Appendix 3

Calculation of Power Required by Air Compressor and Power Recoverable by Turbine in Fuel-Cell Exhaust

A3.1 Power Required by Air Compressor

The following worked example for compressor power is for a 100-kW fuel-cell stack pressurized at 300 kPa (3 bar). Air is fed to the stack using the Lysholm compressor whose chart is shown in Figure 12.4, Chapter 12. The air inlet to the compressor is at 100 kPa (1 bar) and 20°C. The fuel cell is operated at an air stoichiometry of 2.0, and the average cell voltage is 0.65 V, which corresponds to an efficiency of 52% (LHV). The chart of Figure 12.4, Chapter 12, is used to determine the values of the following parameters:

- Required rotational speed of the air compressor.
- Efficiency of the compressor.
- Temperature of the air as it leaves the compressor.
- Power of the electric motor required to drive the compressor.

First, it is necessary to find the mass flow rate of air that will be consumed by the cell using equation (A2.9):

$$\text{Air usage} = \frac{3.58 \times 10^{-7} \times 2 \times 100\,000}{0.65} = 0.11 \text{ kg s}^{-1} \tag{A3.1}$$

This value is then converted to the mass flow factor:

$$\text{Mass flow factor} = \frac{0.11 \times \sqrt{293}}{1.0} = 1.9 \text{ kg s}^{-1} K^{1/2} \text{ bar}^{-1} \tag{A3.2}$$

Note that the pressure units are in bar, i.e., the same as in the chart given in Figure 12.4, Chapter 12. The chart can now be used to determine the speed and efficiency of the compressor, that is, the intercept of a horizontal line drawn from pressure ratio =3 and a vertical line starting from the x-axis at a mass flow factor =1.9. The result will be very close to the 600 rotor speed factor line and the 0.7 'efficiency contour'. Thus, the rotor speed can be taken to be:

$$600 \times \sqrt{293} = 10\,300 \text{ rpm} \tag{A3.3}$$

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The efficiency of the compressor and the mass flow rate are used to find the temperature rise and the compressor power. The former is obtained from equation (12.6), Chapter 12, namely:

$$\Delta T = \frac{293}{0.7} \times \left(3^{0.286} - 1\right) = 155 \text{ K} \tag{A3.4}$$

Since the entry temperature is 20°C, the exit temperature is therefore 175°C. Note that if the system is a PEMFC, cooling will be necessary. Alternatively, if it is a PAFC, then the compressor would enable the fuel gas to be preheated.

The power required for the compressor can be determined from equation (12.10), Chapter 12:

$$\text{Power} = 1004 \times \frac{293}{0.7} \times \left(3^{0.286} - 1\right) \times 0.11 = 17.1 \text{ kW} \tag{A3.5}$$

This is the power for the compressor without considering any mechanical losses in the bearings and driveshafts. The electric motor also will not be 100% efficient — a reasonable estimate of its power would be about 20 kW. It is important to note the following:

- The 20 kW of electrical power will have to be provided by the 100-kW fuel cell, i.e., by consuming 20% of its output. This parasitic load is a major problem when running systems at pressure; its importance for PEMFCs is discussed in Section 4.7.2, Chapter 4.
- In this worked example, the assumption is that the air is not humidified, i.e., it has a low water content. As pointed out in Section 4.4, Chapter 4, the inlet of a PEMFC is sometimes humidified. This action alters both the specific heat capacity and the ratio of the heat capacities, γ, and will influence the performance of the compressor. Humidification, if required, is usually undertaken after compression because the air is hotter at this stage.

A3.2 Power Recoverable from Fuel-Cell Exhaust with a Turbine

The power available from the exit gases of the 100-kW fuel cell, and recoverable by using a turbine, can be found as follows.

The mass of the cathode exit gas is increased by the presence of water in the cells, but since this is the result of replacing O_2 with $2H_2O$, the mass change will be insignificant, as the mass of hydrogen is so small. The mass flow rate, $\dot{m}$, will therefore still be taken as 0.11 kg s^{-1}. The exit temperature can be estimated as 90°C for a typical PEMFC, and the entry pressure is 300 kPa (3 bar). The exit pressure must be a little less than this, and assuming it to be 280 kPa, the mass flow factor can be calculated as:

$$\text{Mass flow factor} = \frac{0.11 \times \sqrt{363}}{2.8} = 0.75 \text{ kg s}^{-1} \text{ K}^{1/2} \text{ bar}^{-1} \tag{A3.6}$$

The speed and efficiency of the turbine can be determined from the performance chart given in Figure 12.8, Chapter 12. The intercept on the chart between 0.75 on the x-axis and 2.8 on the pressure ratio axis is close to the rotor speed factor line of 5000, and in the efficiency region of 0.7 or 70%. Consequently, the required rotor speed is predicted to be:

$$5\,000 \times \sqrt{363} \approx 95\,000 \text{ rpm} \tag{A3.7}$$

This very high speed is suitable for directly driving a centrifugal compressor on the same shaft, but not for a screw compressor. The power available from the turbine can be obtained from equation (12.10), Chapter 12, i.e.,

$$\text{Power} = C_P \frac{T_1}{\eta_C}\left(\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right)\dot{m} \tag{12.10}$$

The exit gas is not normal air; it has less oxygen and a changed specific heat capacity. For engines, standard values are 1150 J kg^{-1} K^{-1} for C_P and 1.33 for γ. In the case of a fuel cell, the change in gas composition is not so great, and a value of 1100 J kg^{-1} K^{-1} will be used for C_P and 1.33 for γ. The constant $(\gamma - 1/\gamma)$ thus becomes 0.275. The temperature T_1 is 363 K, so equation (12.10) becomes:

$$\text{Power available} = 100 \times 0.7 \times 363\left(\frac{1^{0.275}}{2.8} - 1\right) \times 0.11 \approx -7.6 \text{ kW} \tag{A3.8}$$

The minus sign indicates that power is given out by the turbine. This power is a useful addition to the 100 kW of electrical output of the fuel cell, but note that it provides less than half of the power required to drive the compressor, as calculated above. Furthermore, this example is the best possible result — turbine efficiencies will usually be somewhat lower than the 0.7 assumed here. As can be seen from the turbine performance chart in Figure 12.9, Chapter 12, much of the operating region is at greatly lower efficiency.