C_8H_{18,l}$ | −249,910 | 6,610 | 360.79 |
| Benzene | $C_6H_{6,g}$ | 82,930 | 129,660 | 269.20 |
| Methanol vapor | $CH_3OH_g$ | −200,890 | −162,140 | 239.70 |
| Methanol liquid | $CH_3OH_l$ | −238,810 | −166,290 | 126.80 |
| Ethanol vapor | $C_2H_5OH_g$ | −235,310 | −168,570 | 282.59 |
| Ethanol liquid | $C_2H_5OH_l$ | −277,690 | −174,890 | 160.70 |

*Source:* From [1].

Mathew M. Mench, *Fuel Cell Engines*, Wiley, 2008.

✓ System thermal efficiency as the product of the fuel efficiency, thermal voltage efficiency, power-conditioning efficiency, mechanical efficiency

$$\eta_{th} = \eta_{fuel} \times \eta_{V,t} \times \eta_{pc} \times \eta_{mech} \qquad (10.4)$$

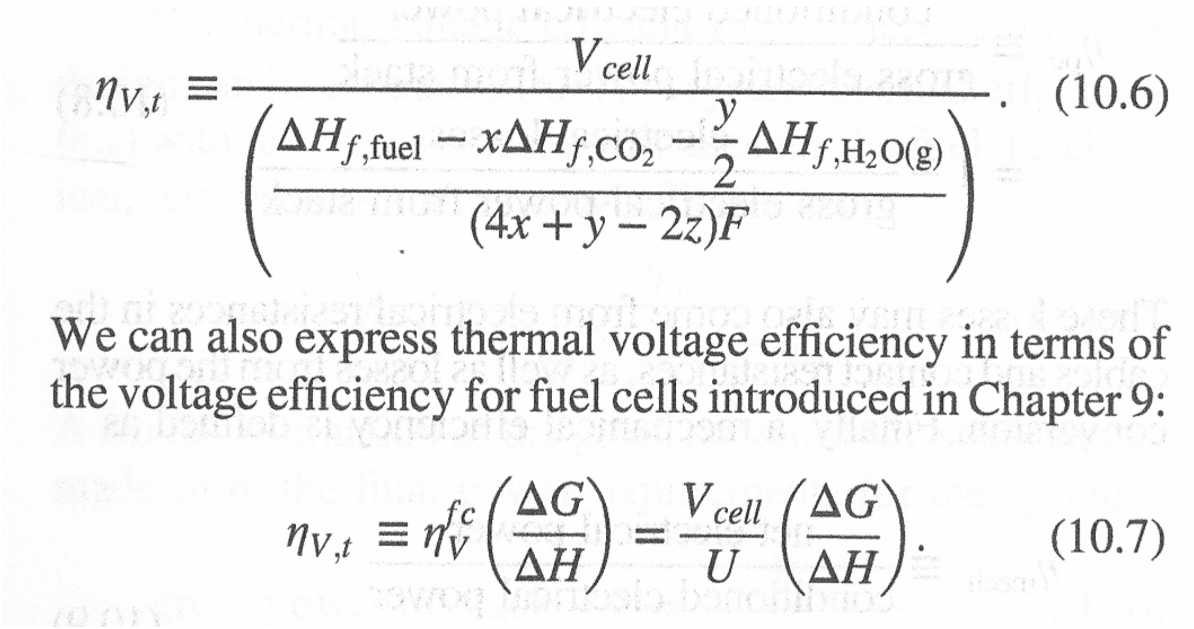
✓ Fuel efficiency($\eta_{fuel}$): the fraction of the fuel fed into the system that contributes to the electrical current in the fuel cell

$$\eta_{fuel} = \frac{\text{fuel that contributes to current in fuel cell}}{\text{total amount of fuel that is supplied}} = \frac{I/(4x+y-2z)F}{\dot{m}_{f,cell}/M_f} = \frac{IN_c/(4x+y-2z)F}{\dot{m}_f/M_f}, \qquad (10.5)$$

Flow rate through a single cell & all of the cells in the stack

\# of electrons: $4x + y - 2z$
\# of cells: $N_c$

- ✓ Thermal voltage efficiency($\eta_{V,t}$): how effectively the energy from the fuel is converted to electrical power in the fuel cell → accounts for voltage losses in the cell → the operating potential of the cell divided by the change in enthalpy of the reaction expressed in [J/C]

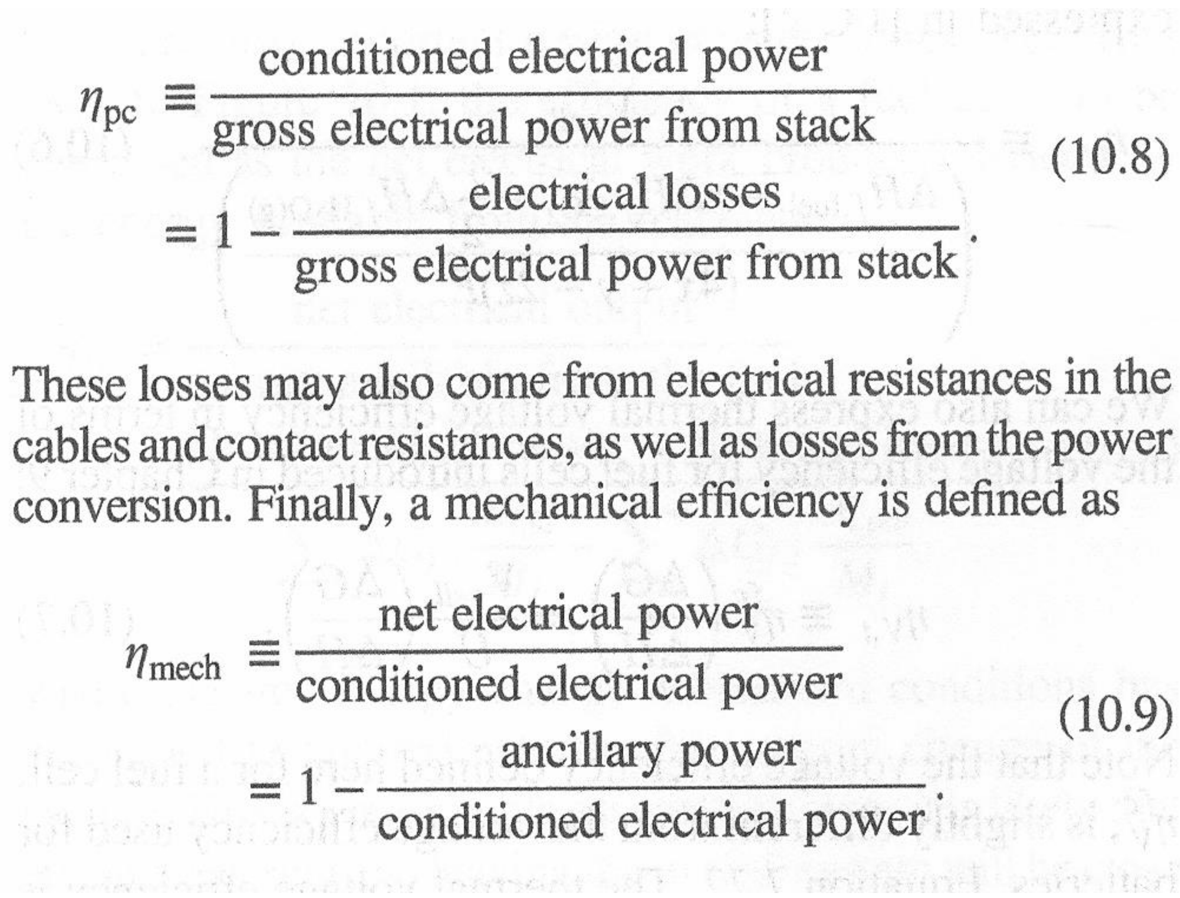


$$\eta_{V,t} \equiv \frac{V_{cell}}{\left(\dfrac{\Delta H_{f,\text{fuel}} - x\Delta H_{f,\text{CO}_2} - \dfrac{y}{2}\Delta H_{f,\text{H}_2\text{O(g)}}}{(4x+y-2z)F}\right)}. \tag{10.6}$$

We can also express thermal voltage efficiency in terms of the voltage efficiency for fuel cells introduced in Chapter 9:

$$\eta_{V,t} \equiv \eta_V^{fc}\left(\frac{\Delta G}{\Delta H}\right) = \frac{V_{cell}}{U}\left(\frac{\Delta G}{\Delta H}\right). \tag{10.7}$$

✓ Power-conditioning efficiency($\eta_{pc}$): converting DC power to AC power



$$\begin{aligned}\eta_{\text{pc}} &\equiv \frac{\text{conditioned electrical power}}{\text{gross electrical power from stack}}\\ &= 1 - \frac{\text{electrical losses}}{\text{gross electrical power from stack}}.\end{aligned}\tag{10.8}$$

These losses may also come from electrical resistances in the cables and contact resistances, as well as losses from the power conversion. Finally, a mechanical efficiency is defined as

$$\begin{aligned}\eta_{\text{mech}} &\equiv \frac{\text{net electrical power}}{\text{conditioned electrical power}}\\ &= 1 - \frac{\text{ancillary power}}{\text{conditioned electrical power}}.\end{aligned}\tag{10.9}$$

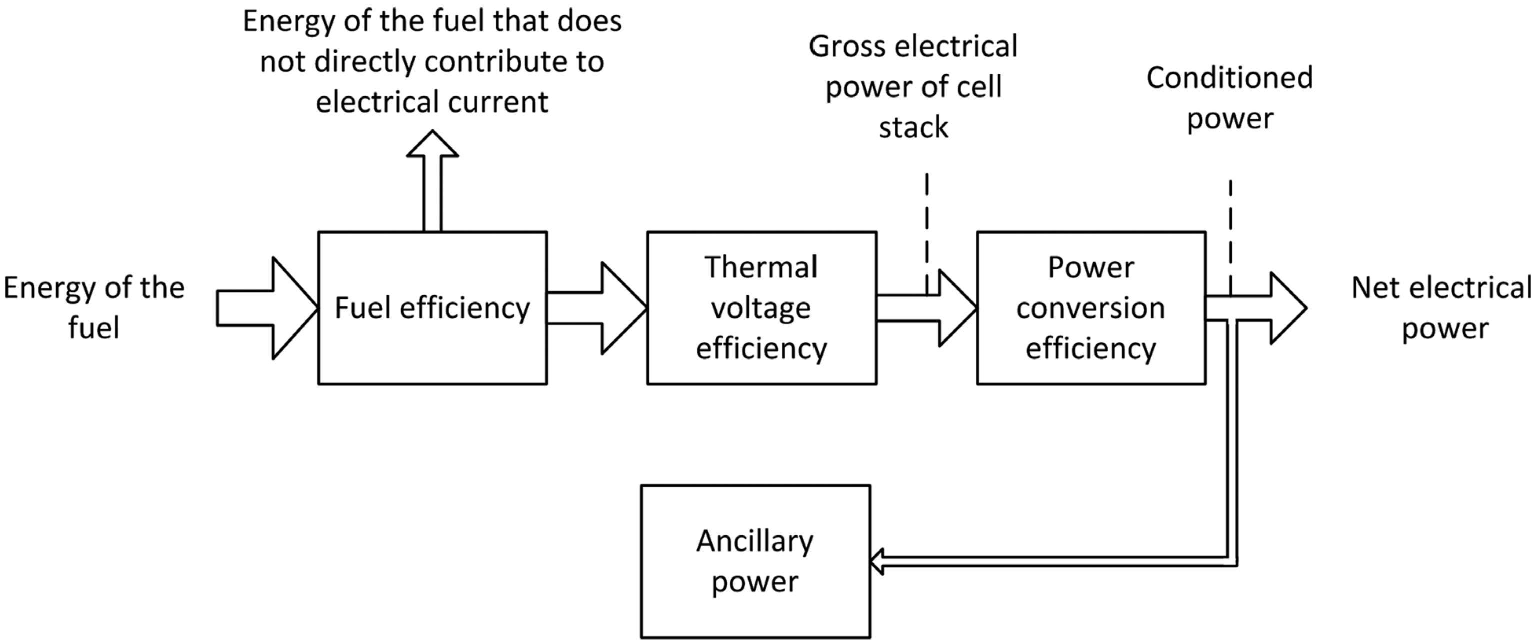


**Figure 10.2** Power flow and efficiencies for fuel-cell systems.

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# Basic stack design concepts

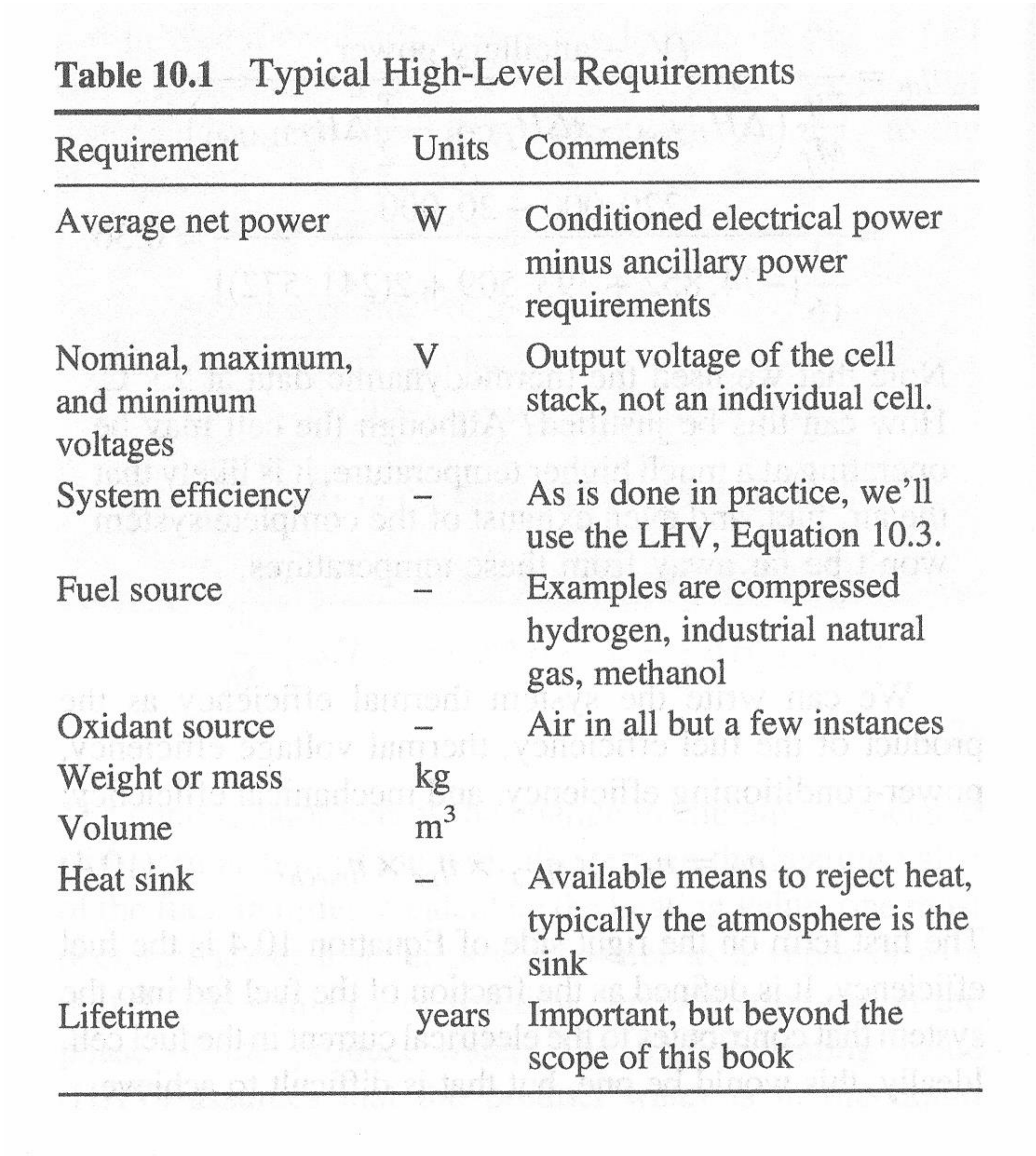


**Table 10.1** Typical High-Level Requirements

| Requirement | Units | Comments |
|---|---|---|
| Average net power | W | Conditioned electrical power minus ancillary power requirements |
| Nominal, maximum, and minimum voltages | V | Output voltage of the cell stack, not an individual cell. |
| System efficiency | – | As is done in practice, we'll use the LHV, Equation 10.3. |
| Fuel source | – | Examples are compressed hydrogen, industrial natural gas, methanol |
| Oxidant source | – | Air in all but a few instances |
| Weight or mass | kg | |
| Volume | $m^3$ | |
| Heat sink | – | Available means to reject heat, typically the atmosphere is the sink |
| Lifetime | years | Important, but beyond the scope of this book |

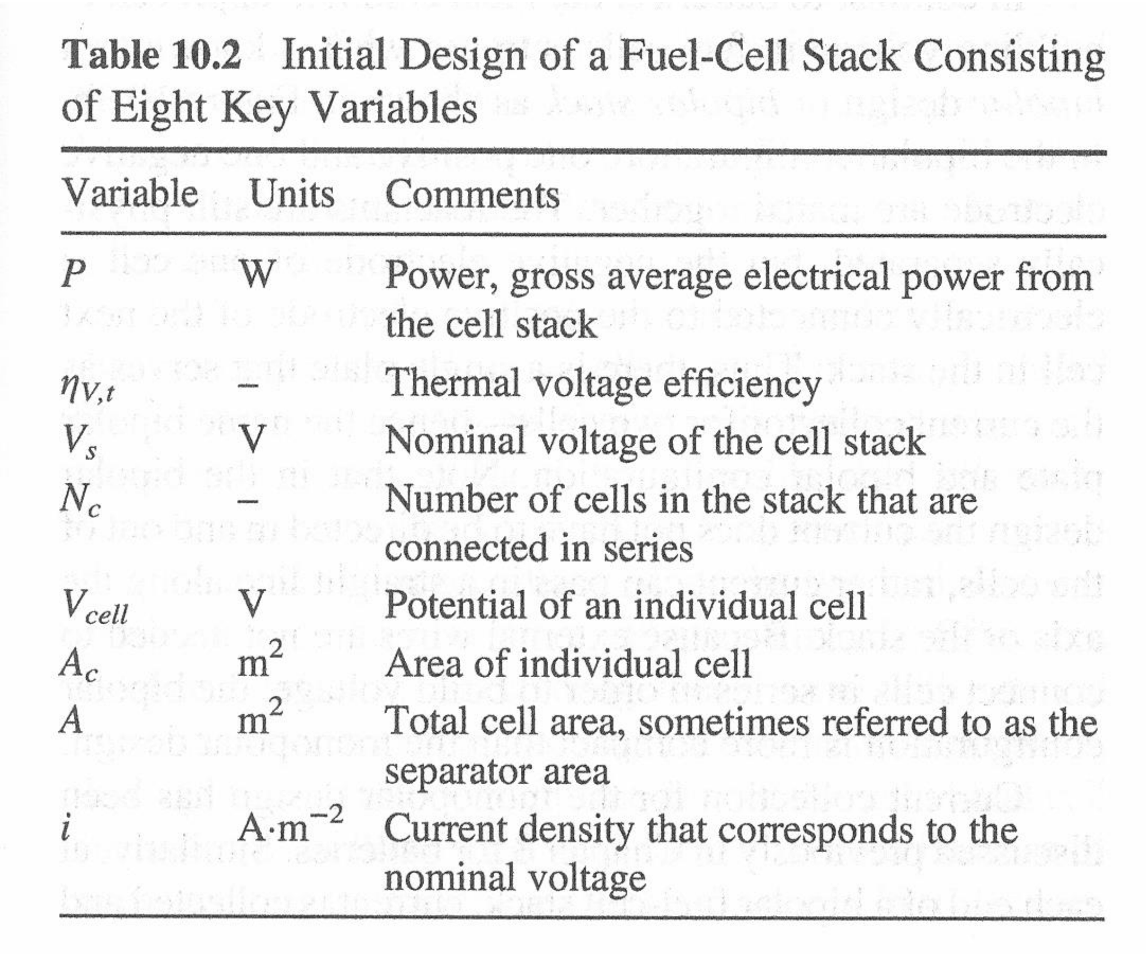


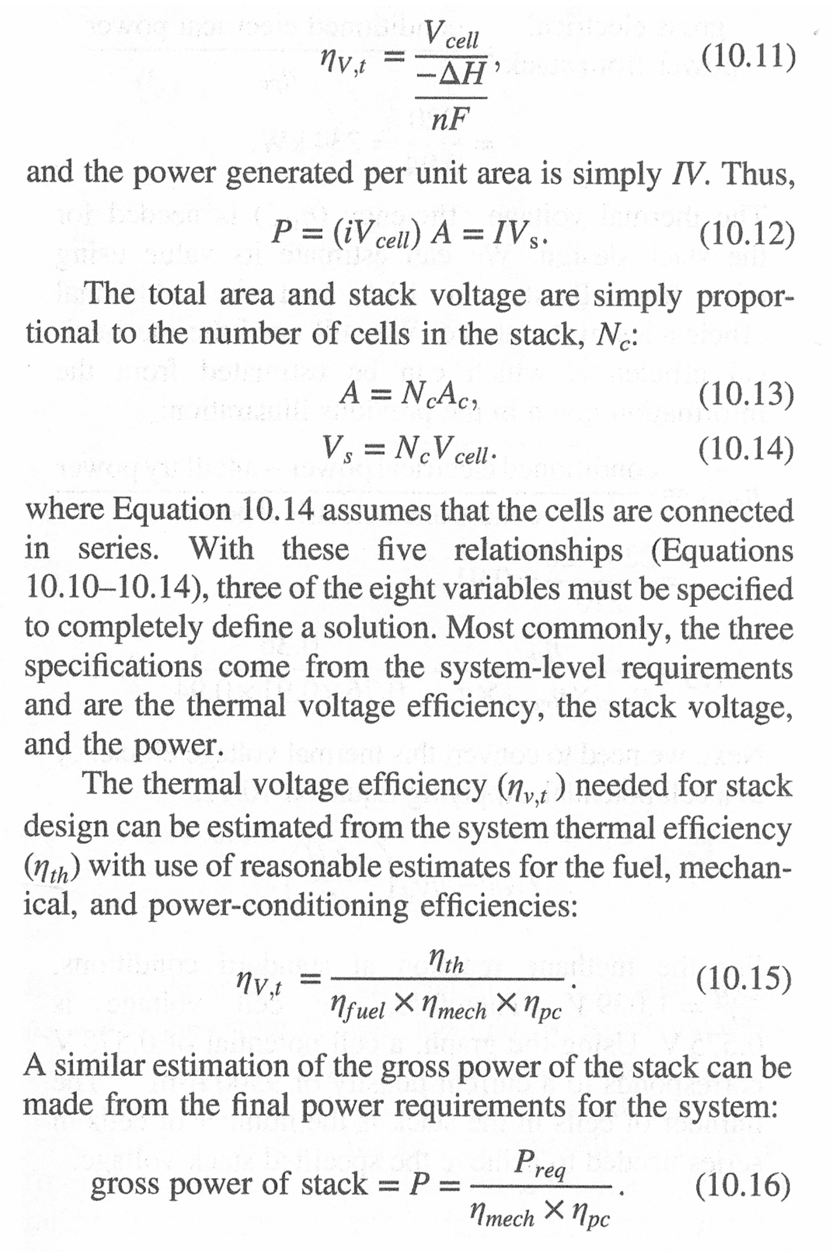
**Table 10.2** Initial Design of a Fuel-Cell Stack Consisting of Eight Key Variables

| Variable | Units | Comments |
|---|---|---|
| $P$ | W | Power, gross average electrical power from the cell stack |
| $\eta_{V,t}$ | – | Thermal voltage efficiency |
| $V_s$ | V | Nominal voltage of the cell stack |
| $N_c$ | – | Number of cells in the stack that are connected in series |
| $V_{cell}$ | V | Potential of an individual cell |
| $A_c$ | $m^2$ | Area of individual cell |
| $A$ | $m^2$ | Total cell area, sometimes referred to as the separator area |
| $i$ | $A \cdot m^{-2}$ | Current density that corresponds to the nominal voltage |

The most important relationship for the design is the polarization curve

$$V_{cell} = f(i) \qquad (10.10)$$

The second and third relationships are the thermal voltage efficiency and the power



$$\eta_{V,t} = \frac{V_{cell}}{\dfrac{-\Delta H}{nF}}, \qquad (10.11)$$

and the power generated per unit area is simply $IV$. Thus,

$$P = (iV_{cell})\,A = IV_s. \qquad (10.12)$$

The total area and stack voltage are simply proportional to the number of cells in the stack, $N_c$:

$$A = N_c A_c, \qquad (10.13)$$

$$V_s = N_c V_{cell}. \qquad (10.14)$$

where Equation 10.14 assumes that the cells are connected in series. With these five relationships (Equations 10.10–10.14), three of the eight variables must be specified to completely define a solution. Most commonly, the three specifications come from the system-level requirements and are the thermal voltage efficiency, the stack voltage, and the power.

The thermal voltage efficiency ($\eta_{v,t}$) needed for stack design can be estimated from the system thermal efficiency ($\eta_{th}$) with use of reasonable estimates for the fuel, mechanical, and power-conditioning efficiencies:

$$\eta_{V,t} = \frac{\eta_{th}}{\eta_{fuel} \times \eta_{mech} \times \eta_{pc}}. \qquad (10.15)$$

A similar estimation of the gross power of the stack can be made from the final power requirements for the system:

$$\text{gross power of stack} = P = \frac{P_{req}}{\eta_{mech} \times \eta_{pc}}. \qquad (10.16)$$

Illustration 10.2

# Cell stack configurations

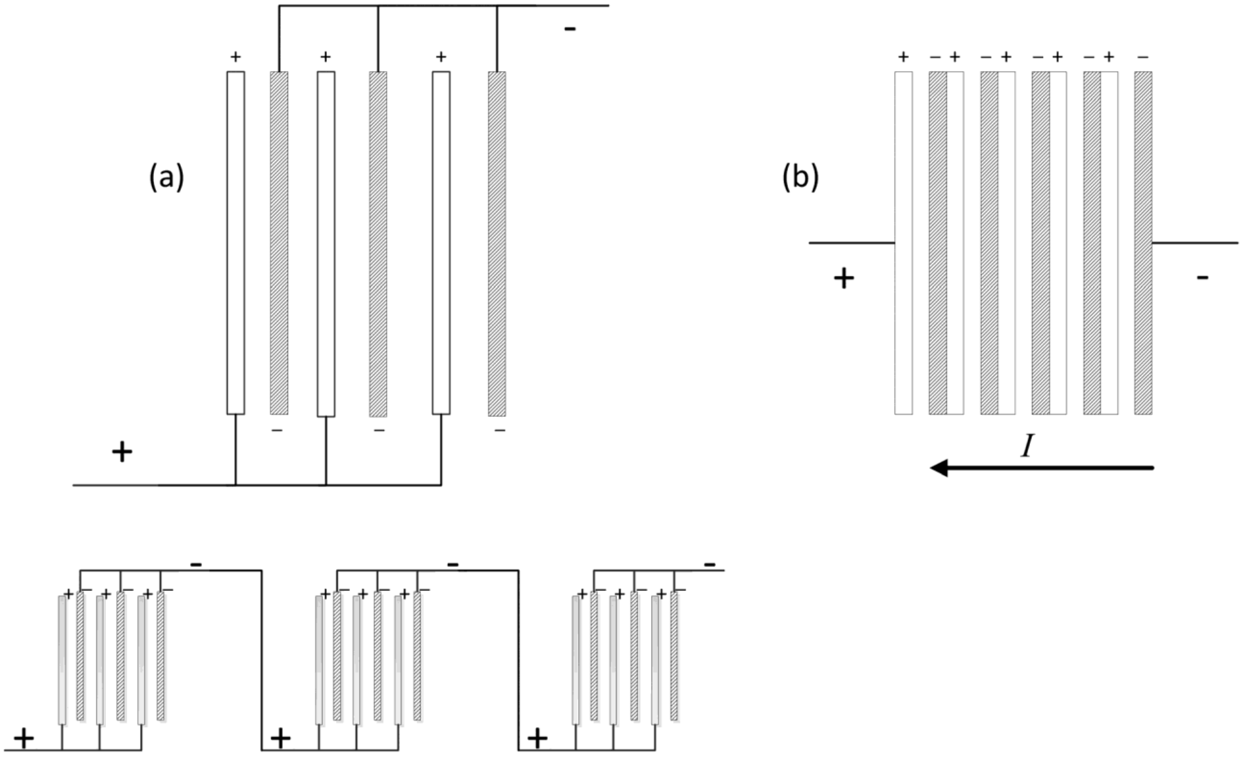


**Figure 10.3** Monopolar and bipolar designs. The diagram on the left (a) shows the monopolar design; below this the connections required to build voltage are illustrated. The bipolar design is shown on the right (b).

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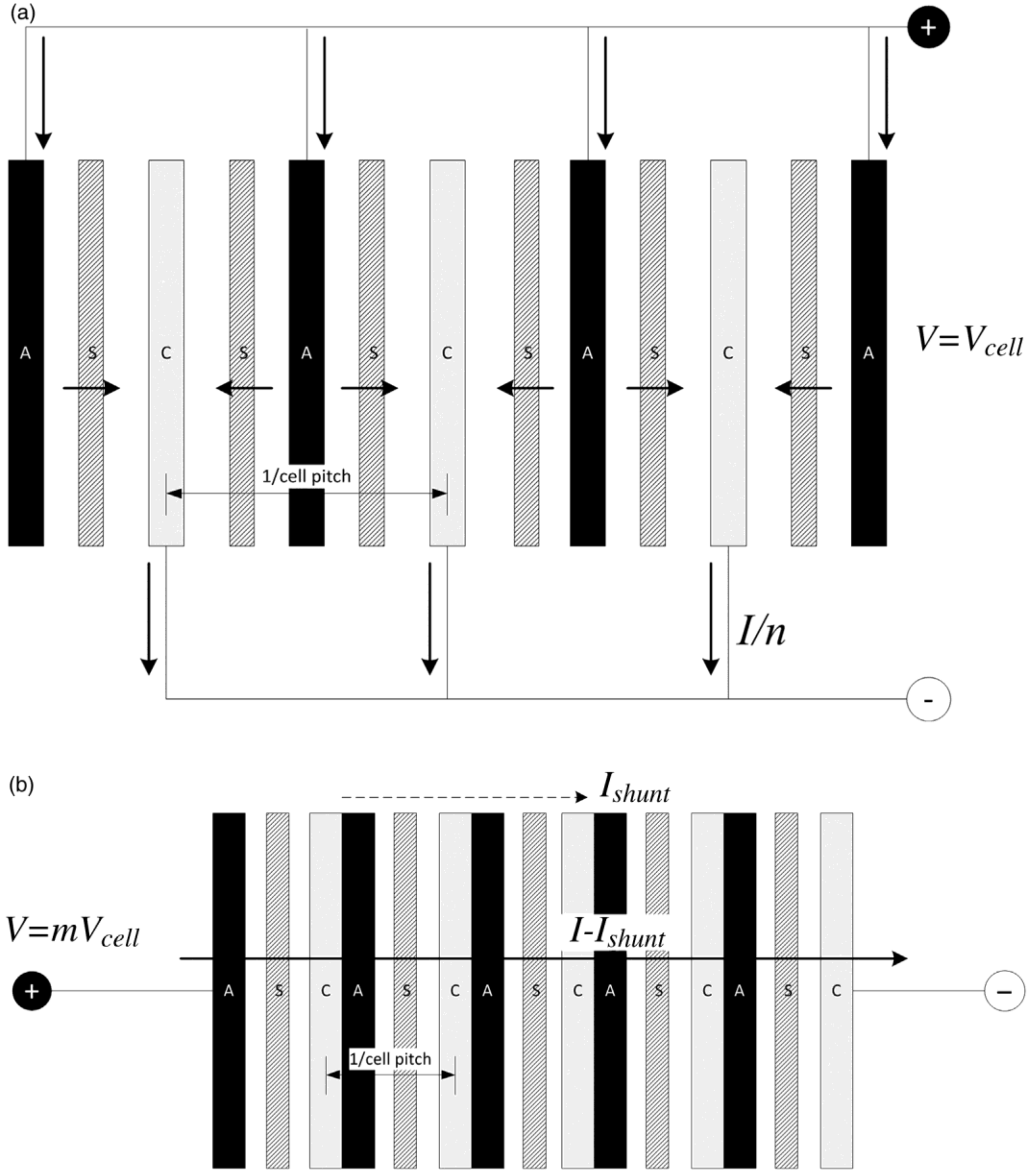

**Figure 14.7** Monopolar (a) shown with a separator and bipolar (b) configurations. Current flow is shown for electrolysis. Cell pitch is the number of electrode pairs per unit length.

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# Basic construction and components

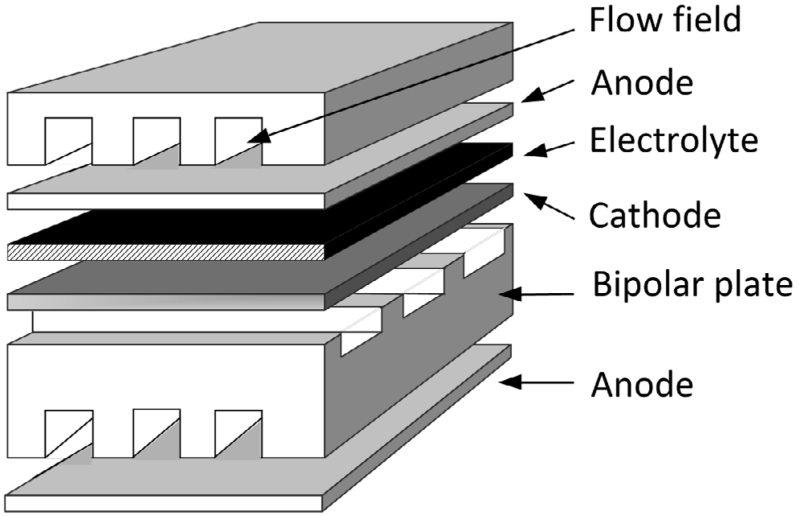

**Figure 10.4** Basic components of a bipolar fuel-cell design.

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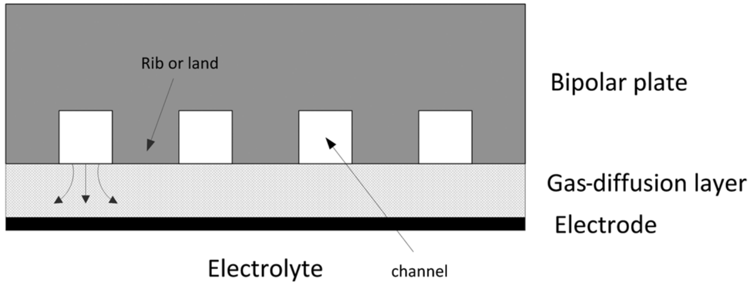

**Figure 10.5** Designs used in PEM and SOFC to distribute reactants across the entire electrode.

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Active area ratio, $A_{act}$ = active electrode area / platform area

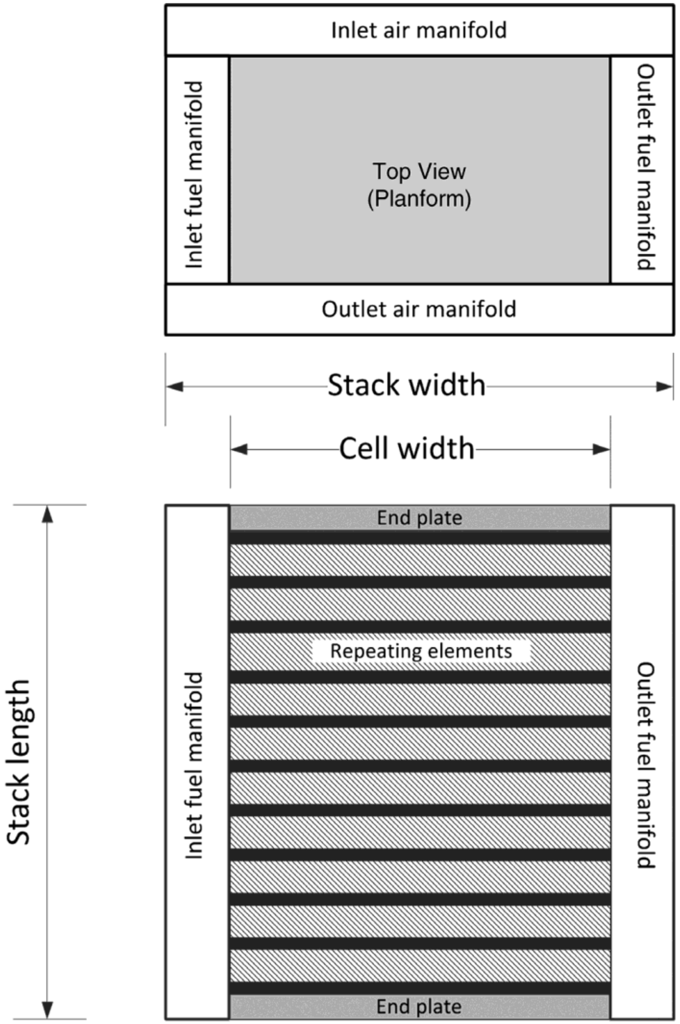

**Figure 10.6** Cell stack assembly showing repeating elements, manifolds, and end plates.

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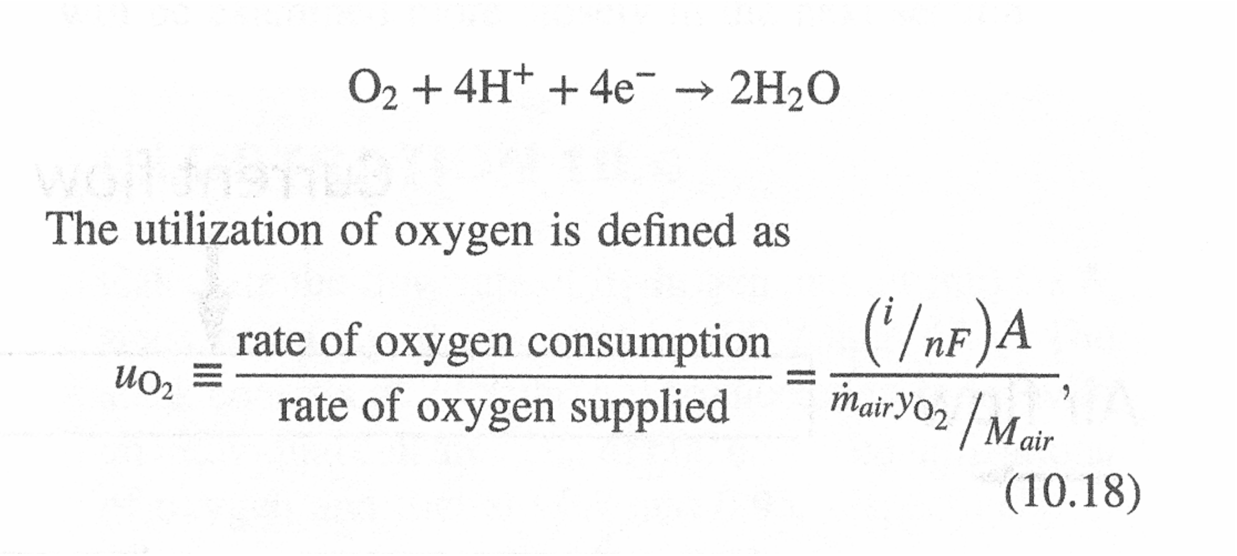
Illustration 10.3

# Utilization of oxidant and fuel

-Utilization is an important design factor: utilization of fuel plays a key role in the fuel efficiency, and utilization of the oxidant (air) affects the mechanical efficiency of the system and polarization losses in the cell
-Oxidant in cathode in PEMFC



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

The utilization of oxygen is defined as

$$u_{O_2} \equiv \frac{\text{rate of oxygen consumption}}{\text{rate of oxygen supplied}} = \frac{\left({}^{i}/_{nF}\right)A}{\dot{m}_{air}y_{O_2}\Big/M_{air}}, \qquad (10.18)$$

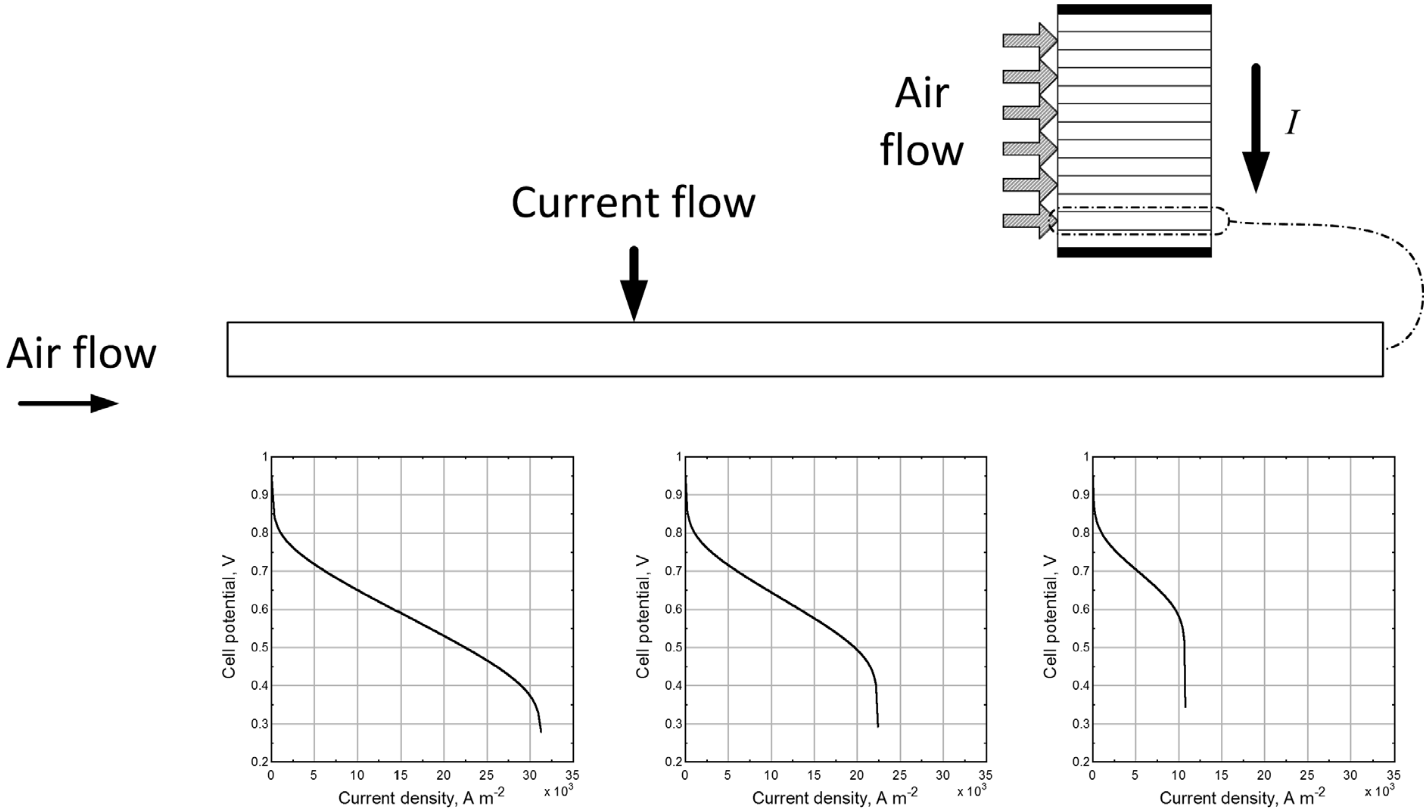


**Figure 10.7** Effect of oxygen consumption on the polarization curve as we move in the direction of the air flow.

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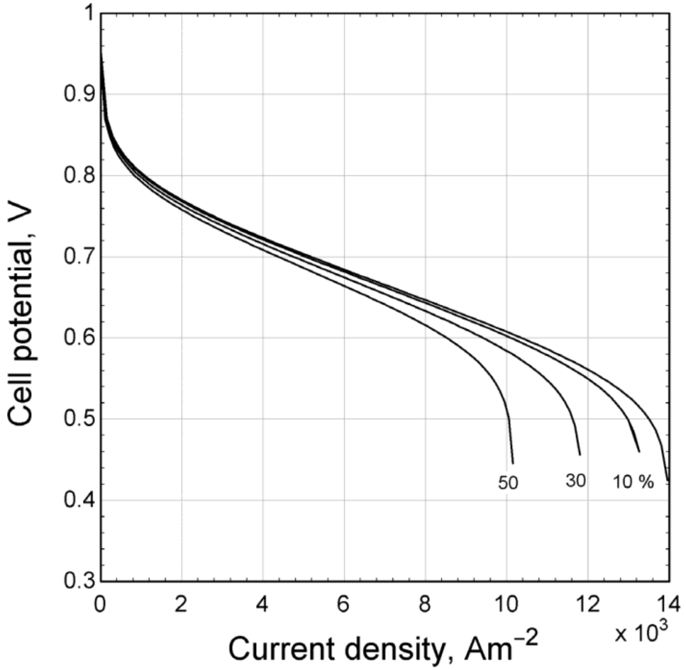

**Figure 10.8** Oxygen utilization sweep. The current is held constant and flow of air varied.

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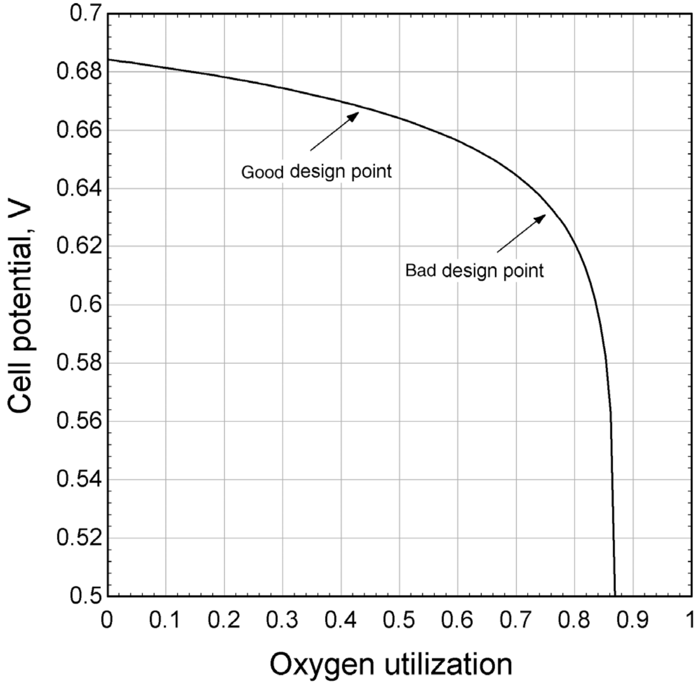

**Figure 10.9** Effect of oxygen utilization on the polarization curve.

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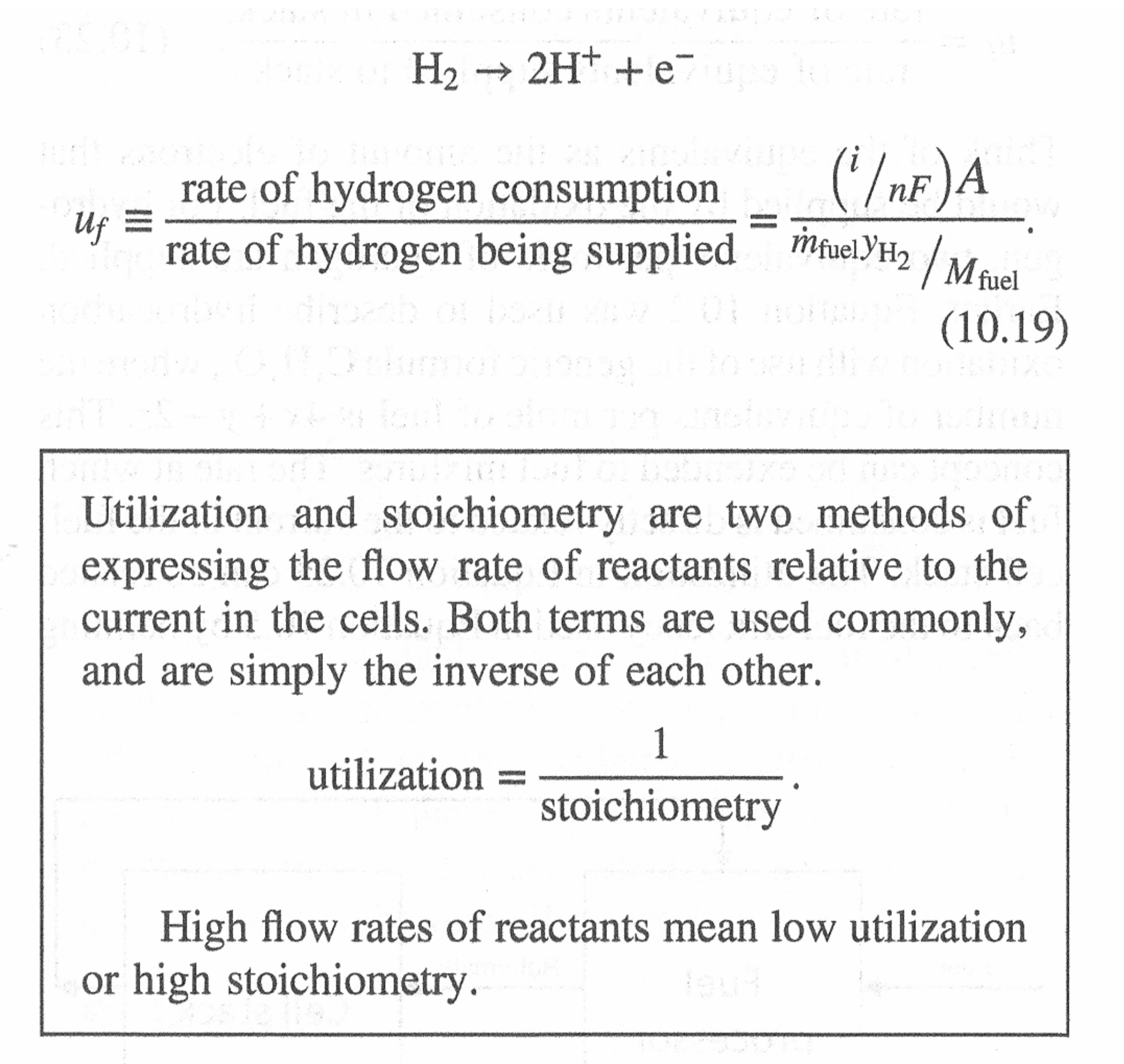
# -Utilization of the fuel



$$H_2 \rightarrow 2H^+ + e^-$$

$$u_f \equiv \frac{\text{rate of hydrogen consumption}}{\text{rate of hydrogen being supplied}} = \frac{\left(i/nF\right)A}{\dot{m}_{\text{fuel}}y_{H_2}/M_{\text{fuel}}}. \quad (10.19)$$

Utilization and stoichiometry are two methods of expressing the flow rate of reactants relative to the current in the cells. Both terms are used commonly, and are simply the inverse of each other.

$$\text{utilization} = \frac{1}{\text{stoichiometry}}.$$

High flow rates of reactants mean low utilization or high stoichiometry.

Illustration 10.4

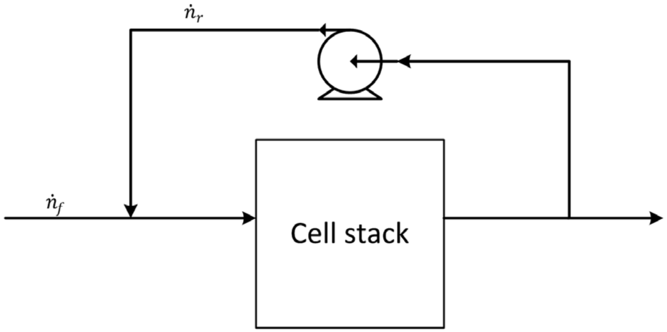


**Figure 10.10** Recycle system for hydrogen fuel cell. Utilization of fuel in the stack is different from utilization of fuel in the system.

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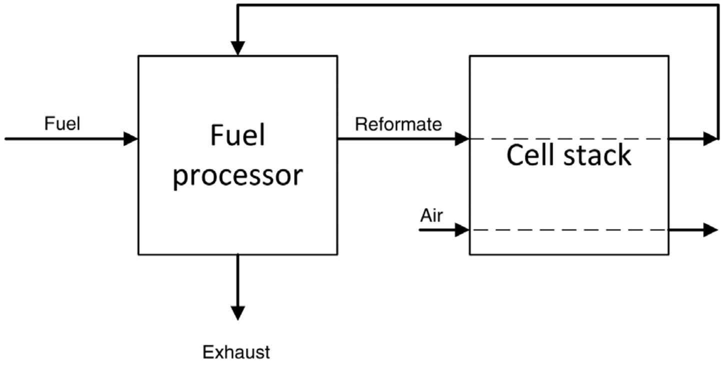

**Figure 10.11** One scheme for the integration of cell stack with a fuel processor.

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Illustration 10.5

# Flow-field design

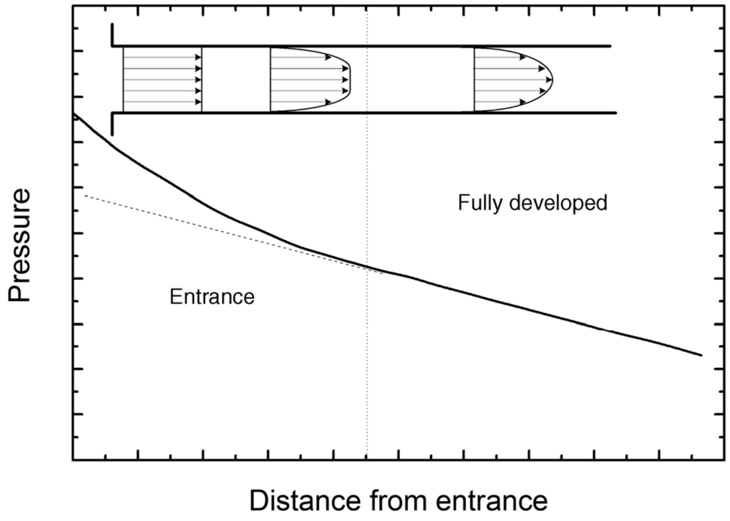

**Figure 10.12** Pressure drop for laminar flow including the entrance effect.

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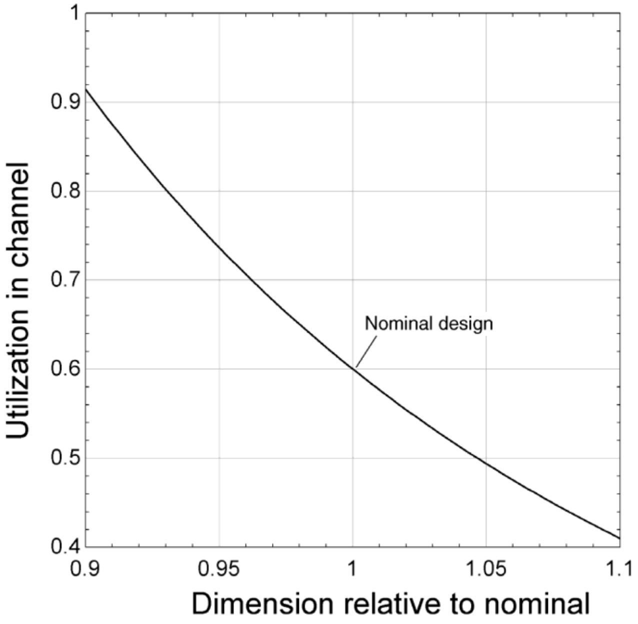

**Figure 10.13** Effect of poor tolerance control of channel dimensions in the flow field.

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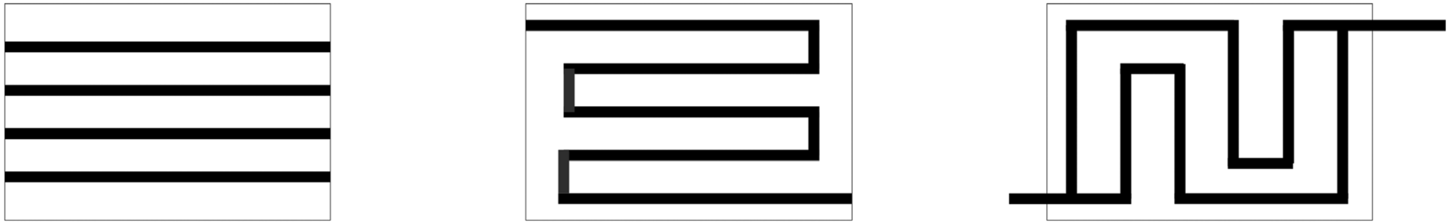
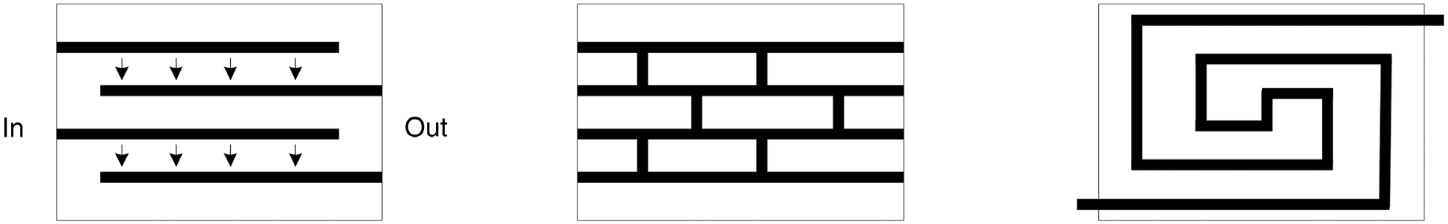
Illustration 10.6



Straight through parallel

Serpentine

Parallel serpentine



Interdigitated

Mesh

Spiral

**Figure 10.14** Examples of flow-field designs.

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# Water and thermal management

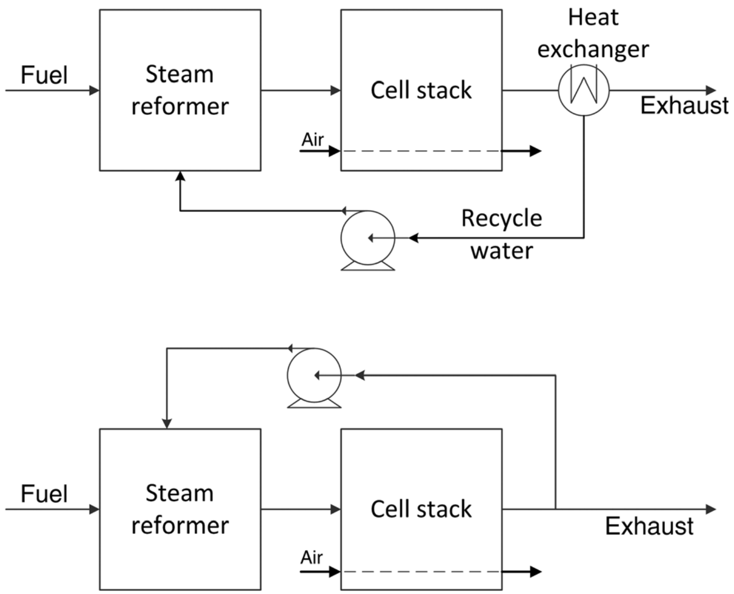

**Figure 10.15** Possible configuration to integrate the cell stack and reformer.

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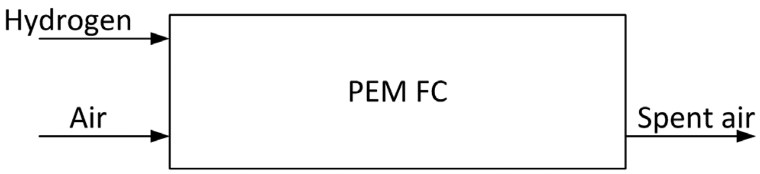

**Figure 10.16** Simplified picture of air flow and water balance for a PEMFC.

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Illustration 10.7

# Structural-mechanical considerations

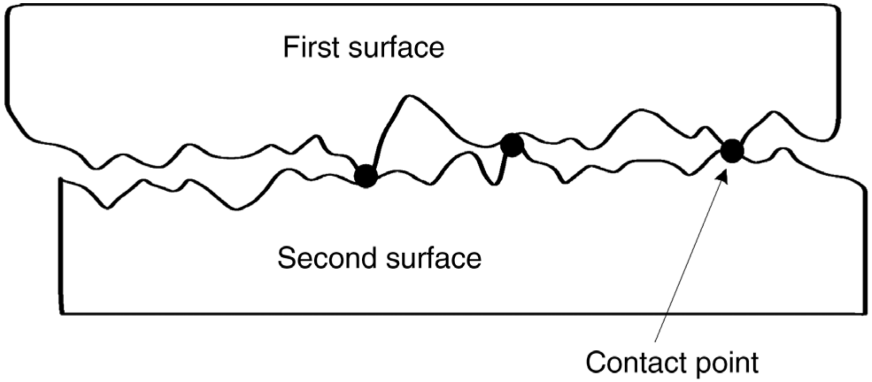

**Figure 10.18** Microscopic picture of two surfaces mated together.

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# Case study

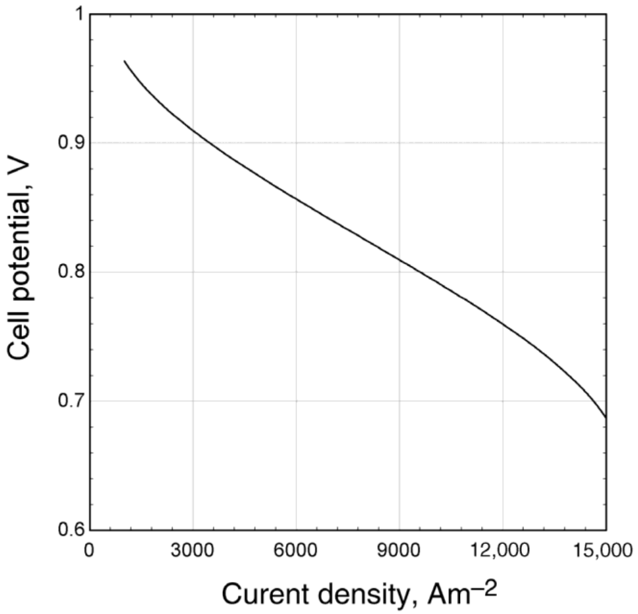

**Figure 10.20** Polarization curve for space fuel cell operating on hydrogen and oxygen. Utilization of hydrogen and oxygen are 0.95.

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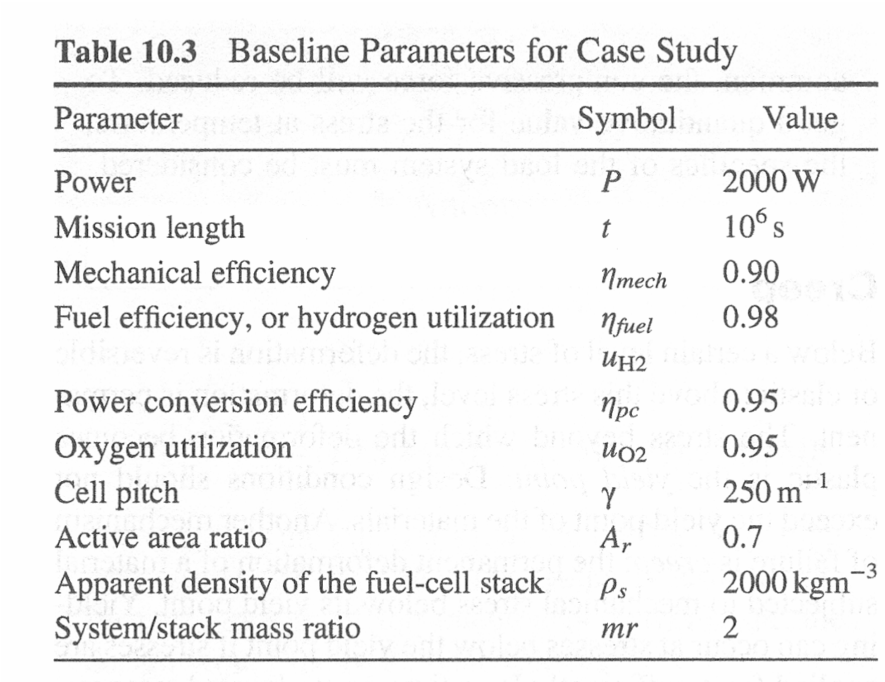

**Table 10.3** Baseline Parameters for Case Study

| Parameter | Symbol | Value |
|---|---|---|
| Power | $P$ | 2000 W |
| Mission length | $t$ | $10^6$ s |
| Mechanical efficiency | $\eta_{mech}$ | 0.90 |
| Fuel efficiency, or hydrogen utilization | $\eta_{fuel}$<br>$u_{H2}$ | 0.98 |
| Power conversion efficiency | $\eta_{pc}$ | 0.95 |
| Oxygen utilization | $u_{O2}$ | 0.95 |
| Cell pitch | $\gamma$ | 250 m$^{-1}$ |
| Active area ratio | $A_r$ | 0.7 |
| Apparent density of the fuel-cell stack | $\rho_s$ | 2000 kgm$^{-3}$ |
| System/stack mass ratio | $mr$ | 2 |