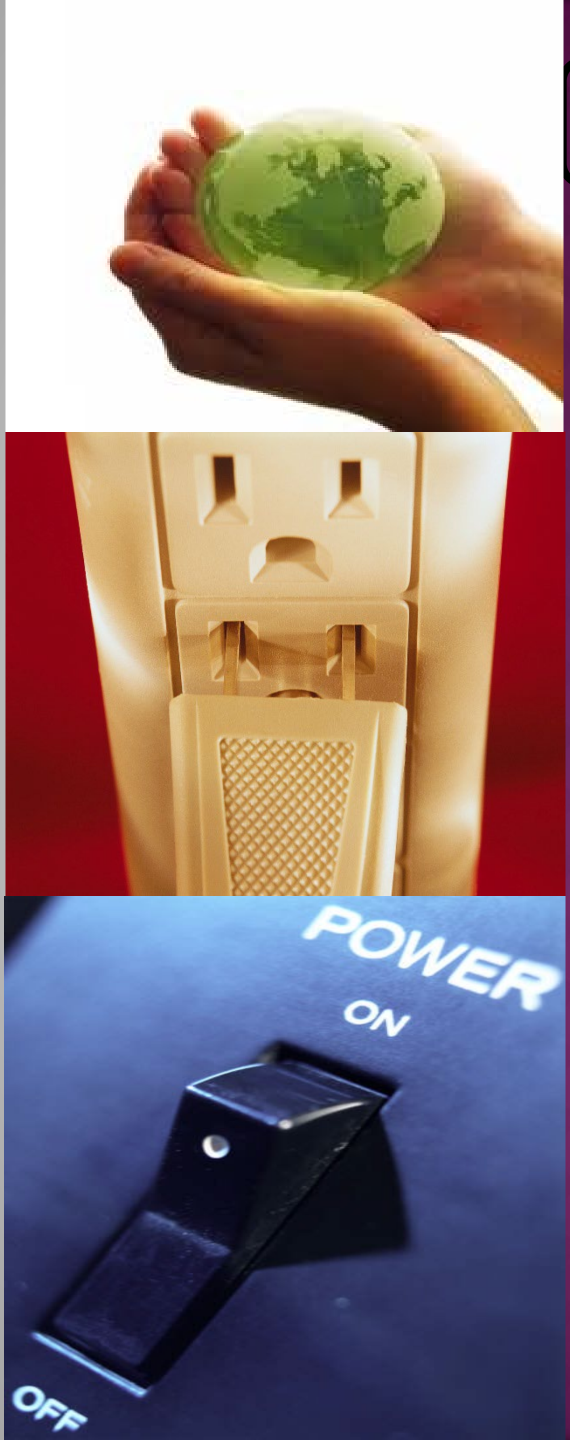

PEM HUMIDIFICATION

MECH-526

FUEL CELL SCIENCE & ENGINEERING

Center for
FUEL CELL
Systems & Powertrain Integration
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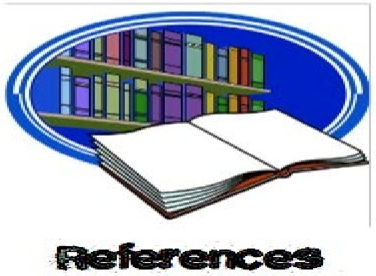
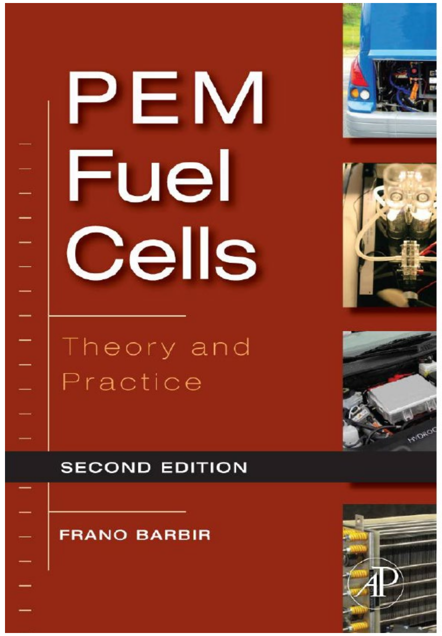
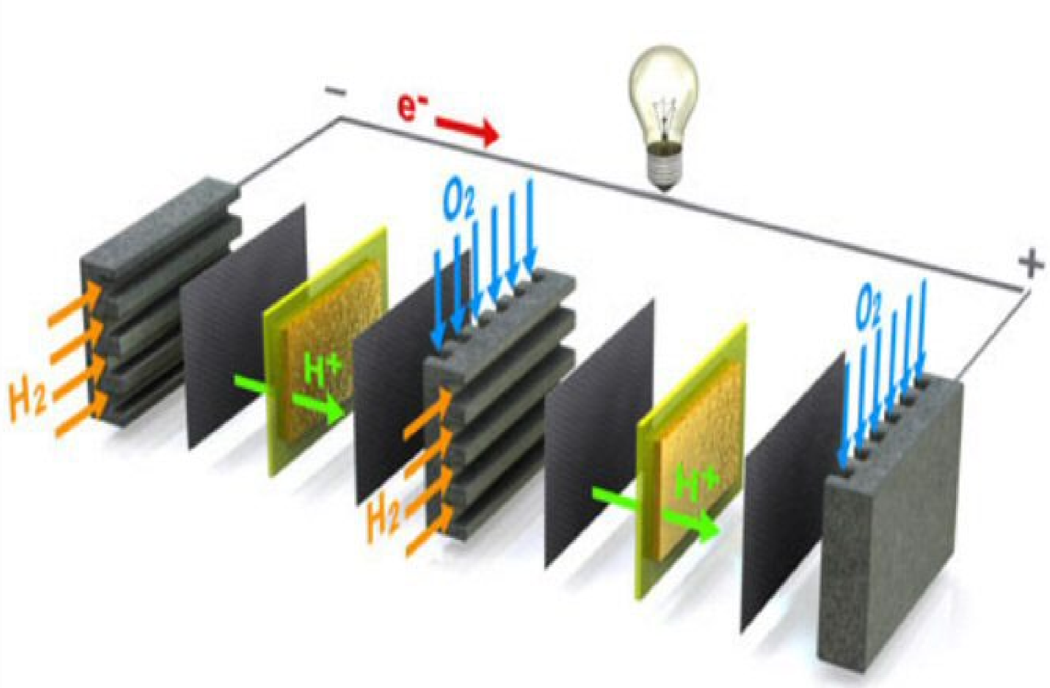
REFERENCES:



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





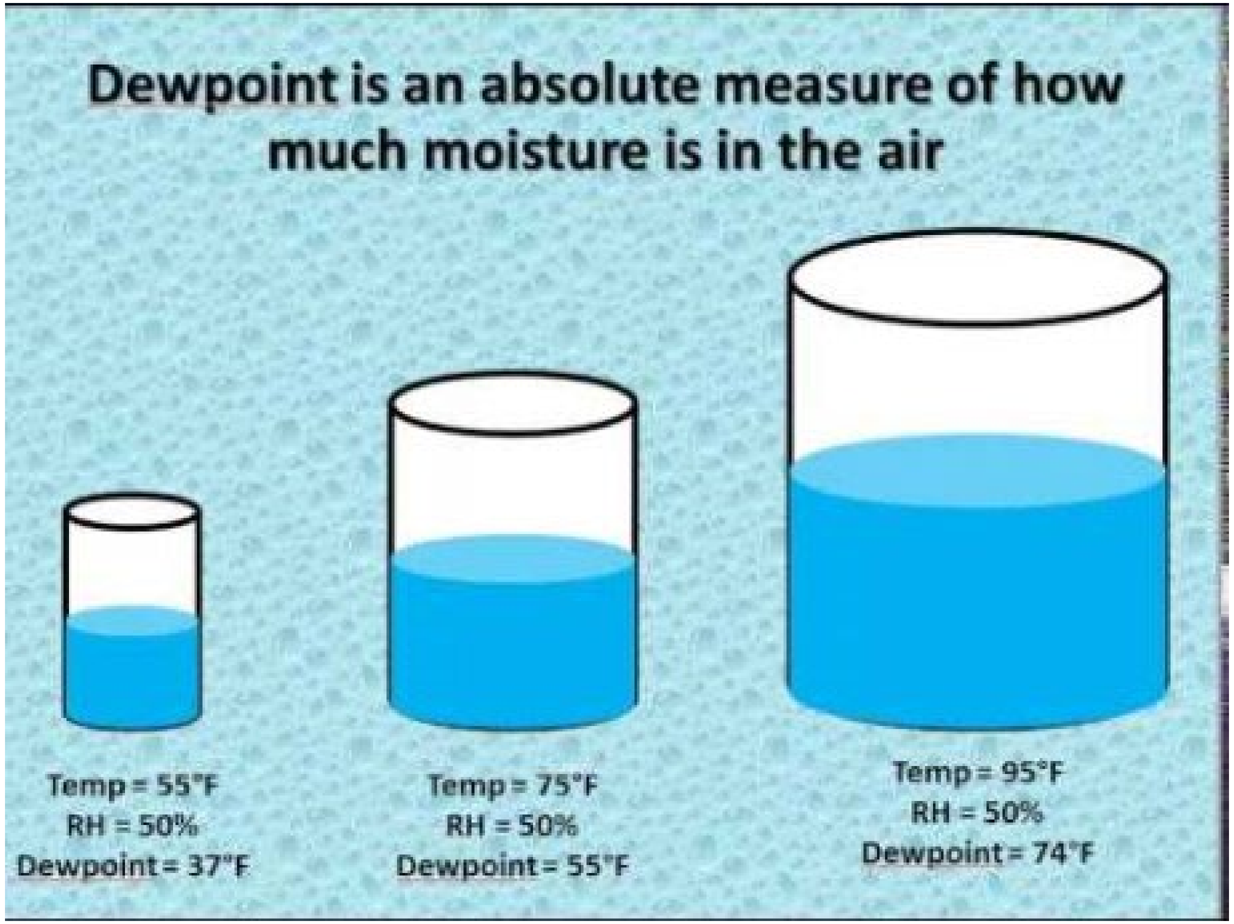
WATER VAPOR CONTENT IN GAS @ SATURATION

PEM FUEL CELL HUMIDIFICATION IS CRITICAL

Water in air will evaporate w/temperature to ensure that enough WATER VAPOR is present in the AIR to ensure equilibrium.

HUMIDITY VS DEWPOINT

HTTPS://WWW.YOUTUBE.COM/WATCH?V=OIEJHVHRDOO



HUMIDITY is how much water is dissolved into air. Has UPPER limit as a function on TEMPERATURE.

RELATIVE HUMIDITY is ratio of how much water is dissolved compared to the MAXIMUM possible. Expressed as % of maximum at this temperarure.

DEWPOINT is an ABSOLUTE measure of how much moisture is in the air and is the temperature air needs to be **COOLED** to reach 100% **RELATIVE HUMIDITY.**

THERMODYNAMICS OF MOIST AIR

- Humidity Ratio (MASS/MOLAR)

Humidity Ratio - MOLAR

$$X = \frac{\text{Moles of Vapor Water } (\mathrm{M}_v)}{\text{Moles of Air } (\mathrm{M}_{air})} = \frac{M_v}{M_a} = \frac{\text{partial pressure water}}{\text{partial pressure air}} = \frac{p_v}{p_a} = \frac{p_v}{P_{total} - p_v}$$

Humidity Ratio - MASS

$$x = \frac{\text{mass of vapor water (g)}}{\text{mass of air (g)}} = \frac{G_v}{G_a} = \frac{\text{Moles of Vapor Water } (\mathrm{M}_v)}{\text{Moles of Air } (\mathrm{M}_{air})} \bullet \frac{M_{H_2O}(g/mole)}{M_{air}(g/mole)}$$

$$x = X\left[\frac{\text{Moles of Vapor Water}}{\text{Moles of Air}}\right] \bullet \frac{M_{H_2O}(g/mole)}{M_{air}(g/mole)} = \frac{\text{GRAMS of Vapor Water}}{\text{GRAMS of Air}}$$

$$= X \bullet \frac{18.0153}{28.9645}$$

$$= X \bullet 0.62198$$

$$= \frac{p_v}{P_{total} - p_v} \bullet 0.62198 \left[\frac{\text{GRAMS of Vapor Water}}{\text{GRAMS of Air}}\right]$$

RELATIVE HUMIDITY

- **Saturation Pressure** of a **vapor** which is in equilibrium with its liquid (as steam with water); specifically :the maximum **pressure** possible by water **vapor** at a given temperature.

$$\varphi = \text{Relative Humidity (RH)} = \frac{\text{"ACTUAL" vapor water partial pressure}}{\text{vapor water SATURATION pressure}} = \frac{p_v}{p_{vs}(T)}$$

$$p_{vs}(T(K))_{Pascals} = e^C; (T = 273K \rightarrow 373K)$$

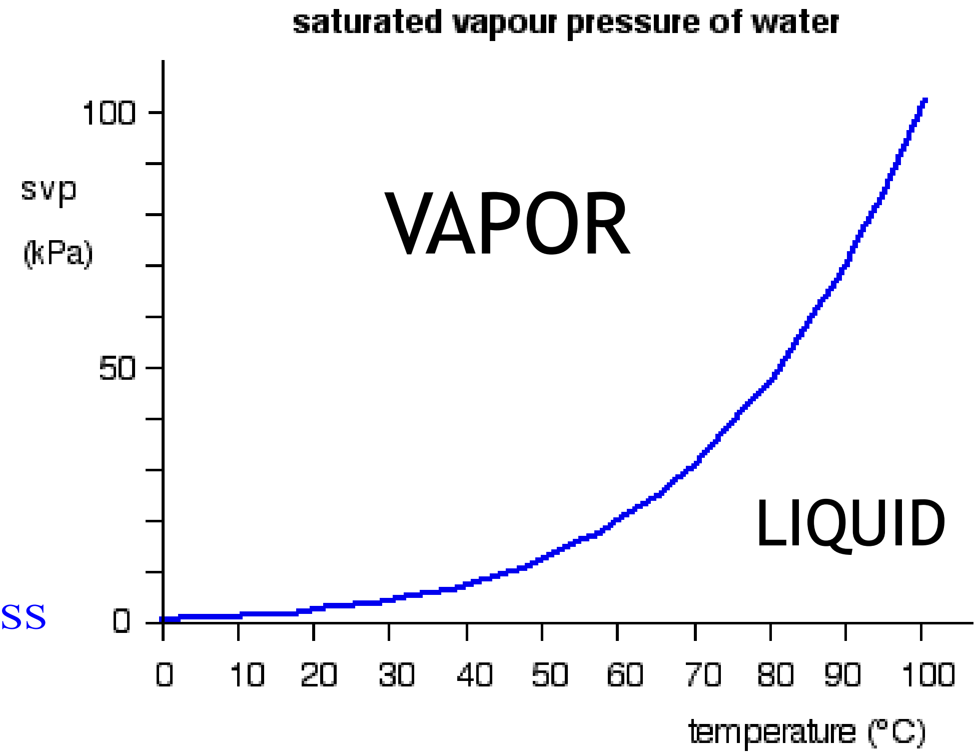
$$C = aT^{-1} + b + cT + dT^2 + eT^3 + f\ln(T)$$

a	-5800.2206
b	1.3914993
c	-0.04864239
d	$0.4176468x10^{-4}$
e	$-0.14452093x10^{-7}$
f	6.5459673

$RATIOS :\rightarrow COMBINING(X \text{ and } \varphi)$

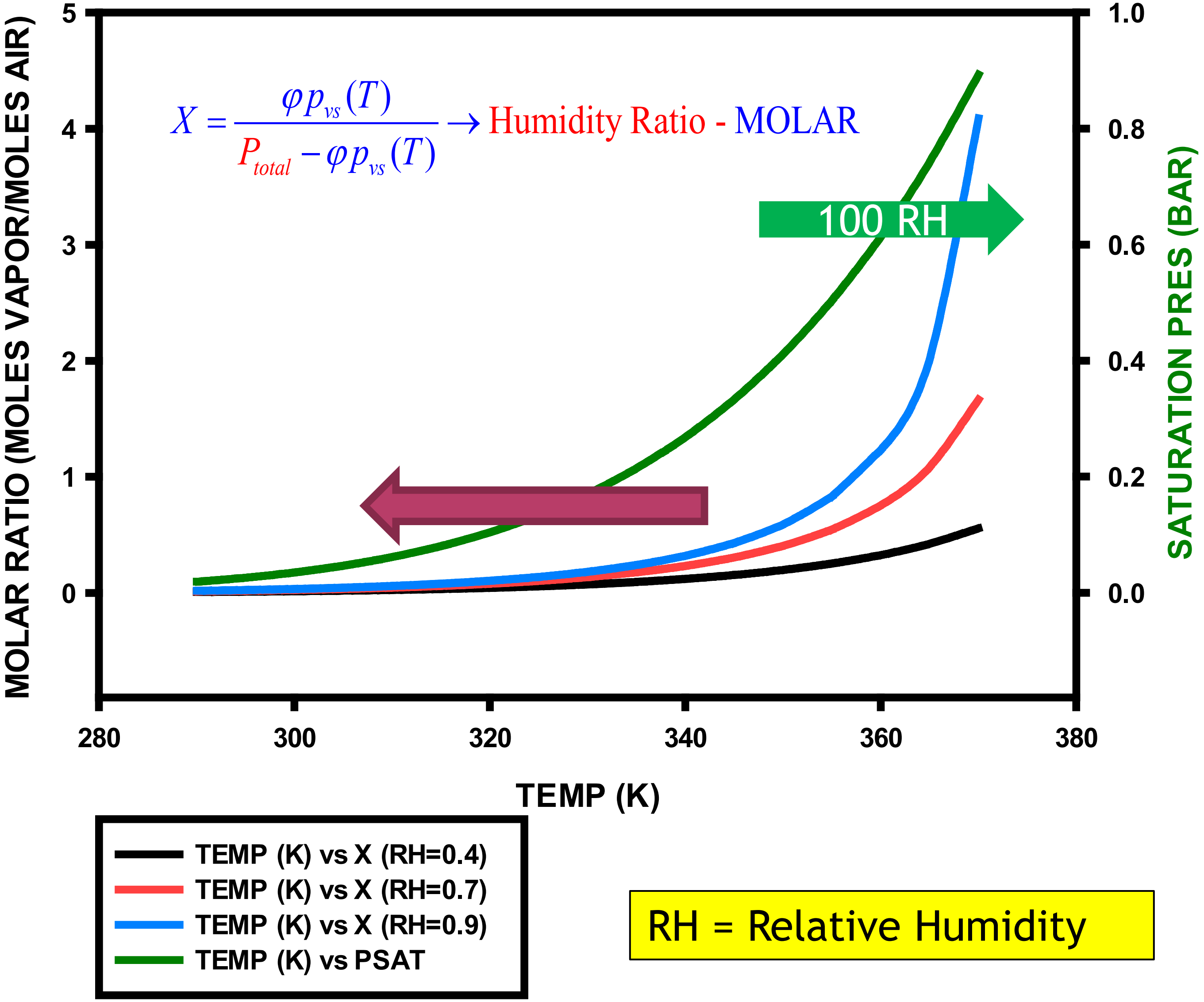
$$X = \frac{\varphi p_{vs}(T)}{P_{total} - \varphi p_{vs}(T)} \rightarrow \text{Humidity Ratio - MOLAR}$$

$$x = X \bullet \frac{M_{H_2O}(g/mole)}{M_{air}(g/mole)} = \rightarrow \text{Humidity Ratio - MASS}$$



# Temperature vs Molar Ratio at Constant Pressure
P = 1 BAR

Increased Temperature w/RH = Increased Water Content (MOIST) at Const. Pressure

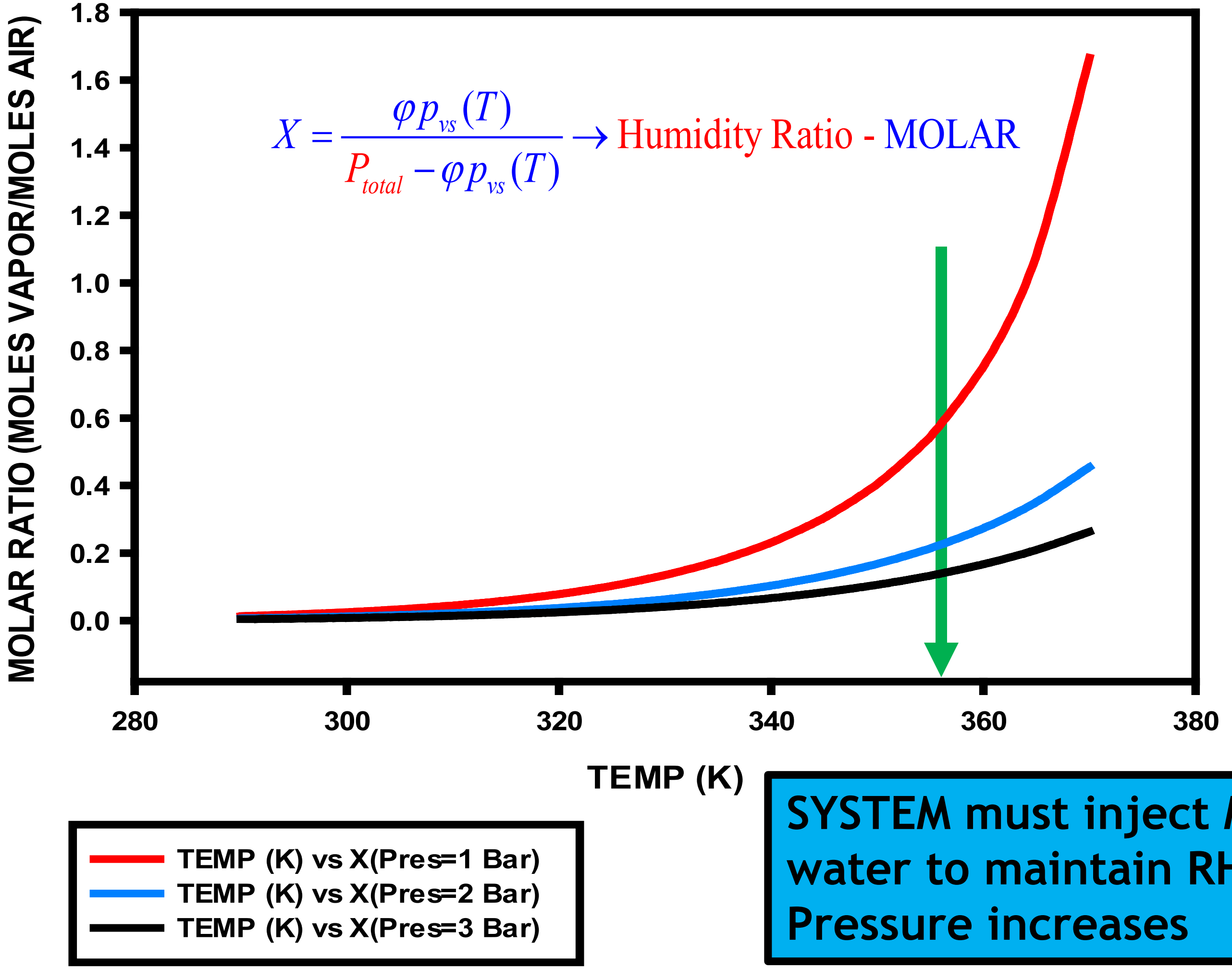


$$X = \frac{\varphi p_{vs}(T)}{P_{total} - \varphi p_{vs}(T)} \rightarrow \text{Humidity Ratio - MOLAR}$$

RH = Relative Humidity

# Temperature vs Molar Ratio at Constant RH
RH = 0.7

Increased Temperature w/Pressure = DECREASED Water Content (DRY) at Const. RH



$$X = \frac{\varphi p_{vs}(T)}{P_{total} - \varphi p_{vs}(T)} \rightarrow \text{Humidity Ratio - MOLAR}$$

SYSTEM must inject MORE water to maintain RH as Pressure increases

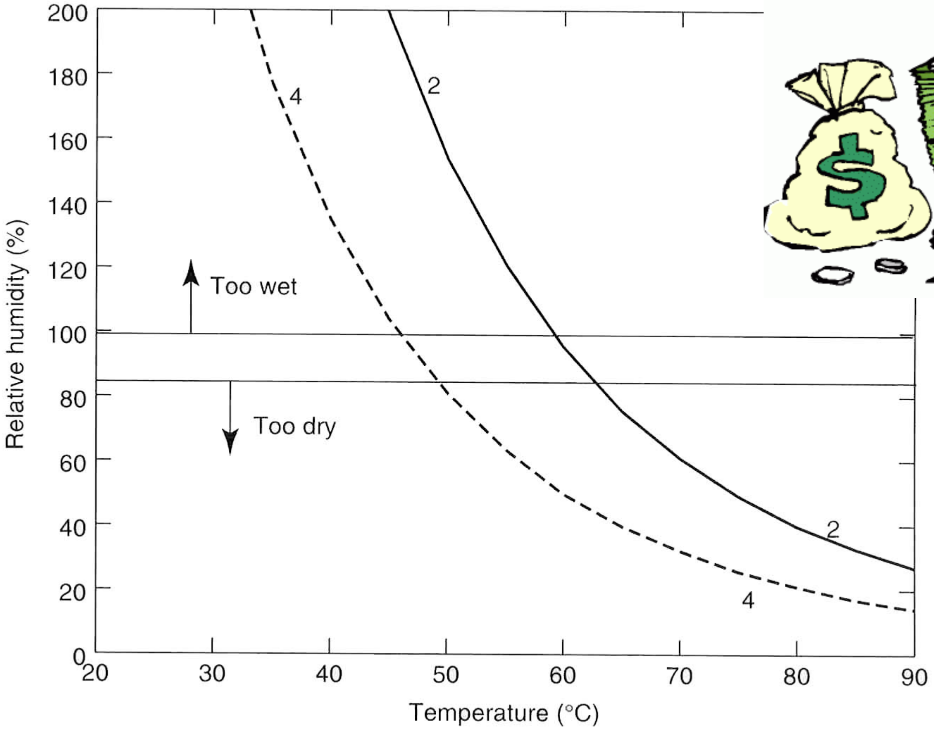
Increased Temperature → Increasure Saturation Pressure → Drier @ Constant RH

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***.

As PRESSURE increases, **RELATIVE HUMIDITY** decreases, i.e. **air becomes dryer**.

As TEMPERATURE increases, **RELATIVE HUMIDITY** increases, i.e. **air becomes moist**.



EXAMPLE 1

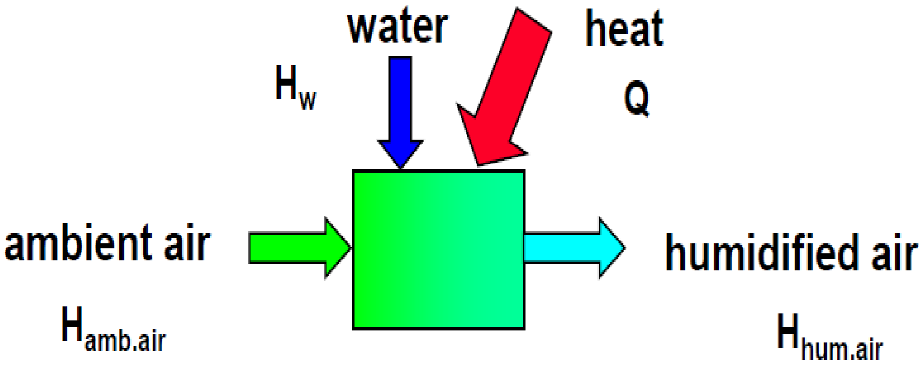
just
another
example

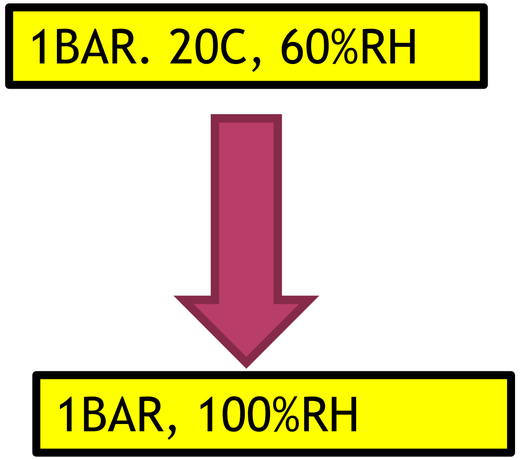
A100 plate fuel cell with 300-cm^2 active area operates at 0.6 A/cm^2 and 0.65 V.

Air is supplied at stoichiometric ratio of 2 and at a pressure of 1.15 bar,
and it is **HUMIDIFIED BY INJECTING HOT WATER (60°C)** just before the stack inlet.

AMBIENT AIR CONDITIONS ARE 1 BAR, 20°C, AND 60% RH.

The requirement is to **SATURATE INLET AIR AT CELL OPERATING TEMPERATURE OF 60°C**. Calculate the air flow rate, the amount of water required for 100% humidification of air at the inlet, and heat required for humidification.





Adopted from Frano Barbir

STEP #1:
WATER MASS FLOW RATE IN EXISTING INLET AIR ?

Air Flow Rate INLET @ 20C, 100 kPa

$$[\dot{m}_{air}]_{STACK} = S_{air}\frac{I}{4F}\frac{1}{0.21} = 2\frac{0.6(A/cm^2)*300(cm^2)*100(plates)}{4*96,485*0.21} = 0.444 mol/s \bullet 28.85 g/mol = \frac{12.81 grams\ air/s}{STACK}$$

Saturation Pressure @ 20C (293K)

$$p_{vs}(T) = e^C$$

$$C = aT^{-1} + b + cT + dT^2 + eT^3 + f\ln(T)$$

$$= 2.339 kPa$$

$$\boxed{x = \frac{\varphi p_{vs}(T)}{P_{total} - \varphi p_{vs}(T)} \bullet \frac{M_{H_2O}(g/mole)}{M_{air}(g/mole)}}$$

Mass Humidity Ratio @ 20C, 100 kPa

$$x = X\left[\frac{\text{moles vapor}}{\text{moles air}}\right] \bullet \frac{M_{H_2O}(g/mole)}{M_{air}(g/mole)} = \frac{\varphi p_{vs}}{P_{TOTAL} - \varphi p_{vs}} \bullet \frac{M_{H_2O}(g/mole)}{M_{air}(g/mole)}$$

$$= \frac{0.6*2.339}{100 - 0.6*2.339} \bullet \frac{18}{28.85} = 0.00888\frac{\text{grams water vapor}}{\text{grams air}} = \text{mass humidity ratio}$$

INLET AIR WATER$=0.0088\left[\frac{\text{grams water vapor}}{\text{grams air}}\right]$

$$\dot{m}_{w@20C} = 12.81\cancel{\text{grams air}}/s \bullet 0.00888\frac{\text{grams water}}{\cancel{\text{grams air}}} = 0.11\text{grams water/s}$$

STEP 2:
INJECTION WATER MASS FLOW RATE (@100%RH)

WATER INJECTION @ 60C, 115 kPa, RH 100%

Saturation Pressure @ 60C, 115kPa

$$p_{vs}(T) = e^{C}$$

$$C = aT^{-1} + b + cT + dT^{2} + eT^{3} + f\ln(T)$$

$$= 19.944\,kPa$$

Mass Humidity Ratio @ 60C

$$\text{x}=\frac{1.0 * 19.944\,kPa}{115\,kPa - 19.944\,kPa} \bullet \left[\frac{18}{28.85}\right] = 0.131\,\frac{\text{grams water}}{\text{grams air}}$$

$$\boxed{x = \frac{\varphi p_{vs}(T)}{P_{total} - \varphi p_{vs}(T)} \bullet \frac{M_{H_2O}(g/mole)}{M_{air}(g/mole)}}$$

Finally

WATER in AIR @ 60C

$$\text{m}_{w@60C} = 12.81\,\text{grams air}/s * 0.131\,\frac{\text{grams water}}{\text{grams air}} = 1.678\ \text{grams water}/s$$

Water Required for Humidification

$$m_w = 1.678 - 0.11 = 1.568\,g/s$$

IN GENERAL: INLET WATER MASS FLOW RATE/CELL

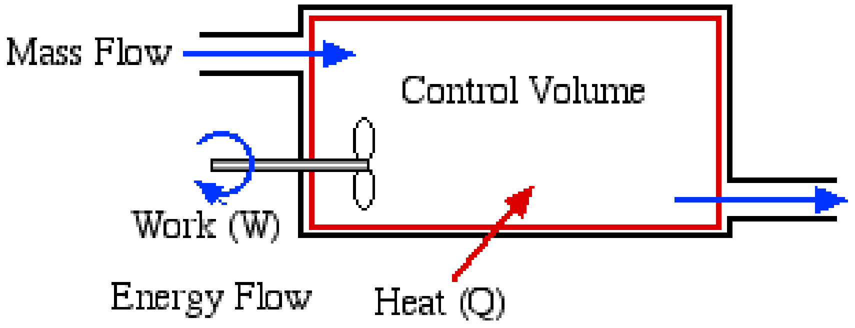
$$\dot{m}_{water_{IN}} = S_{air}\frac{I}{4F}\frac{1}{0.21}\left[\frac{mole}{sec}\right]\bullet MW_{air}\left[\frac{g}{mole}\right]\bullet\frac{\varphi p_{vs}(T)}{P_{TOTAL}-\varphi p_{vs}(T)}\left[\frac{\text{mole vapor}}{\text{mole air}}\right]\bullet\frac{M_{H_2O}(g/mole)}{M_{air}(g/mole)}$$

$$\dot{m}_{water_{IN}} = \left[\frac{\cancel{\text{grams air}}}{s}\right]\bullet\left[\frac{\text{grams water vapor}}{\cancel{\text{grams air}}}\right]$$

$$\dot{m}_{water_{IN}}\left[\frac{\text{g water vapor}}{s}\right] = \dot{m}_{Air_{IN}}\left[\frac{\cancel{\text{grams air}}}{s}\right]\bullet x\left[\frac{\text{grams water vapor}}{\cancel{\text{grams air}}}\right]$$

IN GENERAL

MASS CONSERVATION
ENERGY CONSERVATION



Mass Conservation

$$\sum \dot{m}_{in} = \sum \dot{m}_{out}$$

$\dot{m} \rightarrow$ mass flow rate: kg/s

Energy Conservation

$$\sum \dot{Q}_{in}[W] + \sum \dot{m}_{in} h_{in}[W] = \sum \dot{m}_{out} h_{out}[W] + \sum \dot{Q}_{out}[W] + \dot{W}_{EL}[W]$$

$$h \rightarrow \left(cp \frac{J}{kg - C} \right) (T(C)) \rightarrow \text{enthalpy:J/kg}$$

$\dot{W}_{EL} \rightarrow$ Work Output Electrical

AIR/VAPOR ENTHALPY: THERMODYNAMICS

Enthalpy of Dry Gas (J/g)

$\mathrm{h}_g (J/g) = cp_g t$

cp_g = specific heat of dry gas=J/g-K; $\rightarrow \mathrm{cp}_{AIR} = 1.01 J/g-K$

t= temperature in C (reference state is 0 at 0C)

Enthapy of Water Vapor (J/g)

$\mathrm{h}_v = cp_v t + h_{fg}$; $\rightarrow \mathrm{cp}_{VAPOR} = 1.87 J/g-K$

h_{fg} = heat of evaporation=2500J/g at 0C

Enthalpy of Liquid Water (J/g)

$\mathrm{h}_w = cp_w t$; $\rightarrow \mathrm{cp}_{WATER} = 4.18 J/g-K$

Enthlpy of Humid Gas (J/g)

$\mathrm{h}_{vg} = cp_g t + x_v (cp_v t + h_{fg})$

Enthlpy of Water Vapor and Liquid Water (J/g)

$\mathrm{h}_{vg} = cp_g t + x_v (cp_v t + h_{fg}) + x_w cp_w t$

x_v = water vapor content (grams of vapor per gram of dry gas)

x_w = liquid water content (grams of liquid water per gram of dry gas)

$x = x_v + x_w$

Note: *when* $\mathrm{x_w}$=0, x=$\mathrm{x_v}$;*when* $\mathrm{x_w}$>0, x=$\mathrm{x_{vs}}$(*saturated*)

HEAT CALCULATIONS (CHAPTER 5)

Enthlpy of Humid Gas (J/g)

$$\mathrm{h}_{vg} = cp_g t + x_v(cp_v t + h_{fg}) \rightarrow t = {}^0\ C \rightarrow \text{Reference Zero State is a } 0^0 C$$

$$h_{\text{amb air}} = 1.01J/g-K \bullet 20C + 0.00888 \bullet (1.87J/g-K \bullet 20C + 2500J/g) = 42.73J/g$$

$$H_{\text{AMB AIR}} = h_{\text{amb air}} \bullet \dot{m}_{air}$$

$$= 42.73J/g \bullet 12.81g/s = 546.9W \rightarrow \text{Energy Content}$$

$$h_{\text{hum air}} = 1.01J/g-K \bullet 60C + 0.131 \bullet (1.87J/g-K \bullet 60C + 2500J/g) = 402.8J/g$$

$$H_{\text{HUM AIR}} = h_{\text{hum air}} \bullet \dot{m}_{air}$$

$$= 402.8J/g \bullet 12.81g/s = 5155.8W \rightarrow \text{Energy Content}$$

$$h_{water} = cp_w t$$

$$= 4.18J/g-K \bullet 60C = 250J/g$$

$$H_{\text{water}} = h_{water} \bullet 1.57g/s = 393.8W$$

HEAT

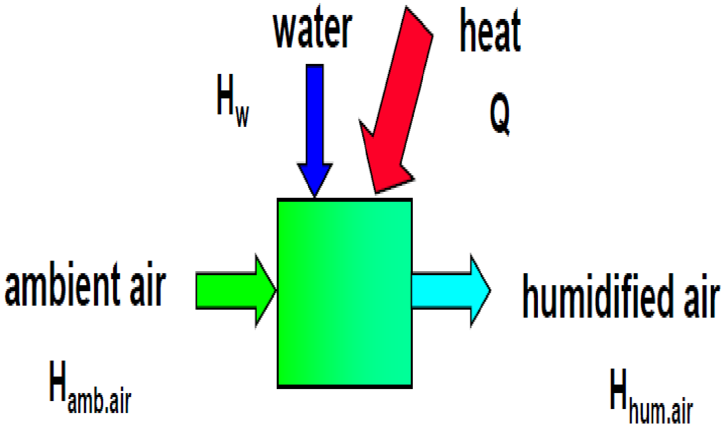
$$\dot{E}_{in} - \dot{E}_{out} = 0$$

$$H_{\text{AMB AIR}} + H_{\text{water}} + Q = H_{\text{HUM AIR}}$$

$$Q = H_{\text{HUM AIR}} - H_{\text{AMB AIR}} - H_{\text{water}}$$

$$= 5155.8W - 546.9W - 393.8W$$

$$= \frac{4215.1W}{STACK}$$



Heat needed from external source or from FUEL CELL STACK

EFFICIENCY AND WATER GENERATION

$$\text{Cell Power} = \frac{\dot{W}_{elec}}{STACK} = I^*\left[\frac{Amps}{cm^2}\right]\bullet Area\left[cm^2\right]\bullet\frac{V}{cell}\bullet\#cells$$

$$= 0.6\left[\frac{Amps}{cm^2}\right]\bullet 300cm^2\bullet 0.65\frac{V}{cell}\bullet 100\text{ cells}$$

$$= 11{,}700\text{ W}$$

$$\text{Efficiency} = \eta = \frac{V/cell}{1.482} = 0.439$$

$$\text{Heat Generated} = \frac{\dot{W}_{elec}}{\eta} - \dot{W}_{elec}$$

$$= 14{,}951 Watts \rightarrow \text{External Work and for Removal}$$

$$\frac{\text{Water Generated}}{Stack} = \frac{\frac{I^*\bullet Area}{2F}MW_{H_20}}{cell}\bullet\#cells$$

$$= \frac{0.6\bullet 300}{2\bullet 96{,}485}\bullet 18\bullet 100$$

$$= 1.68\frac{g}{s} = 145.15\frac{kg}{day}\bullet\frac{1L}{kg_{WATER}} = 145L/day$$

IN GENERAL

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

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

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

Heat generated from stack and to be dumped: 14.9kW.

Can this be used for HUMIDIFICATION at 4.2kW?

But do we have correct heat transfer driving temperature differential? Can not transfer heat from LOW to HIGH. LTPEM FC have low grade heat.

SUMMARY-100 CELL STACK

$$POWER = 0.6A/cm^2 * 300cm^2 * 0.65V/CELL * 100CELLS = 11,700W$$

$$EFF = 0.65/1.482 = 44\%$$

$$HEAT_{LOSS} = 11,700/0.44 - 11,700 = 14,951W \rightarrow DISSIPATION$$

$$HEAT_{HUMID\ \mathrm{AIR}} = 5155.8W$$

$$HEAT_{AIR\ \mathrm{Ambient}} = 402.8W$$

$$HEAT_{WATER} = 393.8W$$

$$WATER_{GEN} = 93.x10^{-6} \frac{g/s}{A-Cell} * \left(0.6A/cm^2 * 300cm^2 * 100cells\right) = 1.679g/s$$

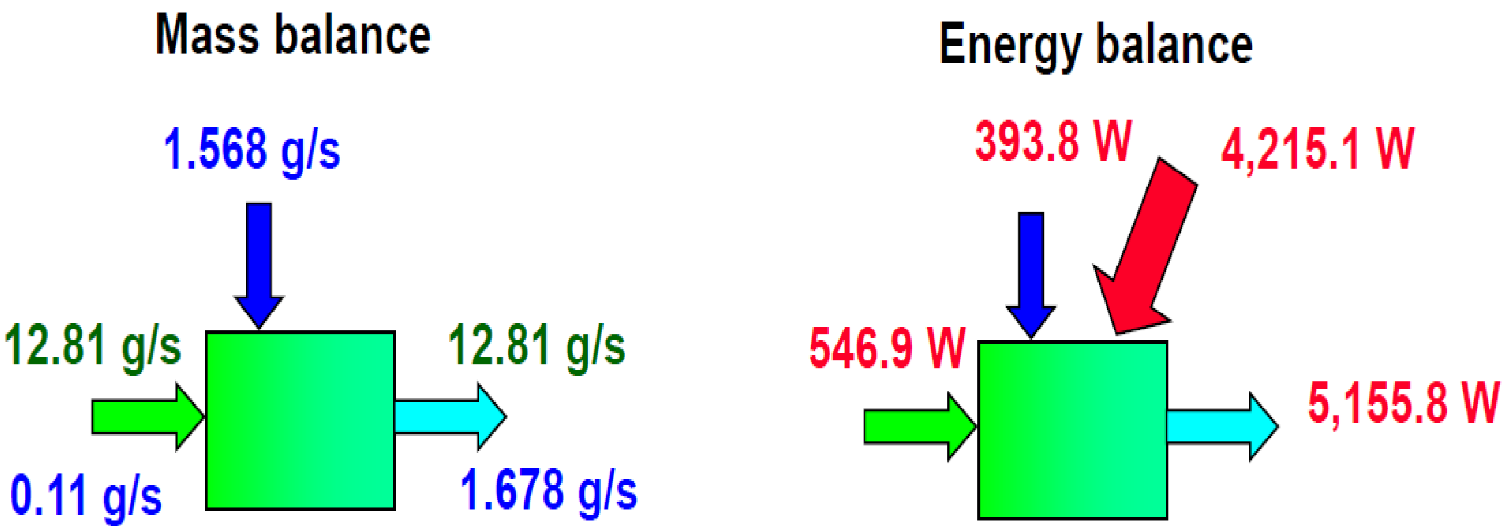
$$WATER_{\mathrm{AIR\ HUMD}} = 1.568g/s$$

CONSUMPTION RATES → *LIQUID PRODUCTS*

$$\dot{m}_{H_2O}\left[\frac{g}{\mathrm{sec}}\right] = \frac{I}{2F}\left[\frac{moles\ of\ H_2O\ Product}{\mathrm{sec}}\right] \bullet Mw_{H_2O}\left[\frac{g}{moles\ of\ H_2O}\right]$$

$$\dot{m}[SLM] = \frac{I}{nF}\left[\frac{moles}{\mathrm{sec}}\right] \bullet Mw_{H_2O}\left[\frac{g}{mole}\right] \bullet \frac{60\mathrm{sec}}{\mathrm{min}} \bullet \frac{1}{\rho_{H_2O}\frac{g}{m^3}} \bullet \frac{1000L}{m^3}$$

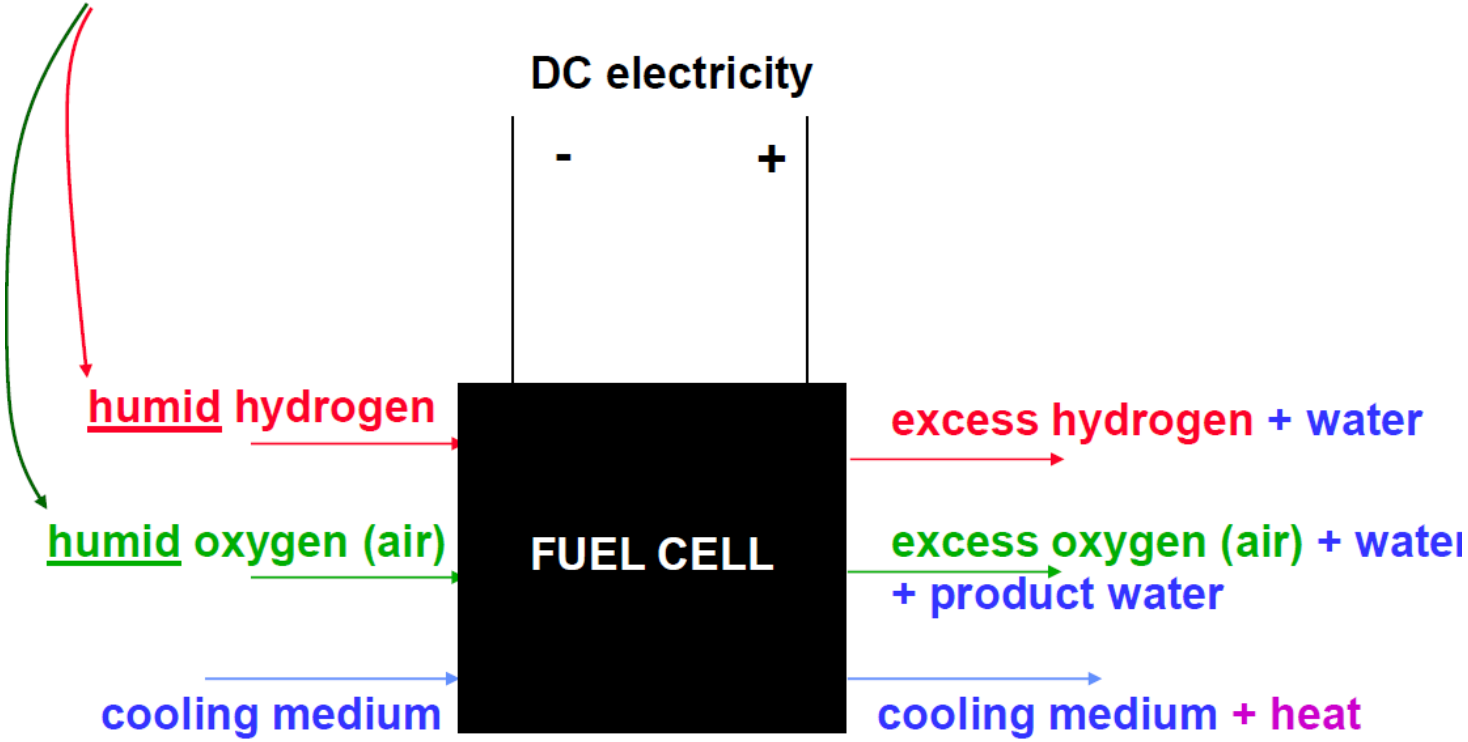
WATER MASS AND ENERGY BALANCE



Adopted from Frano Barbir

HUMIDIFICATION OF REACTANT GASSES

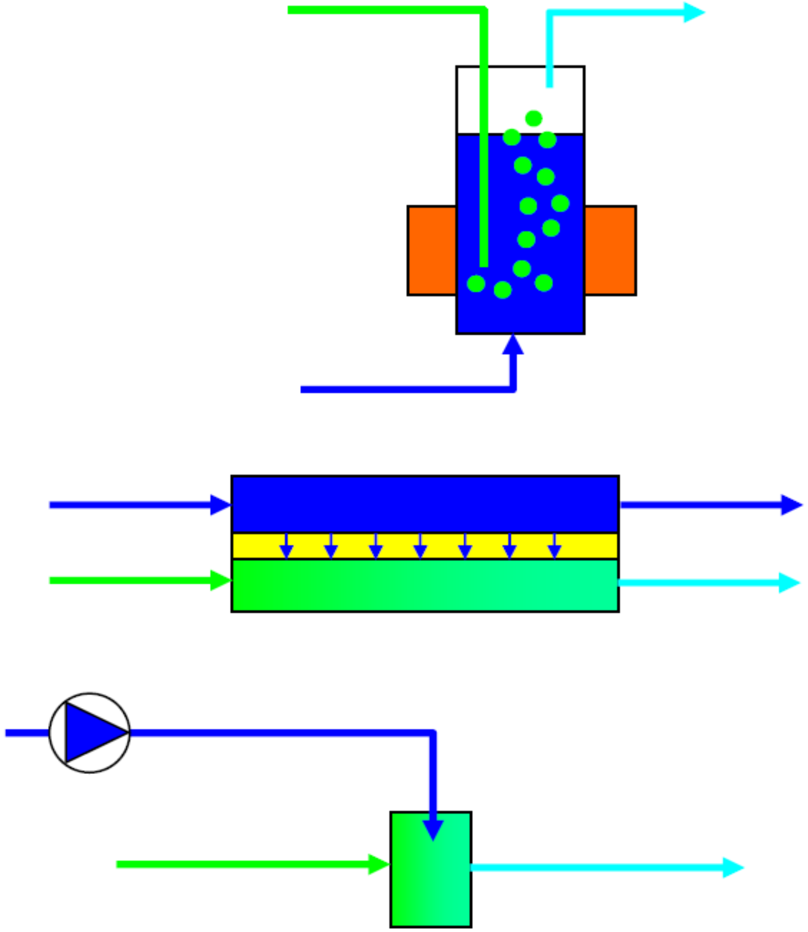
Typically both air (oxygen) and hydrogen must be humidified before entering the cell



Adopted from Frano Barbir

HUMIDIFICATION METHODS

- Bubbling
- Membrane
- Water injection
- Steam injection



Adopted from Frano Barbir

EXIT CONDITIONS

EXIT H2 MASS FLOW

$$\frac{\dot{m}_{H2out}}{cell} = \dot{m}_{H2in} - \dot{m}_{H2CONSUMPTION}$$

$$= S_{H_2}\frac{I}{2F}M_{H_2} - \frac{I}{2F}M_{H_2}, \rightarrow g/\sec$$

$$= (S_{H_2} - 1)\frac{I}{2F}M_{H_2} \text{ g/sec per cell}$$

EXIT AIR/N2 MASS FLOW

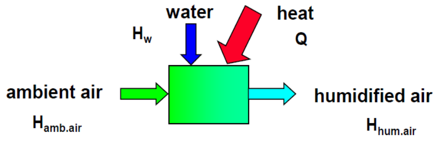
$$\frac{\dot{m}_{AIRout}}{cell} = \dot{m}_{O_2OUT} + \dot{m}_{N_2IN} \text{ (Nitrogen does not participate in the reaction)}$$

$$= \left[(S_{O_2} - 1)M_{O_2} + S_{O_2}\frac{1 - r_{O2in}}{r_{O2in}}M_{N_2}\right]\frac{I}{4F} \text{ g/sec per cell}$$

EXIT OXYGEN VOLUME FRACTION

$$\mathrm{r}_{O2out} = \frac{O_{2\ OUT}}{AIR_{\ IN}} = \frac{S_{O2} - 1}{\frac{S_{O2}}{r_{O_2in}} - 1}; \quad r_{O_2in} = 0.21 \text{ Normally}$$

EXAMPLE 2



- 10kW H2/Air FC operates at 0.7V/cell at TFC=70C, ambient pressure (101.3kPa), T0=23C, RH=75%, and So2=2.25. How much water is needed for seven days of operation?

$$\varphi = \text{Relative Humidity} = \frac{\text{"ACTUAL" vapor partial pressure}}{\text{vapor SATURATION pressure}} = \frac{p_v}{p_{vs}(T)}$$

Saturation Pressure @ 23C=296.15K

$$p_{vs}(T) = e^C; C = aT^{-1} + b + cT + dT^2 + eT^3 + f\ln(T)$$

$$p_{vs}(T = 23C) = 2.810kPa$$

Saturation Pressure @ 70C=343.15

$$p_{vs}(T = 70C) = 31.198kPa$$

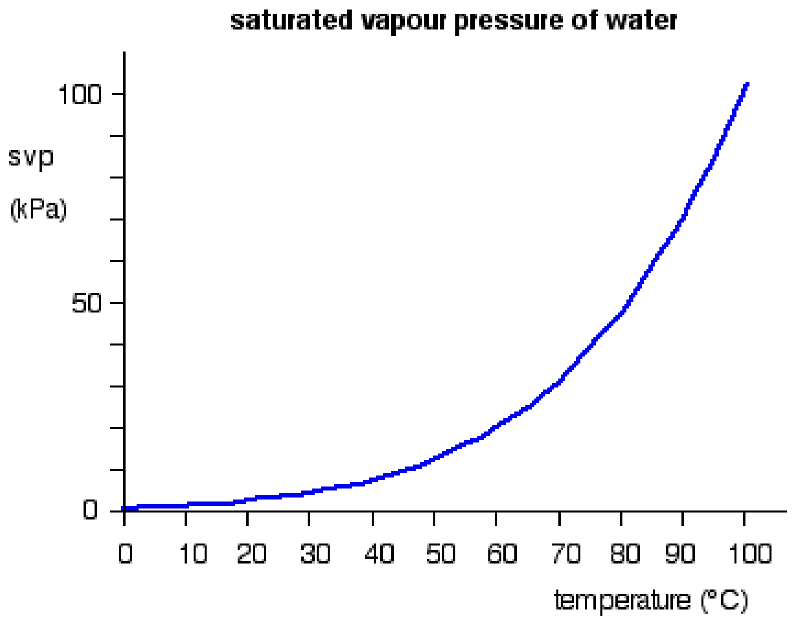
Mass Humidity Ratio - Ambient (23C, RH=75%) ←

$$x = X \bullet \frac{M_{H_2O}(g/mole)}{M_{air}(g/mole)} = \frac{\varphi p_{vs}}{P - \varphi p_{vs}} \bullet \frac{M_{H_2O}(g/mole)}{M_{air}(g/mole)}$$

$$= \frac{18}{28.85}\frac{0.75 * 2.81}{101.3 - 0.75 * 2.81} = 0.01326 \frac{\text{grams water}}{\text{grams air}} = \text{mass humidity ratio}$$

Mass Humidity Ratio - Fuel Cell Inlet (70C, RH=100%) ←

$$= \frac{18}{28.85}\frac{1.0 * 31.198}{101.3 - 1.0 * 31.198} = 0.2776 \frac{\text{grams water}}{\text{grams air}} = \text{mass humidity ratio}$$



$$\boxed{x\left[\frac{\text{grams H}_2\text{0}}{\text{grams Air}}\right] = \frac{\varphi p_{vs}(T)}{P_{total} - \varphi p_{vs}(T)} \bullet \frac{M_{H_2O}(g/mole)}{M_{air}(g/mole)}}$$

Air Flow @ INPUT AMBIENT CONDITIONS

$$\frac{m_{air}}{cell} = S_{air}\frac{I}{4F}\frac{1}{0.21}\left[\frac{mole}{s}\right]M_{air}\left[\frac{g_{air}}{mole}\right] = 2.25\frac{10000W \div 0.7V/cell}{4x96,485}\frac{1}{0.21}28.85;\ I=\frac{W}{V}$$

$$=11.44\frac{g_{air}}{\sec}/cell$$

$$\boxed{\dot{m}_{H_2O_{AIR}}\left[\frac{\text{grams } H_2O}{s}\right] = \dot{m}_{AIR}\left[\frac{\text{grams Air}}{s}\right]\bullet x\left[\frac{\text{grams } H_2O}{\text{grams Air}}\right]}$$

Water in Air INPUT(23C,75RH)

$$\mathrm{m}_{wairINPUT} = 11.44\frac{g_{air}}{\sec}/cell \bullet 0.01326\frac{\text{grams water}}{\text{grams air}} = 0.1516\frac{grams\ water}{\sec}/cell$$

Water Generated

$$\mathrm{m}_{wgen} = \frac{I}{2F}M_{H_2O} = 1.333\frac{g}{s}/cell\ (\text{eqn.5-7})$$

Water at Fuel Cell Outlet "AIR"

$$m_{wout} = \mathrm{m}_{wairINPUT} + \mathrm{m}_{wgen} = (0.1516+1.333) = 1.4846\frac{grams\ water}{\sec}/cell \rightarrow \text{WATER OUT}$$

AIR OUT FLOW RATE

$$\mathrm{m}_{AirOut} = 10.27976\frac{g_{air}}{s}/cell\ (\text{eqn.5-68}) \rightarrow \text{ DEPLETED AIR FLOW OUT}$$

Mass Hummidity Ratio at Outlet

$$x_{OUTLET} = \frac{\text{grams water}}{\text{grams air}} = \frac{m_{wout}}{\mathrm{m}_{AirOut}} = \frac{1.4846\frac{grams\ water}{\sec}/cell}{10.27976\frac{g_{air}}{s}/cell} = 0.14456\frac{\text{grams water}}{\text{grams air}}$$

For 100% Humidity at Exit, We Need

$$\left[\mathrm{m}_{H_2O}\right]_{OUT} = 10.27976\frac{g_{air}}{s}/cell\bullet(0.2776-0.14456)\frac{\text{grams water}}{\text{grams air}} = 1.3676\frac{grams\ water}{\sec}/cell$$

$$\mathrm{m}_{H_2O_{7-DAYS}} = 1.3676\frac{grams\ water}{\sec}/cell\bullet\frac{3600\sec}{hr}\bullet\frac{24hr}{Days}\bullet 7Days = 827kg\bullet\frac{m^3}{1000kg}\bullet\frac{1000L}{m^3} = 827\frac{Liters}{cell}$$

Fuel cell generates 100 amps at 0.6V. H2 flow is 1.8 Nl/m,
Air flow is 8.9 Nl/m. Find
a. H2 Stoic; b. O2 Stoic, c. O2 at Oulet

Problem 5.1						
I	100	Amps				
Vcell	0.6	V				
q_dot_H2_in	1.8	Nl/min				
q_dot_Air_in	8.9	Ni/min				
rho_H2	0.090	kg/m3	(g/l)	from P = rhoRT		
rho_Air	1.287	kg/m3	(g/l)			
m_dot_H2_in	0.0027	g/s				
m_dot_Air_in	0.1909	g/s				
S_H2	2.58		from Eq. 5-50			
S_O2	5.36		from Eq. 5-53			
c_O2_out	0.1778		from Eq. 5-17			