Fuel Cell System Design

How to Design A FC System?

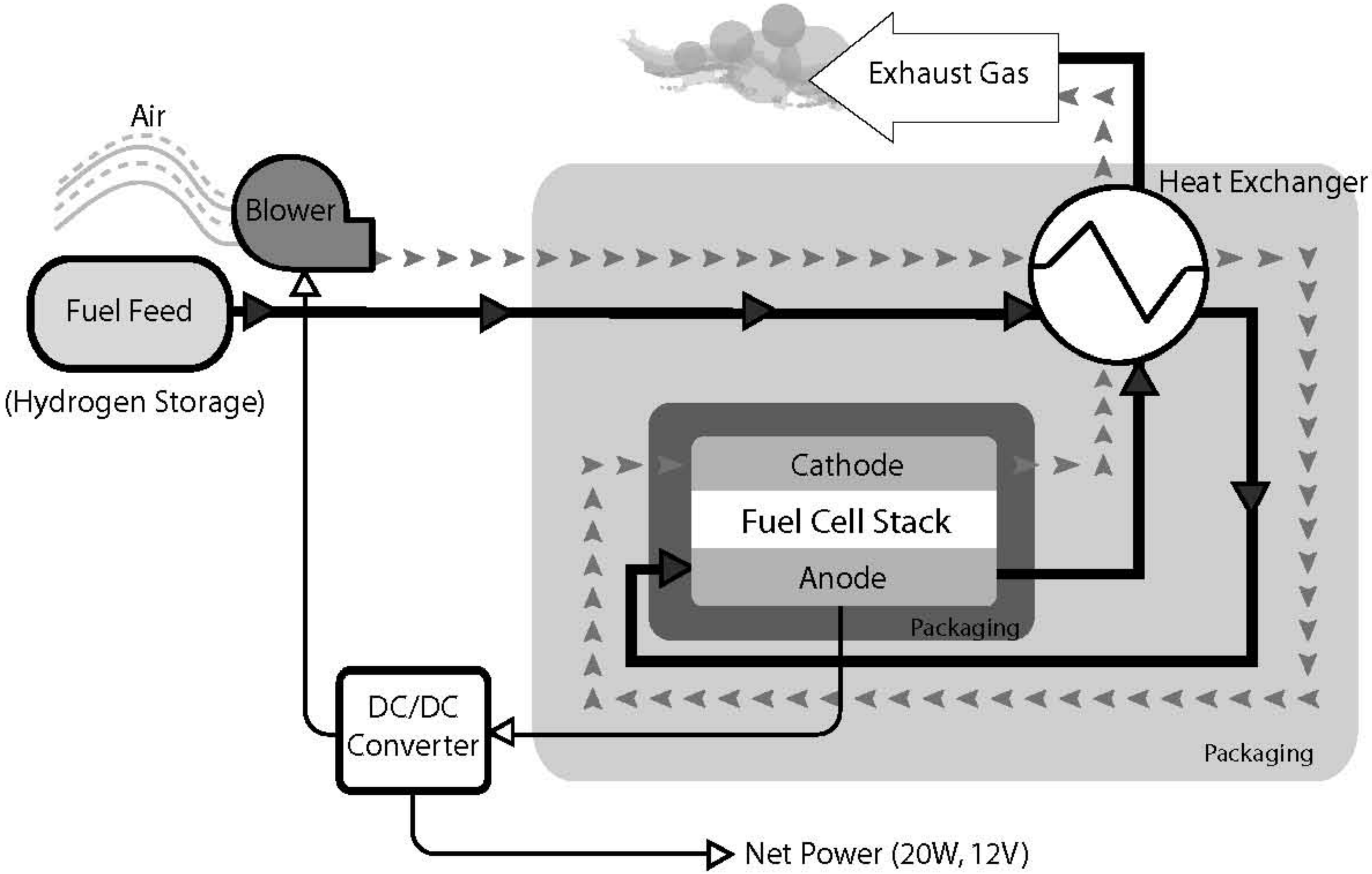
1. Construct a reasonable system configuration and make a good guess on the specifications.

2. Calculate the thermal and mass balance of the complete system based.

3. Refine the choice and specification of system components according to the thermal and mass balance calculated in 2. For coupled components, verify compatibility based on the expected magnitude and rate of mass, heat or current transfer between them.

4. Review the system's performance considering the original design goals. If system refinement is required, decide which components or parameters should be changed and repeat the design process.

20 W (12 V)Portable SOFC Schematic



SOFC System Components

1. Fuel cell stack:
    - Should supply net power output of 20 W.
    - Obviously, stack power is significantly larger than 20W.
    - Support BOP's such as the air blower and the DC/DC converter
    - Power at 12 V (17 cells at 0.7 V or alternatively fewer cells with a 12 V DC-DC converter)
2. Hydrogen supply
    - Use metal hydrides for simplicity in a portable system.
    - Relatively high pressures/flow rates
    - Hydrocarbon-fuel provide better energy density, but complicated

SOFC System Components

3. Air Supply:
   - For electricity and thermal management (cooling)
   - Relatively large flow rates will be needed for cooling
   - Options: compressor, fan, or blower
   - Choose blower working at 12 V DC

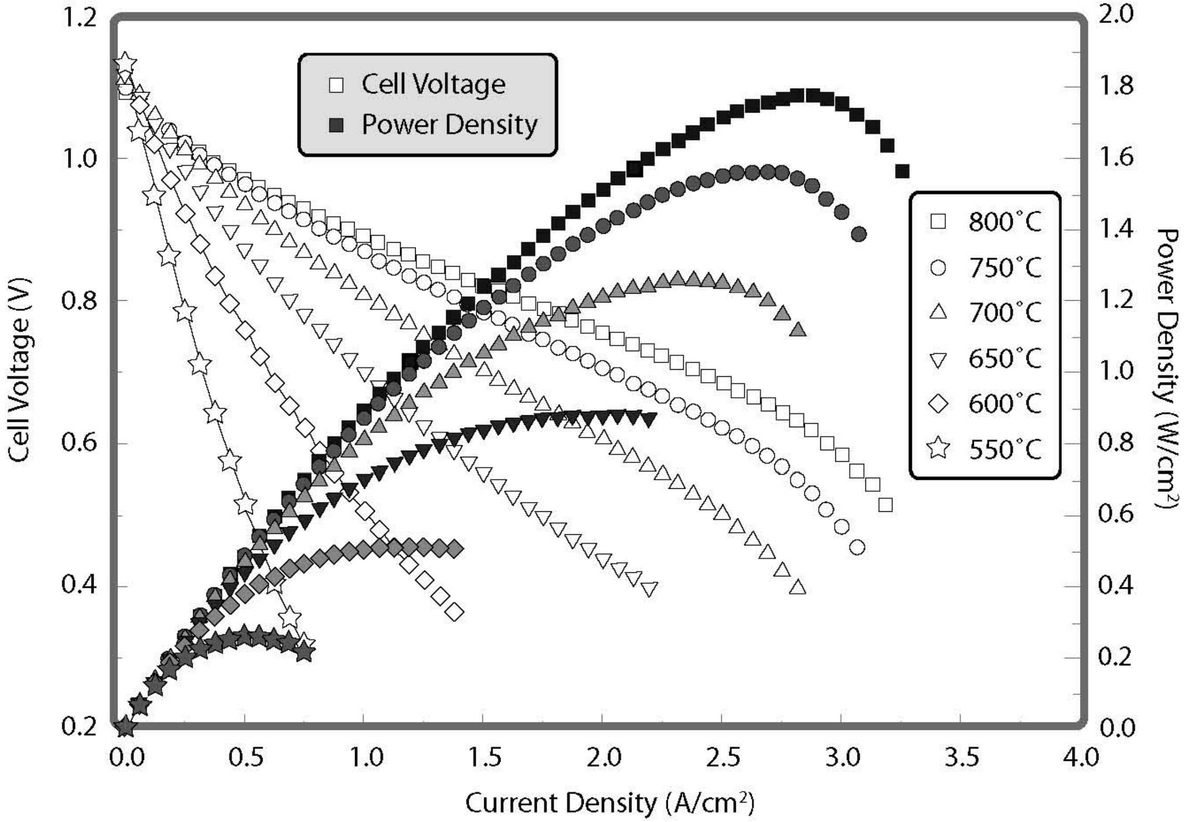
4. Heat management
   - Recycle heat from the stack
   - Heat exchanger can warm up the cold fuel cell inlet gases using the hot fuel cell exhaust gases.

SOFC System Components

5. DC-DC converter

- 6~8 cells generates 4.2~5.6V at 0.7V.
- DC-DC converter to boost up the output voltage to 12 V sacrificing efficienty.
- Stabilizes stack voltage fluctuation

SOFC Unit Cell Performance



Q1: How to get this?
Q2: Operating point? (voltage, cell temerpature, stoichiometry, efficiency
Q3: How many stacks?

System Design = Chicken and Egg

Stack power = f(power density)
Power density of SOFC = f(operating temperature)
Operating temperature = f(cooling flow rate, say air)
Flow rate = f(blower power)
Blower power = f(stack power)

-The various parameters in the system are strongly coupled nonlinearly

- Solve thorough initial guess and iteration

Initial Guess on Stack and BOPs

Stack design parameters	Value
Fuel cell operating temperature, T_{fc}	700 C
Hydrogen and air pressure	1 atm
Hydrogen stoichiometry,	1.2
Air stoichiometry,	8
Fuel cell operating voltage, V_{oper}	0.7 V
Fuel cell output power, P_{fc}	50W

System component design parameters	Value
DC-DC converter efficiency,	90%
Heat exchanger efficiency,	90%

Bookkeeping: 1, Mass Balance

$A_{fc\_}$ = 47.62 cm^2 = 50 W / (0.7 V X 1.5A/cm^2)) .
i_{total} = 71.43 A (= 50_W / 0.7 V).

$$v_{H_2,\text{supply}} = \frac{i_{total}}{nF} \times \lambda_{H_2} = \frac{71.43\,A}{2 \times 96400\,C/mol} \times 1.2$$

$$= 4.442 \times 10^{-4}\,mol/s = 0.02665\,mol/\text{min}$$

$$v_{O_2,\text{supply}} = \frac{i_{total}}{nF} \times \lambda_{O_2} = \frac{71.42\,A}{4 \times 96400\,C/mol} \times 8$$

$$= 0.001481\,mol/s = 0.08884\,mol/\text{min}$$

$$v_{N_2,\text{supply}} = v_{O_2,\text{supply}} \times \omega = 1.481 \times 10^{-3}\,mol/s \times \frac{0.79}{0.21}$$

$$= 0.005571\,mol/s = 0.3342\,mol/\text{min}$$

Bookkeeping: 1, Mass Balance

$$v_{Air,\text{supply}} = v_{N_2,\text{supply}} + v_{O_2,\text{supply}} = 0.3342 mol/\min + 0.08884 mol/\min = 0.4230 mol/\min$$

$$\dot{V}^{25C}_{Air,\text{supply}} = \frac{v_{Air,\text{supply}} RT}{p} = \frac{0.4230\, mol/\min \times 0.0820578\, atm \cdot L/mol \cdot K \times 298.15\, K}{1 atm}$$

$$= 10.35 LPM$$

$$v_{H_2O,prod} = \frac{i_{total}}{nF} = \frac{71.42\, A}{2 \times 96400\, C/mol} = 3.702 \times 10^{-4}\ mol/s = 0.0222\, mol/\min$$

$$v_{H_2,exhaust} = v_{H_2,\text{supply}} - v_{H_2,cons} = 7.403 \times 10^{-5} mol/s$$

$$v_{O_2,exhaust} = v_{O_2,\text{supply}} - v_{O_2,cons} = 0.001296 mol/s$$

$$v_{N_2,exhaust} = v_{N_2,\text{supply}} = 0.005571 mol/s$$

$$v_{H_2O,exhaust} = v_{H_2O,prod} = 3.702 \times 10^{-4} mol/s$$

Bookkeeping: 1, Mass Balance

FLOW RATES	VALUE (MOL/S)
$v_{H2,supply}$	4.442×10^{-4}
$v_{O2,supply}$	0.001481
$v_{N2,supply} = v_{N2,exhaust}$	0.005571
$v_{H2,exhaust}$	7.403×10^{-5}
$v_{O2,exhaust}$	0.001296
$v_{H2O,exhaust} = v_{H2,cons} = 2v_{O2,cons}$	3.702×10^{-4}

Bookkeeping: 2, Thermal Balance

Assuming adiabatic $P_{heat} = (E^H - V_{oper}) \times i_{total}$

$$= (1.28V - 0.7V) \times 71.43 = 41.71W$$

Heat is only removed by convection

$$P_{heat} = \left(\sum_i c_{p,i} v_{i,exhaust} \right) \Delta T_{fc} = \left(\sum_i c_{p,i} v_{i,exhaust} \right) \left(T_{fc,out} - T_{fc,in} \right)$$

$$P_{heat} = 41.71W =$$

$$\left[c_{p,H_2} v_{H_2,exhaust} + c_{p,O_2} v_{O_2,exhaust} + c_{p,N_2} v_{N_2,exhaust} + c_{p,H_2O} v_{H_2O,exhaust} \right] \left(T_{fc,out} - T_{fc,in} \right)$$

$$= (30.116J/mol\,K \times 0.00007403 mol/s +$$

$$34.366J/mol\,K \times 0.001296 mol/s +$$

$$32.409J/mol\,K \times 0.005571 mol/s +$$

$$40.924J/mol\,K \times 0.00037 mol/s) \left(T_{fc,out} - 973.15 \right)$$

$$\therefore T_{fc,out} = 1145K$$

Bookkeeping: 2, Thermal Balance

Heat exchanger $\dot{Q}_{HX} = \left(\sum_i c_{p,i} v_i \right) \Delta T_{hot} \varepsilon_{HX} = \left(\sum_i c_{p,i} v_i \right) \left(T_{hot,in} - T_{hot,out} \right) \varepsilon_{HX}$

$$= \left(\sum_i c_{p,i} v_i \right) \Delta T_{cold} = \left(\sum_i c_{p,i} v_i \right) \left(T_{cold,in} - T_{cold,out} \right)$$

$$\dot{Q}_{HX} = \left[c_{p,H_2} v_{H_2,exhaust} + c_{p,O_2} v_{O_2,exhaust} + c_{p,N_2} v_{N_2,exhaust} \right] \left(T_{cold,out} - T_{cold,in} \right)$$

$$= (30.116 J/mol\,K \times 0.000444 mol/s +$$

$$34.366 J/mol\,K \times 0.001481 mol/s +$$

$$32.409 J/mol\,K \times 0.005571 mol/s) \left(973.15K - 298.15K \right)$$

$$= 165.3W$$

Bookkeeping: 2, Thermal Balance

$$\dot{Q}_{HX} = 165.3W =$$

$$\left[c_{p,H_2} v_{H_2,exhaust} + c_{p,O_2} v_{O_2,exhaust} + c_{p,N_2} v_{N_2,exhaust} + c_{p,H_2O} v_{H_2O,exhaust}\right]\left(T_{hot,in} - T_{hot,out}\right)\varepsilon_{HX}$$

$$= (30.116 J/mol\,K \times 0.00007403 mol/s +$$
$$34.366 J/mol\,K \times 0.001296 mol/s +$$
$$32.409 J/mol\,K \times 0.005571 mol/s +$$
$$40.924 J/mol\,K \times 0.00037 mol/s)\left(1145K - T_{hot,out}\right) \times 0.9$$

$$\therefore T_{hot,out} = 388K = 115C$$

THERMAL PARAMETERS	VALUES
P_{Heat}	41.7 W
	165.3 W
$T_{fc,in} = T_{cold,out}$	973.15 K
$T_{fc,out} = T_{hot,in}$	1145 K
$T_{cold,in} = T_{ambient}$	298.15 K
$T_{cold,out}$	388K

Component Selection

Air Blower

SPECIFICATION	VALUE
Max flow rate	15.5 LPM
Max current	3.2 A
Operating voltage	12 V
Max pressure	1200 mbar
Power vs. flow rate	Linear ( )

Heat Exchanger

Specification	Values
Max fluid temperature	900°C
Rated flow range	5–20 LPM
Number of paths	4
Thermal efficiency	90%

Component Selection

DC-DC converter

SPECIFICATION	VALUES
Input voltage	Min 4.0 V, Max 25 V
Output voltage (Adjustable)	Min 1.5, Max 15 V
Max input current	20 A
Max output current	5 A
Efficiency	90%

Metal hydride

SPECIFICATION	VALUES
Dimension	D 6.4cm, H 26.5cm
Weight	2.2 kg
Hydrogen capacity	250 L
Internal pressure	17 atm

System Characteristic

Net power $$P_{net} = P_{fc} \times \varepsilon_{DC-DC} - P_{blower}$$

Blower power $$P_{blower} = \frac{\text{Max current}}{\text{Max flow rate}} \times \text{Actual flow rate} \times \dot{V}_{blower}$$

$$= \frac{3.2A}{15.5LPM} \times 10.35LPM \times 12V = 25.64W$$

Net power $$P_{net} = 50W \times 0.9 - 25.64W = 19.36W$$

Efficiency $$\varepsilon_{net} = \frac{P_{net}}{\left|\Delta \dot{h}_{HHV}\right|} = \frac{P_{net}}{\left|\Delta h_{HHV}\right| \times v_{H_2,\text{supply}}}$$

$$= \frac{19.36W}{247,700 \frac{J}{mol\ H_2} \times 4.442 * 10^{-4} \frac{mol\ \mathrm{H}_2}{s}} = \frac{19.36W}{110W} = .176$$

Design Review

SPECIFICATION	VALUE
System net power	19.35 W (Need to be increseas)
Fuel cell power	50 W
Fuel cell voltage	4.2 V (Maybe too low)
Number of cells in the fuel cell stack	6 (Need to be increase)
Temperature range of the fuel cell	700~872°C (T_diff too high)
Temperature range of the heat exchanger	25~872°C (T_diff larege)
System operation time	6.4 hour (Too short)
Air blower power consumption	25.64 W (More than 50%)

- Heat dissipation to the environment
- Increase air flow? Blower power?
- Increase cell number? How about cost?
- Pressure drop in the stack?
- Weight, volume and cost?
- Cell performance change in different operation condition?
- Single cell performance vs stack performance?