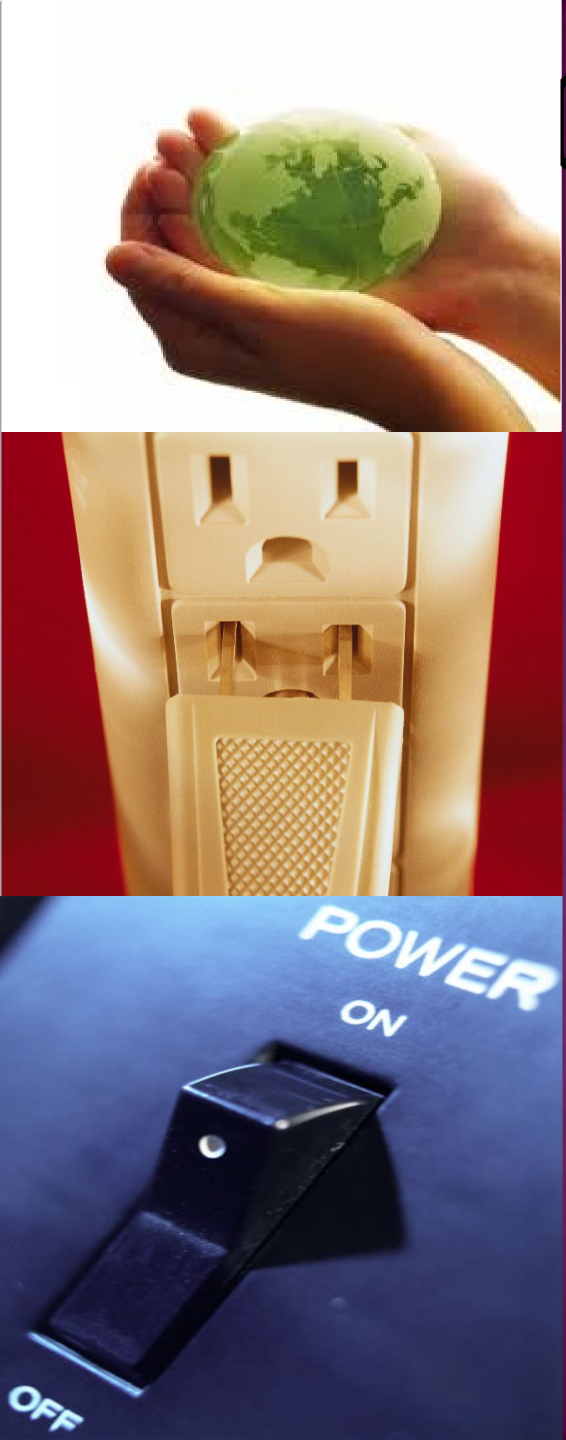

Air Supply & PEM COOLING

MECH-526

FUEL CELL SCIENCE & ENGINEERING

Center for
FUEL CELL
Systems & Powertrain Integration
Kettering University

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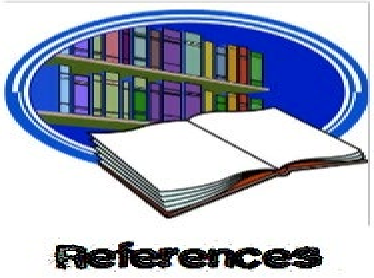
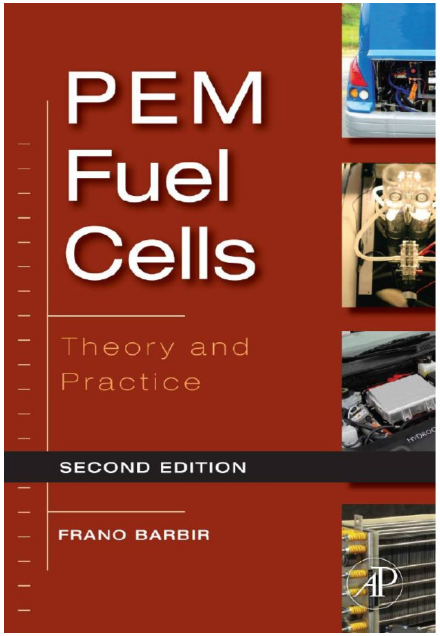
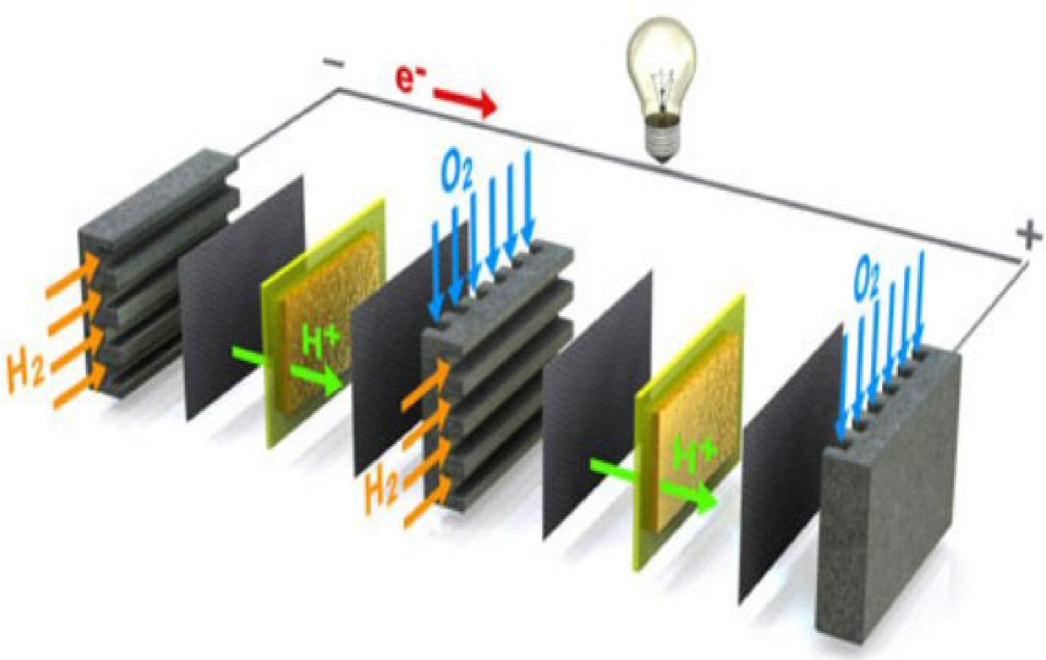
REFERENCES:



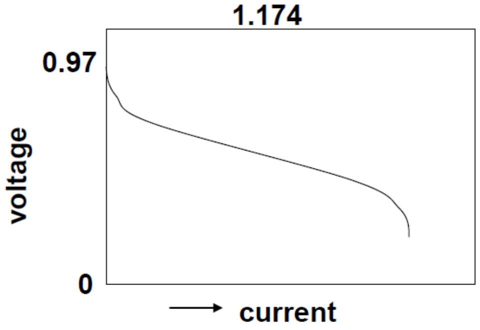
- PEM Fuel Cells: Frano Barbir, ELSEVIER.
- Fuel Cell Explained: Larmie & Dicks, WILEY.
- Fuel Cell Fundamentals: O'hayre, Cha, et al., WILEY.


PEM
Fuel
Cells
Theory and
Practice
SECOND EDITION
FRANO BARBIR



ACTUAL FC STACK FLOW RATES

P=1ATM



- In general for real systems:

$$\lambda_f \equiv \text{FUEL ULTIZATION EFF.} = \frac{1}{S} = \frac{1}{STOICIOMETRY}$$

$$S \equiv \text{stoichiometric factor} \equiv \frac{\text{actual fuel supplied}}{\text{exact fuel amount needed for reaction}} \geq 1$$

$$\frac{\dot{m}(I)\left[\frac{g}{\sec}\right]}{stack} = \frac{I\left[\frac{C/s}{cm^2}\right] A_p \frac{Area}{Plate}\left[cm^2 \bullet \frac{\#\,plates}{stack}\right]}{n\left[\frac{\text{moles of electrons}}{\text{moles of reactant}}\right] F \left[\frac{C}{\text{moles of electrons}}\right]} \bullet \frac{1}{\lambda_f} \bullet Mw_{H2}\left[\frac{g}{\text{moles of reactant}}\right]$$

$$\frac{\dot{m}\left[\frac{L}{\min}\right]}{stack} = \frac{\dot{m}\left[\frac{g}{\sec}\right]}{stack} \bullet \frac{1}{Mw_{H2}}\left[\frac{\text{moles of reactant}}{g}\right] \bullet \frac{22.42\text{Liters}}{\text{mole of reactant}} \bullet \frac{T(^0K)}{273.15} \bullet \frac{60\sec}{\min}$$

$$CD \equiv \text{CURRENT DENSITY} = \left[\frac{C/s}{cm^2}\right] = \frac{Amps}{cm^2}$$

"AIR" FLOW CONSUMPTION

P=1 ATM

$$\left.\frac{\dot{m}\left[\frac{L}{\min}\right]}{stack}\right|_{AIR} = \left.\frac{\dot{m}\left[\frac{g}{\sec}\right]}{stack}\right|_{O2} \bullet \frac{1}{p_{O2}}\frac{1}{Mw_{O2}}\left[\frac{\text{moles of reactant}}{g}\right] \bullet \frac{22.42\text{Liters}\,(@\,0\text{C})}{\text{mole of reactant}} \bullet \frac{60\sec}{\min} \bullet \frac{T(K)}{273.15}$$

$p_{O2} \equiv$ partial pressure oxygen in air = 0.21

$$\left.\frac{\dot{m}(I)\left[\frac{g}{\sec}\right]}{stack}\right|_{O2} = \frac{I\left[\frac{C/s = Amp}{cm^2}\right] A_p \frac{Area}{Plate}\left[cm^2 \bullet \frac{\#\,plates}{stack}\right]}{n\left[\frac{\text{moles of electrons}}{\text{moles of reactant}}\right] F\left[\frac{C}{\text{moles of electrons}}\right]} \bullet S_{Air} \bullet Mw_{O2}\left[\frac{g}{\text{moles of reactant}}\right]$$

$n = 4$

$$= \frac{I}{4F} \bullet S_{Air} \bullet Mw_{O2},$$

P_e = Stack Power = V_cI(total current)

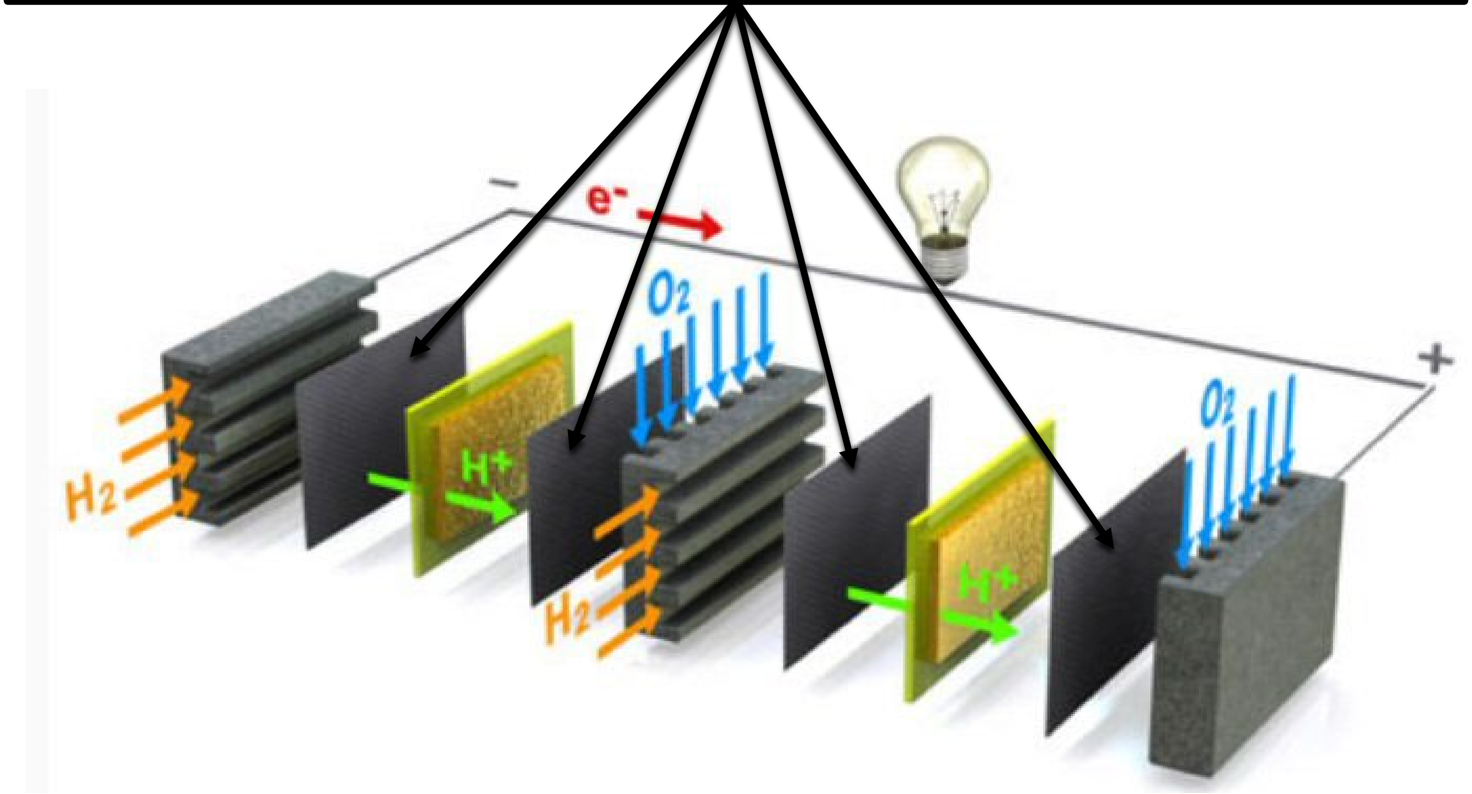
V_c=Average Cell Voltage

$$\left.\frac{\dot{m}(I)\left[\frac{g}{\sec}\right]}{stack}\right|_{AIR} = \frac{P_e}{V_c \bullet 4F} \bullet S_{Air} \bullet Mw_{O2}(=32g/mole) \bullet \frac{1}{p_{O2}}$$

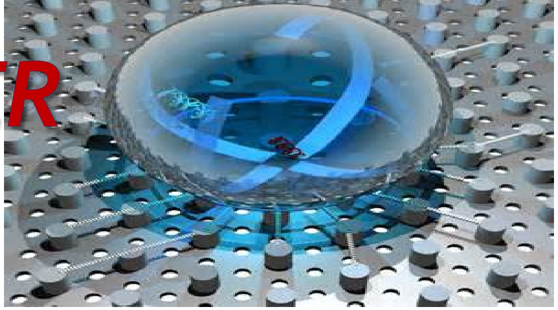
$$= \frac{P_e}{V_c} \bullet S_{Air} \bullet \frac{32g/mole}{1000g/kg} \bullet \frac{1}{4mole\ electrons/mole \bullet 96485C/mole\ electrons} \bullet \frac{1}{0.21}$$

$$\left.\frac{\dot{m}(I)\left[kg/s\right]}{stack}\right|_{AIR} = 8.29x10^{-8}\frac{P_e}{V_c} \bullet S_{Air} \bullet \frac{1}{0.21} kg/s$$

GDL
GAS DIFFUSION LAYER

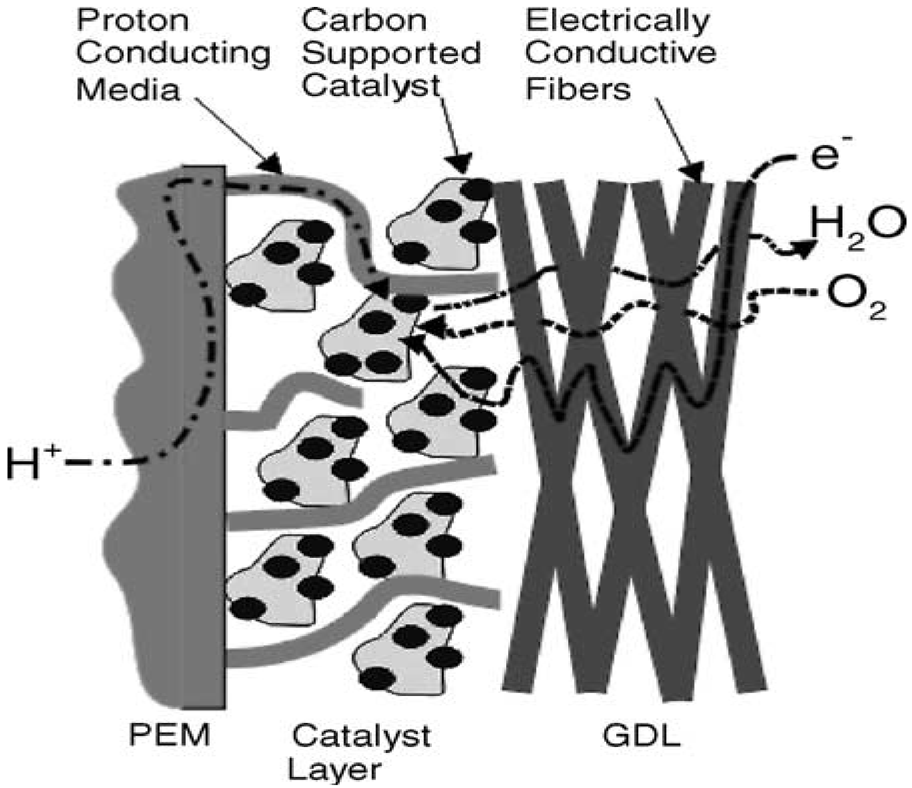


GDL: GAS DIFFUSION LAYER FUNCTION



- *Provides a Pathway* for reactant gases from the flow field channels to the catalyst layer, allowing then access to the entire active area (not just to those adjacent to the channels).
- ***Provides a Pathway for product water from catalyst layer to the flow field channels.***
- ***Electrically Connects*** the Catalyst Layer to the Bipolar Plate, allowing electrons to complete the electrical circuit.
- ***Thermally Conducts Heat*** generated in the electrochemical reactions in the catalyst layer to the bipolar plate, which has means for heat removal.
- *Provides Mechanical Support* to the ***MEA***, preventing it from sagging into the flow fields. Must support "flimsy" MEA but must have rigidity to maintain good electrical contacts.
- Made ***HYDROPHOBIC*** to avoid flooding and to expel water.

MEA HUMIDIFICATION



MEMBRANE ELECTRODE ASSEMBLY (MEA)

- The anode-electrolyte-cathode assembly is referred to as *Membrane Electrode Assemblies (MEAs)*, only a few hundred micron thickness; ***it is the heart of PEMFC.***
- It generates electric power at cell voltages around 0.7 V and power densities of up to 1 W/cm^2 of electrode area when supplied with hydrogen and air.
- ***The membrane relies on the presence of liquid water to conduct protons effectively, and HUMIDIFICATION limits the operating PERFORMANCE of the PEMFC.***
- The MEA is located between a pair of current collector plates which have machined flow fields for distributing the fuel and air to anode and cathode. **Cooling passages in a central channel are provided to remove the heat generated in the fuel cell due to exothermic reaction.**

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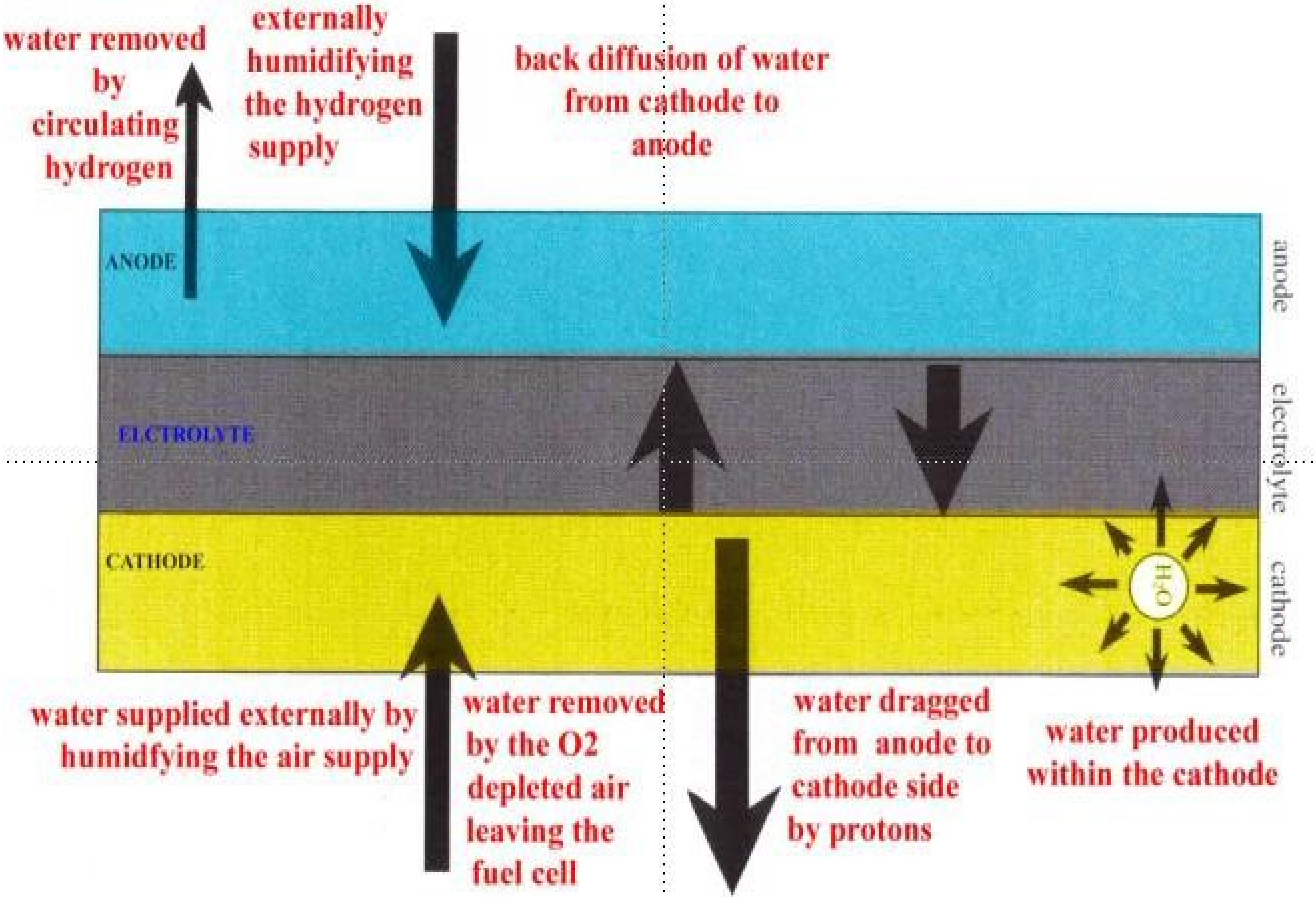
MEA DESIGN REQUIREMENTS

- MEA is the heart of the PEMFC. Its design requirements are
  - Minimize the OVER-POTENTIAL and maximize the power density
  - Minimize the Pt or Pt alloy loading by using the right size Nano Particles.
    - *Low Pt loading and the deposition of thin active layers of the supported electro catalyst and proton conductor.*
    - *The thin active layers (10-20 μm) minimize the OHMIC and Mass Transport over-potentials in electrodes.*
  - *OPTIMIZE THE WATER MANAGEMENT AND THERMAL MANAGEMENT IN THE CELLS.*
  - Have durable and long life design for the required number of hours for stationary and mobile applications

WATER MANAGEMENT IN THE PEMFC



water removed by circulating hydrogen

externally humidifying the hydrogen supply

back diffusion of water from cathode to anode

water supplied externally by humidfying the air supply

water removed by the O2 depleted air leaving the fuel cell

water dragged from anode to cathode side by protons

water produced within the cathode

Source: J. Larminie and A. Dicks, Fuel Cell Systems Explained, John Wiley, UK, 2000

WATER MANAGEMENT IN THE PEMFC

- It is an extremely important and complex problem in the PEMFC.
  - *There must be sufficient water in the polymer electrolyte; otherwise ion conductivity will decrease, and the increased OHMIC over-potential in the membrane will result in a major loss of cell efficiency.*
  - *There must not be too much water on the cathode so that it floods and thus blocks the pores to diffuse air for reaction.*

- ***Ideally***, there is a possibility of good hydration of the electrolyte.
  - Water is generated at the cathode due to the chemical reaction of O_2, H^+ and e^-. This water supply should keep the electrolyte at the proper level of hydration. But the air blowing over the cathode will dry out any excess water.
  - Water will diffuse from the cathode to anode side because the electrolyte is so thin, and hopefully, there will be sufficient hydration of the whole electrolyte (and vice versa).

WATER MANAGEMENT IN THE PEMFC

- **Water management issue becomes more severe for increasing size and number of cells in the stack.**
  - **The removal of product water becomes difficult in larger systems.**
  - **High water pressure in reactant flows reduces the cell voltage and increases over-potential at the cathode.**
  - **Water condensation, electrode flooding and occlusion of gas channels could lead to operational failure.**
- **The thermal management issue is coupled with the water management.**
  - **Heat generated in the stack is approximately the same order of magnitude as the electricity generated ($\varepsilon \approx 50\%$).**
  - **If the cell temperature is too low, *water condensation* problem may lead to cell operational failure.**
  - **If the cell temperature is high, it leads to local or global cell *dehydration* and resultant loss of performance.**

WATER MANAGEMENT IN THE PEMFC
ELECTRO-OSMOTIC DRAG & BACK DIFFUSION

- Now we will discuss about the prediction and control of this water movements.
  - ***WATER PRODUCTION and WATER DRAG both are proportional to the current.***
    - *Water is "DRAGGED" from the ANODE to the CATHODE by protons moving through the electrolyte. (ELECTRO-OSMOTIC DRAG)*
  - ***The BACK DIFFUSION of water from CATHODE to ANODE depends on the thickness of the electrolyte membrane and the relative humidity of each fluid side.***
    - *Back diffusion and electro-osmotic drag create concentration gradients across the membrane; Some water can diffuse back from the cathode to the anode.*
  - ***WATER PERMEATION (PRESSURE DRIVEN):***
    - *Water may be hydraulically pushed from one side of the membrane to the other due to a pressure difference between ANODE and CATHODE.*
  - ***Water EVAPORATION can be predicted reasonably well with from THERMODYNAMICS for Relative Humidity determination.***
  - ***If the external humidification of the reactant gases is used before entering the fuel cell, it can be controlled as desired.***

WATER DRAG AND BACK-DIFFUSION:
"CONSTANT CONFLICT"

- There are several complications.
  - During the operation, H^+ ions will drag the 1 to 2.5 water molecules per H^+ ion from the anode/electrolyte to the cathode; ***a process referred to as electro-osmotic drag process.*** ***This means the anode will dry out at high current densities, even though the cathode is well hydrated.***
  - ***For temperatures higher than 60°C, the air will always dry out the cathode faster than the water generated there due to the H_2/O_2 reaction.***
  - This means that we need to supply water at the inlet of both anode and cathode when theoretically we are generating water in the fuel cell! But sometimes this is done to greatly improve the fuel cell performance.
  - The water balance must be correct in the electrolyte throughout the cell. ***In practice, the air flowing over the cathode may be dry at the entrance, just right in the middle, and fully saturated near the exit*** so that it cannot dry off any more excess water. This problem is of importance for larger cells and stacks.

MEA WATER: CRITICAL

- *The polymer electrolyte requires liquid water to conduct protons.*
  - *otherwise ion conductivity will decrease, and the increased OHMIC (iR) over-potential & major loss of cell efficiency.*
  - *must not be too much water on the cathode so that it floods and thus blocks the pores to diffuse air for reaction.*
- *For temperatures higher than 60℃, the air will always dry out the cathode faster than the water generated due to the H_2/O_2 reaction*
  - *dry at inlet, just right in the middle, and fully saturated @ exit.*
- **Must supply water at inlet of anode and cathode although generating water in the fuel cell!**

HUMIDIFICATION ISSUES

- The higher the cell temperature, the better the performance due to reduced cathode overvoltage. However, for operating temperatures higher than 60°C, the humidification problem becomes more serious.
- For smaller fuel cells, the cost/weight of extra equipment needed for humidification can exceeds the savings, and the decision may be to go without extra humidification and operate at lower temperatures.
- A typical PEMFC will have about ***30% reduction in performance*** if un-humidified reactants are used.

AIRFLOW AND WATER EVAPORATION

- We supply the air with ***stoichiometry*** S of 2 or more to minimize the concentration losses in the fuel cell.
- It is an universal practice to remove the product water from the cathode side by the air flowing on that side. The drying effect of air is very nonlinear. The humidity ratio, absolute humidity or specific humidity ratio is defined as

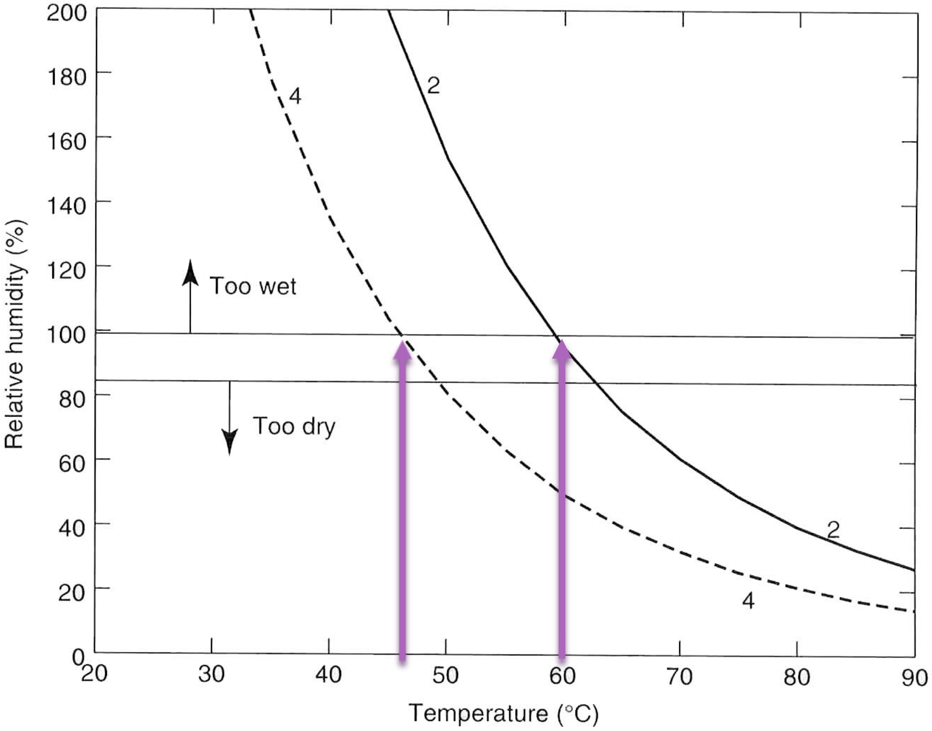
$$\text{humidity ratio,} \quad \omega = \frac{m_w}{m_a}$$

- where m_w is the mass of water present in the mixture and m_a is the mass of dry air, and $m_w + m_a$ is total mass of humid air.
- When air cannot hold any more water in the vapor form, it is fully saturated and the corresponding pressure is P_{sat}.
- The partial pressure of water in air is referred to as P_w. relative humidity,

$$\varphi = \frac{P_w}{P_{sat}}$$

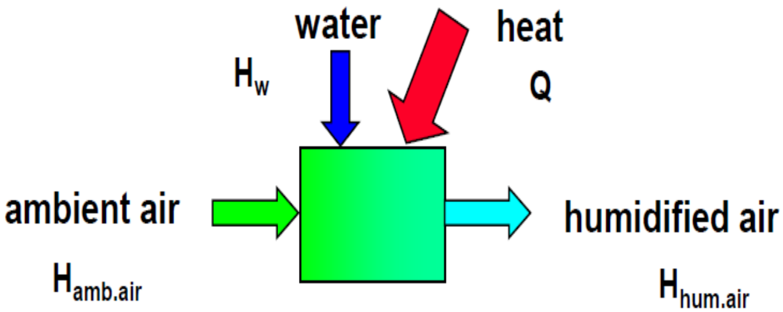
CONDITIONS FOR PEMFC OPERATION WITHOUT EXTRA HUMIDIFICATION

- **In limited operating conditions, a PEMFC can be run without extra humidification. Review the figure below for exit air humidity versus its temperature with S = 2 and 4 at operating pressure of *1 bar*. Between the operating temperature of 50 and 60°C, the *PEMFC can be run without humidification*.**



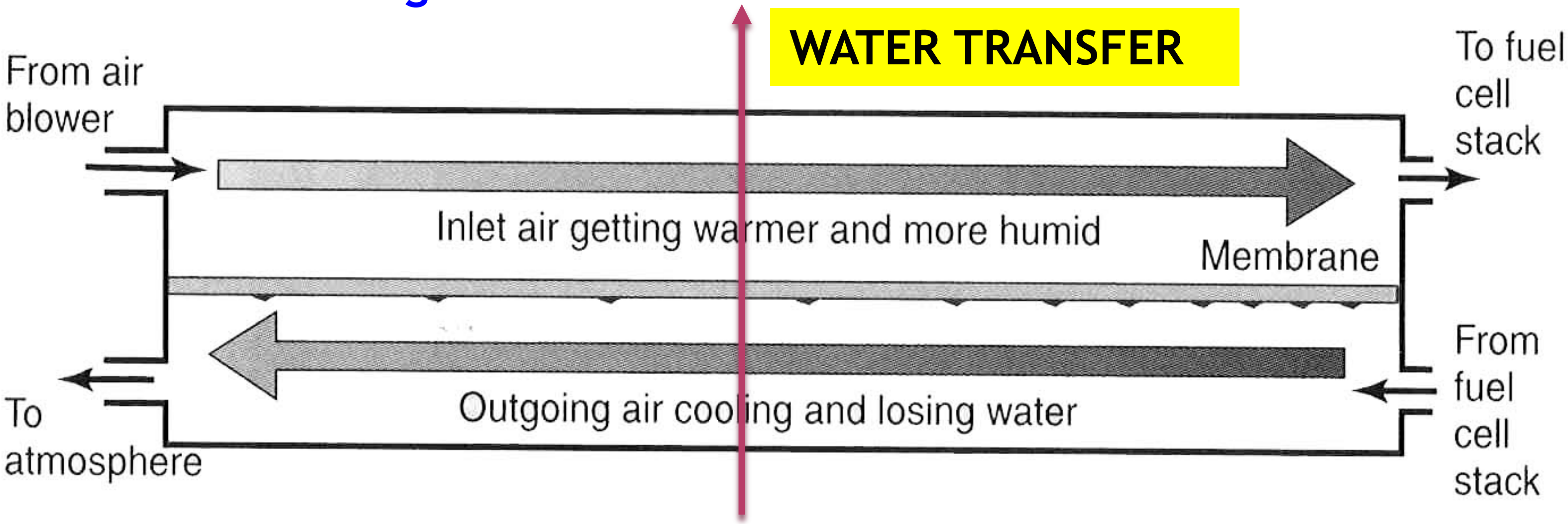
EXTERNAL HUMIDIFICATION METHODS

- There are many methods have been used for external humidification as follows:
- *For laboratory test systems, reactant gases of fuel cell are humidified by bubbling them through water at desired temperature. This process is called sparging.*
- In large fuel cell systems, pressurized water is directly injected as a spray in the air, which will also cool the air, a desirable feature if the air is compressed. This is fairly expensive.
- Use metal foams to make a kind of *fine water spray* to humidify air. Only a pump is needed to move the water.



EXTERNAL HUMIDIFICATION METHODS

- This method uses the exit water to humidify air without a condenser, pump and tank. As shown below in a MASS TRANSFER EXCHANGER, the warm damp air leaving the fuel cell passes over one side of the membrane, where it is cooled. Some water condenses on the membrane. Liquid water passes through the membrane and is evaporated by the drier air (going into the fuel cell) on the other side of the mass exchanger.



- The next method does not use the water leaving the cell, but **generates the water within the membrane** at the expense of using some hydrogen. The thin electrolyte is impregnated with nanocrystals of platinum for reaction and producing water, and also impregnated with particles of silica and titania as hygroscopic materials.

PEM FUEL CELL COOLING AIR SUPPLY

- **The cathode air supply can cool the fuel cell.**
- **Typical fuel cell efficiency of energy of chemical reaction to electrical energy is about 40%. *That means the rest 60% of the energy is converted into heat, q .***
- **The actual heat generated in a fuel cell stack of "n" cells at current "I" can be calculated based on actual voltage and power generated in a fuel cell as follows:**

$$P_{loss} = q_{heat} = P_{\max} - P_{actual}$$

$$= \frac{1.482V}{cell} \bullet \frac{\#cells}{stack} \bullet I - \frac{V_{actual}}{cell} \frac{\#cells}{stack} \bullet I$$

$$\frac{q_{heat}}{stack} = nI(1.482 - V_{cell_{average}}); WATTS$$

For cell voltage of 0.7 *V and cell power of* 100 *Watts,*

$$q = \mathrm{nI(1.482\text{-}V)}$$

$$\frac{I}{cell} = \frac{100W}{0.7V/cell} = 142.9A/cell$$

$$\frac{q}{cell} = I(1.482 - 0.7)$$

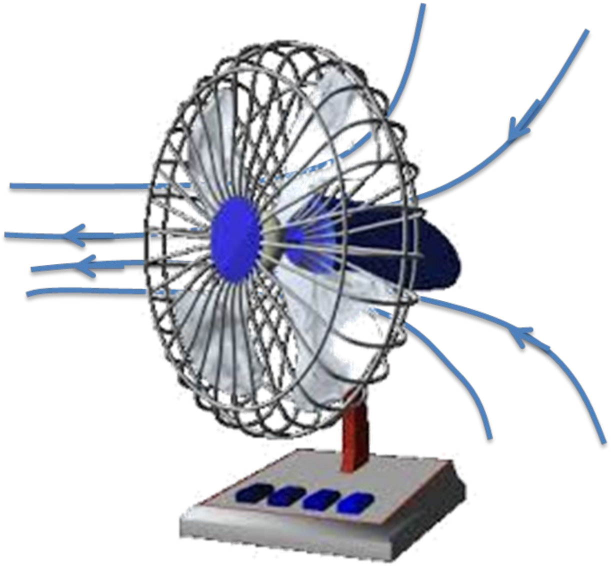
$$= 111.74 Watts/cell$$

Note the thermal cell efficiency is:

$$\frac{V_c}{1.482} \times 100 = \frac{0.7}{1.482} \times 100 = 47.2\%$$

PEM FUEL CELL COOLING AIR SUPPLY

- For fuel cell below 100 W, the air supply (without any extra fan) can cool the cell convectively and evaporate the water with the cell spacing of 5-10 mm. ***Most heat will be lost through natural convection and radiation to the ambient.***
- For a more compact fuel cell, a small fan can be used to cool it.
- For more than 200 W power generation, must have a separate means of cooling the cell, i.e.,
  - *Separate reactant and cooling air flows*
  - *Separate liquid cooling like engine cooling with a radiator*



AN EXAMPLE FOR A NEED FOR COOLING AIR

- The following data are given for a fuel cell:
  - $T_{\text{fuel cell}}$ = 50°C
  - V_c = 0.6 V
  - Cooling air T_{in} = 20°C
  - T_{out} = 50°C (100% heat exchanger effectiveness!)
  - Consider only 40% heat is removed by the air and the rest by natural convection and radiation to the ambient. Determine the cooling airflow rate.

$$P_e = V_c I \rightarrow \text{STACK POWER}$$

$$\underbrace{0.4 \times P_e \bullet \left(\frac{1.23}{V_c} - 1 \right)}_{\textit{heating rate}} = \underbrace{\dot{m} c_p \Delta T_{air}}_{\textit{heat gained by air}} \rightarrow 1st\ \text{Law: Conservation of Energy}$$

Heat Loss by Fuel Cell Stack = Heat Gained by Cooling Air

AN EXAMPLE FOR A NEED FOR COOLING AIR

- For air, c_p = 1004 J/kgK, ΔT_{air} = 30°C; V_c = 0.6 V

$$\dot{m}_{air_{COOLING}} = \frac{0.4}{c_p \Delta T_{air}} \bullet P_e \bullet \left(\frac{1.23}{V_c} - 1 \right) = 1.4 \times 10^{-5} \times P_e\ , kg/s, (1)$$

- The formula from SLIDE 4 for the reactant airflow rate is:

- $$\left. \frac{\dot{m}(I)\left[kg/s\right]}{stack} \right|_{AIR} = 8.29x10^{-8} \frac{P_e}{V_c} \bullet S_{Air} \bullet \frac{1}{0.2} kg/s\ (2)$$

- Equating Eqs. (1) and (2), we get

$$S = \frac{1.4 \times 10^{-5} \times 0.6x0.2}{8.29x10^{-8}} \approx 20.3$$

AN EXAMPLE FOR A NEED FOR COOLING AIR

- With S = 24 and $T_{fuel\ cell}$ = 50°C, an exit air humidity is 26% from Slide 8, very dry! The inlet humidity was assumed 70% for the data of Table 4.2. ***HENCE, AIR WILL QUICKLY DRY OUT!*** The realistic value of S is between 3 and 6 at 50°C for 100% humid air at exit. That means the airflow must be reduced drastically and provide a separate cooling system. This occurs when more than 25% of heat is to be removed by the cooling fluid; the typical fuel cell power for this condition is ~ 200-300 W.

SLIDE 8:

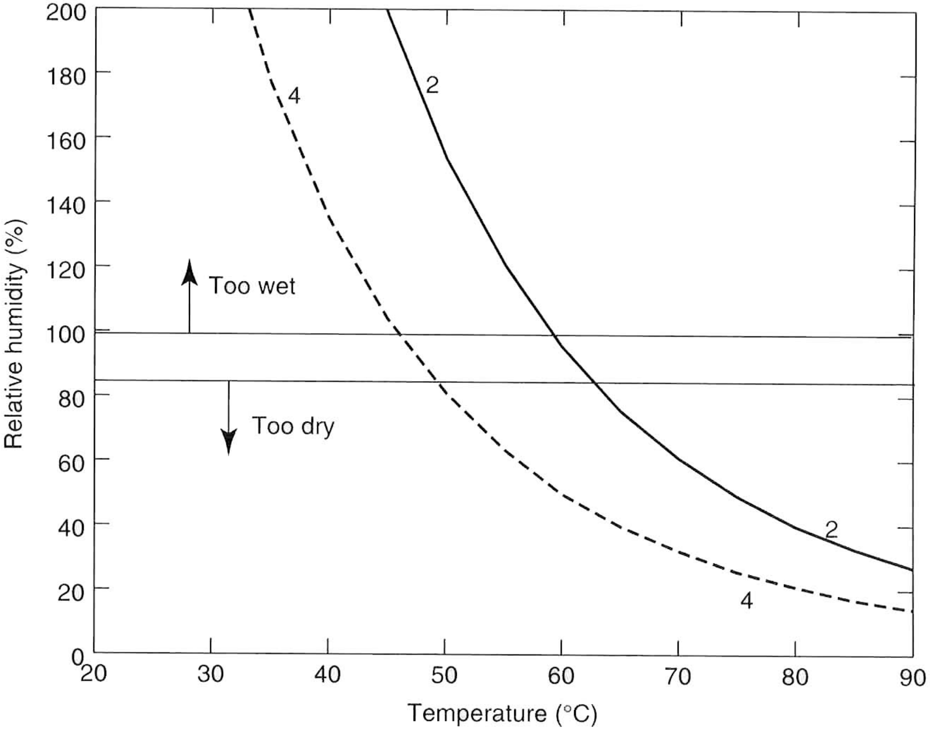
EXIT AIR RELATIVE HUMIDITY at given T and S for inlet

T = 20°C and 70% relative humidity

T,°C	S = 1.5	S = 2	S = 3	S = 6	S = 12	***S = 24***
20					213	142
30				194	117	78
40		273	195	112	68	45
50	208	164	118	67	40	***26***
60	129	**101**	72	41		
70	82	65	46			
80	54	43	30			
90	37	28				

CONDITIONS FOR PEMFC OPERATION WITHOUT EXTRA HUMIDIFICATION

- In limited operating conditions, a PEMFC can be run without extra humidification. Review the figure below for exit air humidity versus its temperature with S = 2 and 4 at operating pressure of *1 bar*. Between the operating temperature of 50 and 60°C, the *PEMFC can be run without humidification*.



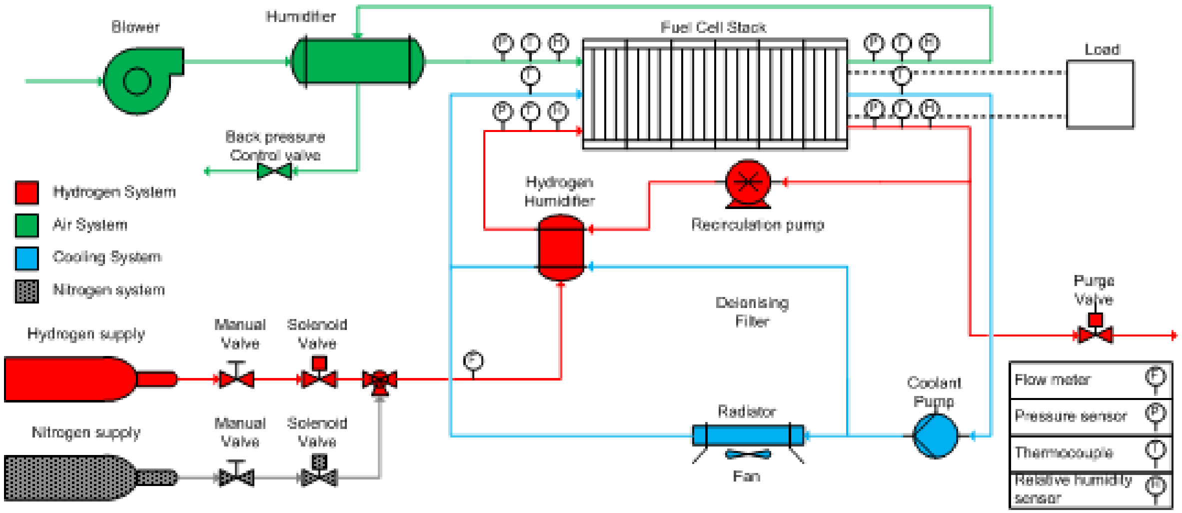
AIR OR LIQUID COOLING ??

- The fuel cell voltage and power generation is highly dependent upon the fuel cell operating temperature as we discussed earlier. Hence, the performance is much more variable with a fuel cell than an ICE (Internal Combustion Engine). Hence, we must minimize the temperature variation in the fuel cell operation.
- Criteria of AIR vs. LIQUID cooling are the same as those in the Internal Combustion Engine.
- Air Cooling
  - Used for small power generation, less than about 2 kW.
  - Air has a low heat transfer coefficient and the low density. Hence, the cooling channels are large for sufficient airflow.
  - If the heat is going to be rejected in the atmosphere, the air cooling will be simpler. For heat recovery through domestic heat and power system (CHP), liquid cooling will be much more attractive.
  - The complete fuel cell may not be cooled uniformly due to flow non-uniformity associated with the Airflow.

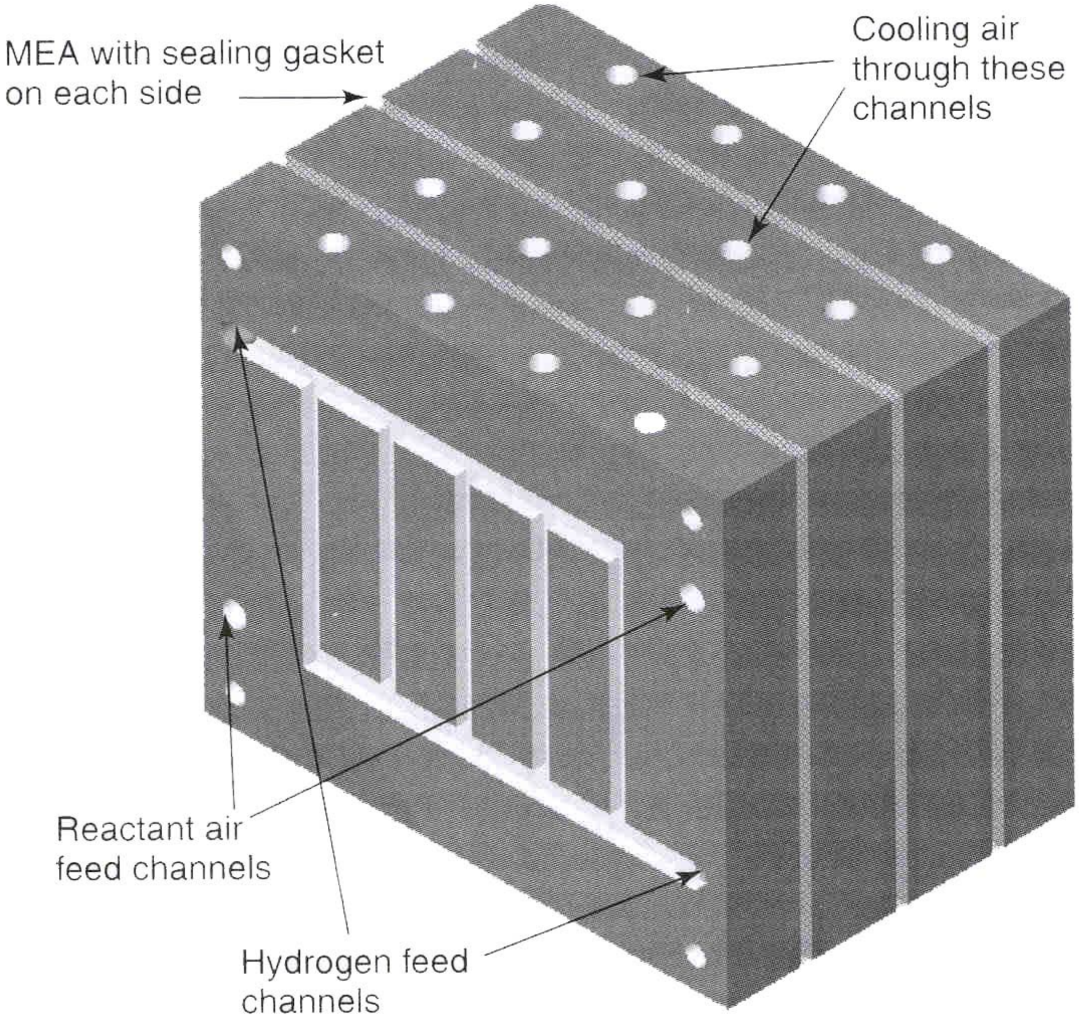
AIR OR LIQUID COOLING

Liquid Cooling

- Used for power generation larger than about 10 kW.
- Liquid cooling will be much more efficient due to high heat transfer coefficients (liquids), low volume flow rate (due to large density). Hence, the cooling channels will be small.
- For fuel cell with $2 < P_e < 10$ kW, the cooling system is decided based on the PEMFC construction.

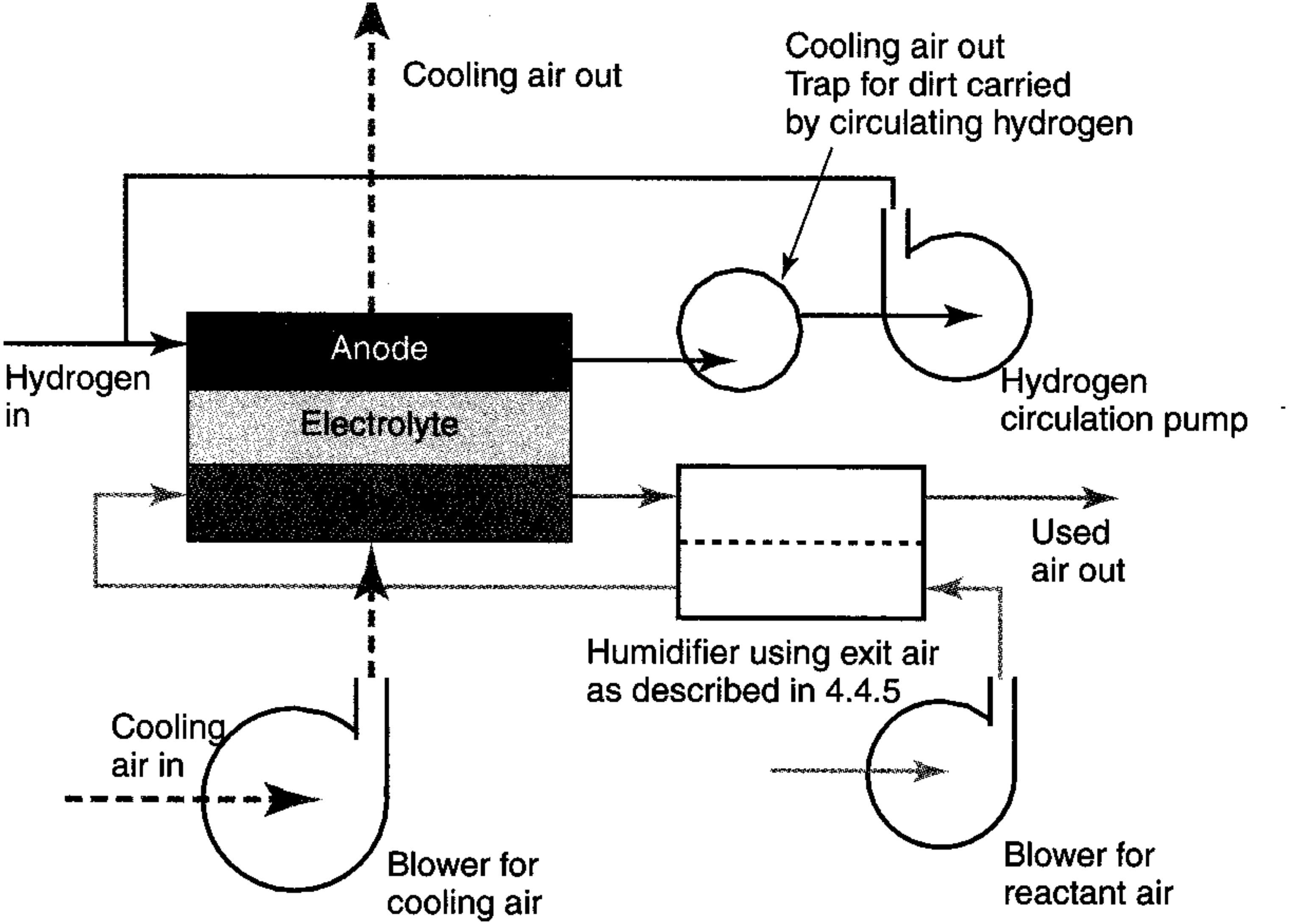


PEMFC STACK WITH COOLING AIR CHANNELS

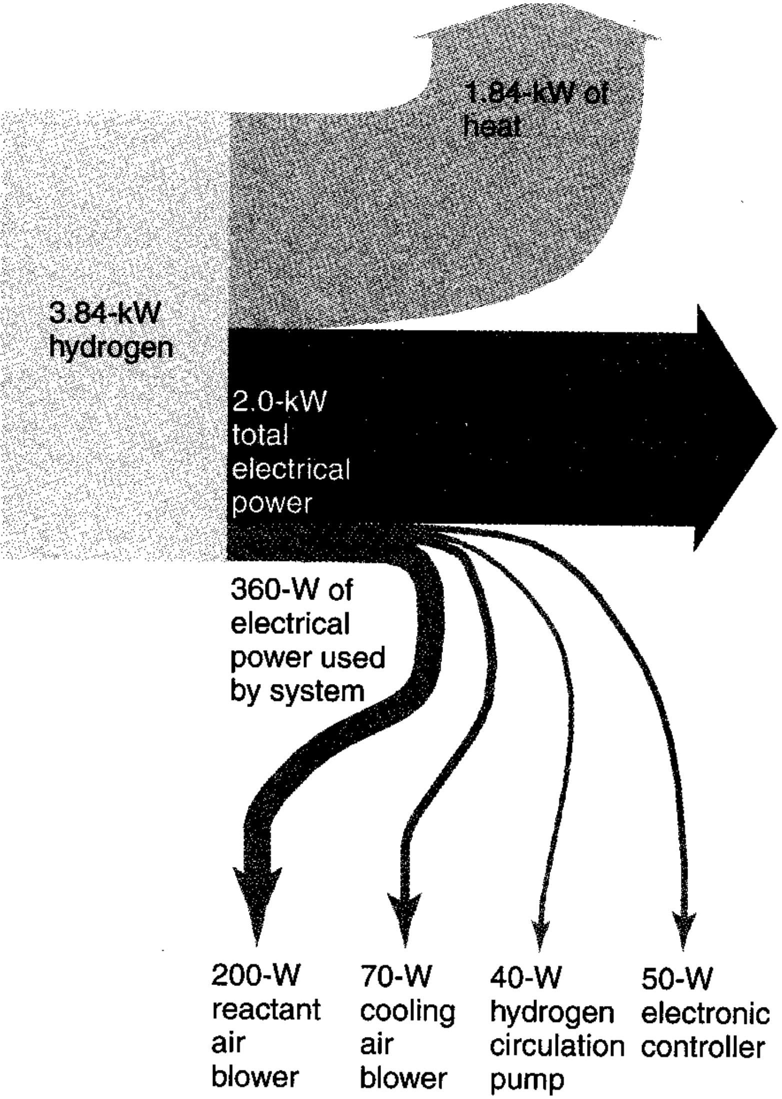


Three cells from a stack, with the bipolar plate modified for air cooling using separate reactant and cooling air.

SYSTEM DIAGRAM FOR A 2 KW FUEL CELL



SANKEY DIAGRAM:2 KW FUEL CELL SYSTEM

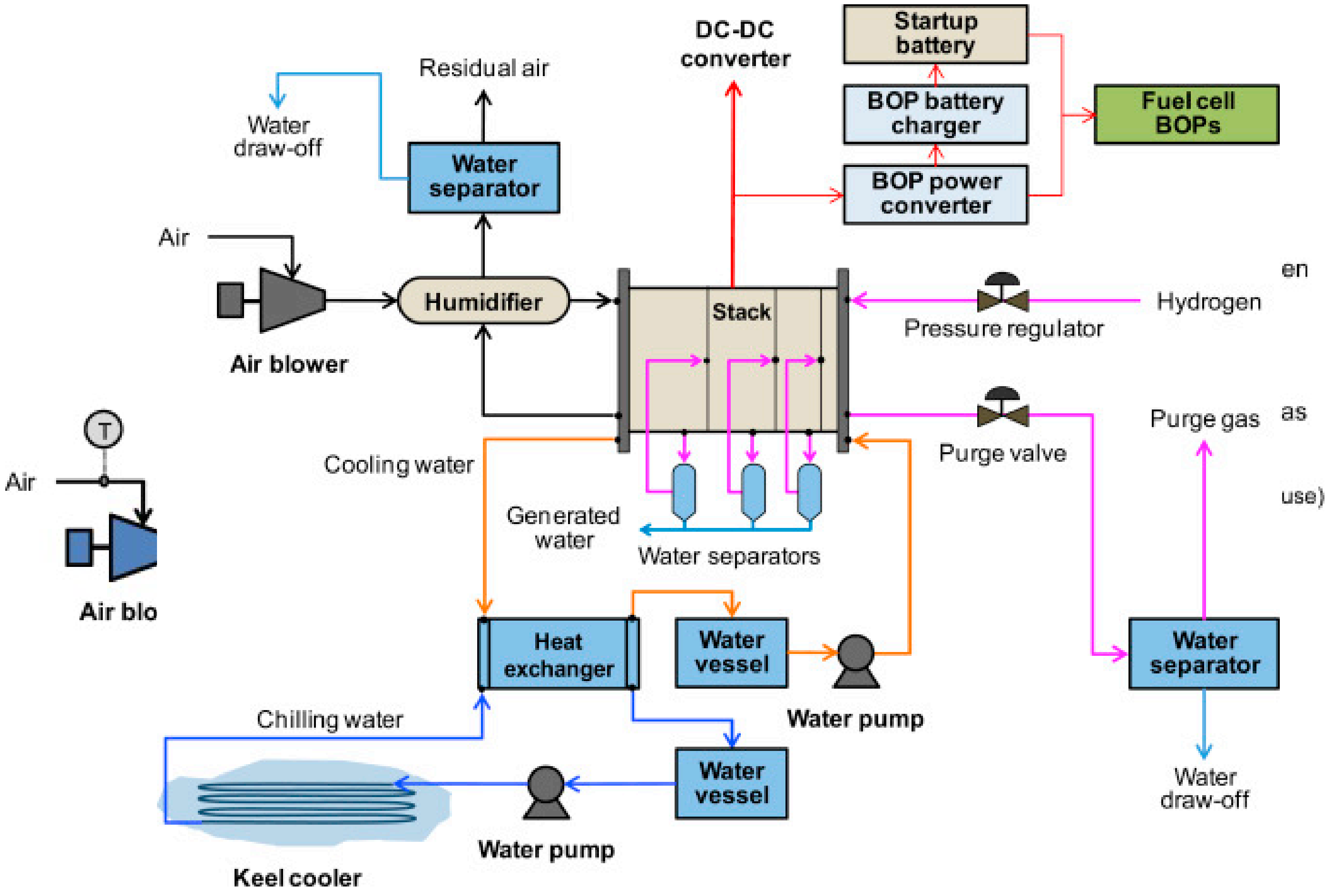


From the total 3.84 kW electrical power generated from hydrogen, 1.84 kW is lost through heat rejection, 0.36 kW to run the balance of power plant, and 1.64 kW useful power is received, 0.2 kW for reactant air blower, 0.07 kW for cooling air blower, and 0.040 kW for H2 circulation pump, and 0.050 kW for controls.

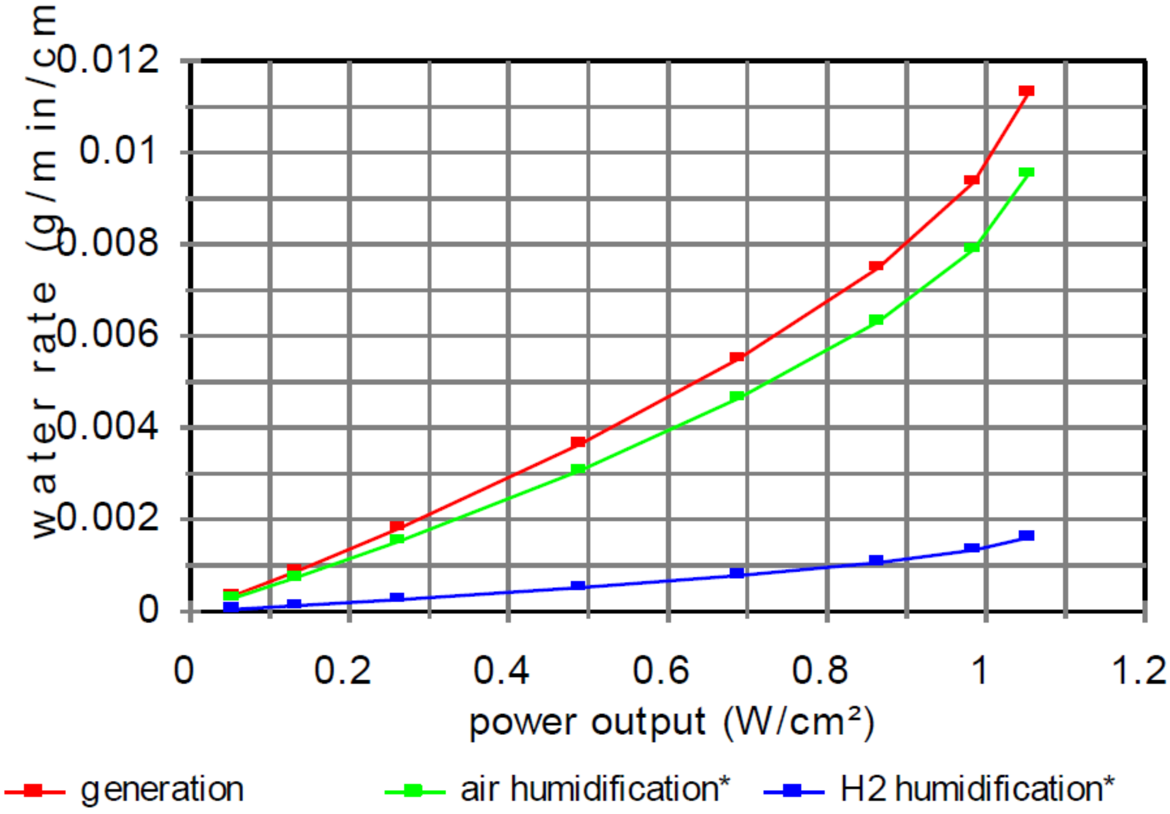
$$\eta_{THERMAL\ SYSTEM} = \frac{1.64}{3.84} = 42\%$$

The hydrogen flow rate is much less than the reactant air flow, and requires 50 W pump.

BOP MANAGEMENT IS “KEY” TO PROPER STACK PROTECTION



WATER PRODUCTION AND REQUIREMENTS



at 75°C and 300 kPa; or at 60°C and atmospheric pressure

Adopted from Frano Barbir