Dewvaporation

“Carrier-Gas Enhanced Atmospheric Pressure Desalination”

Noah Abbas and Kehinde Adesoye

Outline

- Existing Technologies
  - Reverse Osmosis
  - Thermal Processes
- Dewvaporation Explanation
- Mathematical Model
- Cost Calculations

Desalination

- Process of purifying seawater
- A solution to water shortages around the world
- Existing technologies
  - Reverse Osmosis
  - Thermal Evaporation
  - Dewvaporation

Factors of Comparison

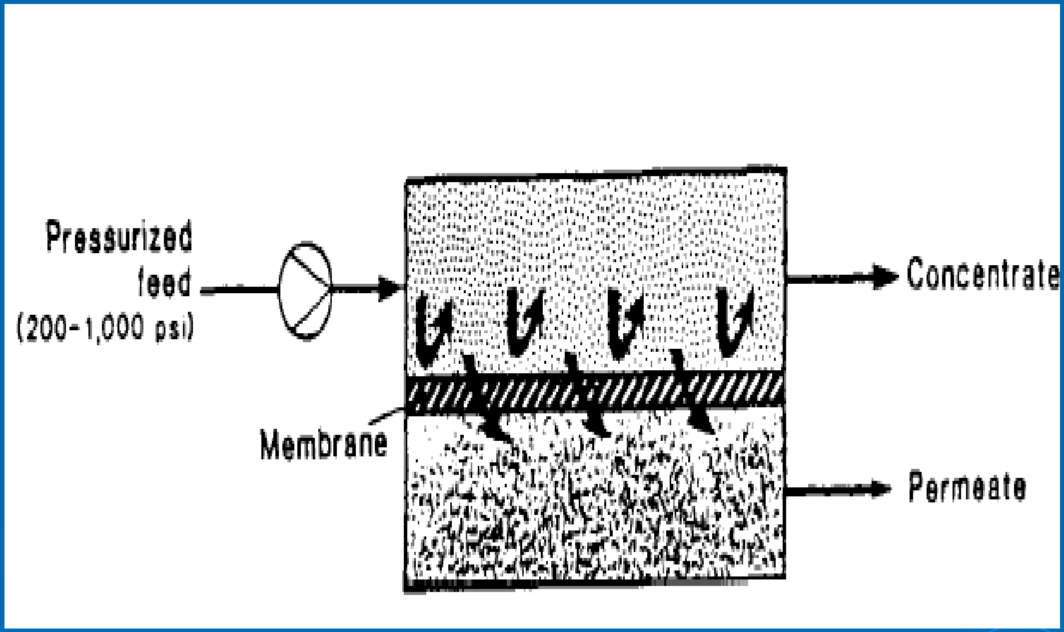
- Purity of water
- Economics
  - Energy efficiency
  - Production rate
- Regional factors
  - Resources vary from region to region
  - Proximity to ocean
  - Availability of fuel

Reverse Osmosis

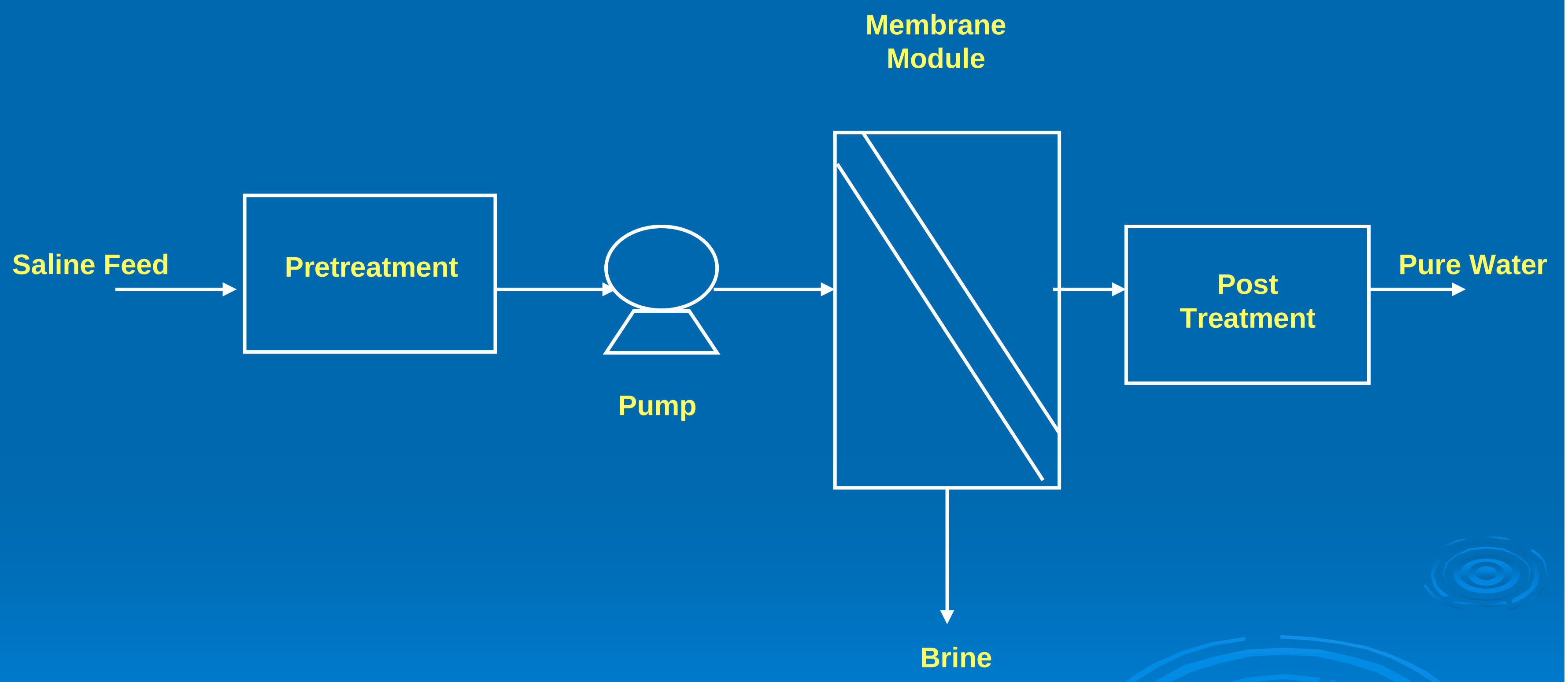
- Most common in the USA
- Solvent forced through membrane
- Energy consumption from pressure
- Susceptible to fouling, scaling and degradation

Process of Reverse Osmosis

- Pressurized feed
- Applied pressure > Osmotic pressure
- Semi-permeable membrane
- Incomplete salt removal (different rates)



Typical RO Plant



Problems

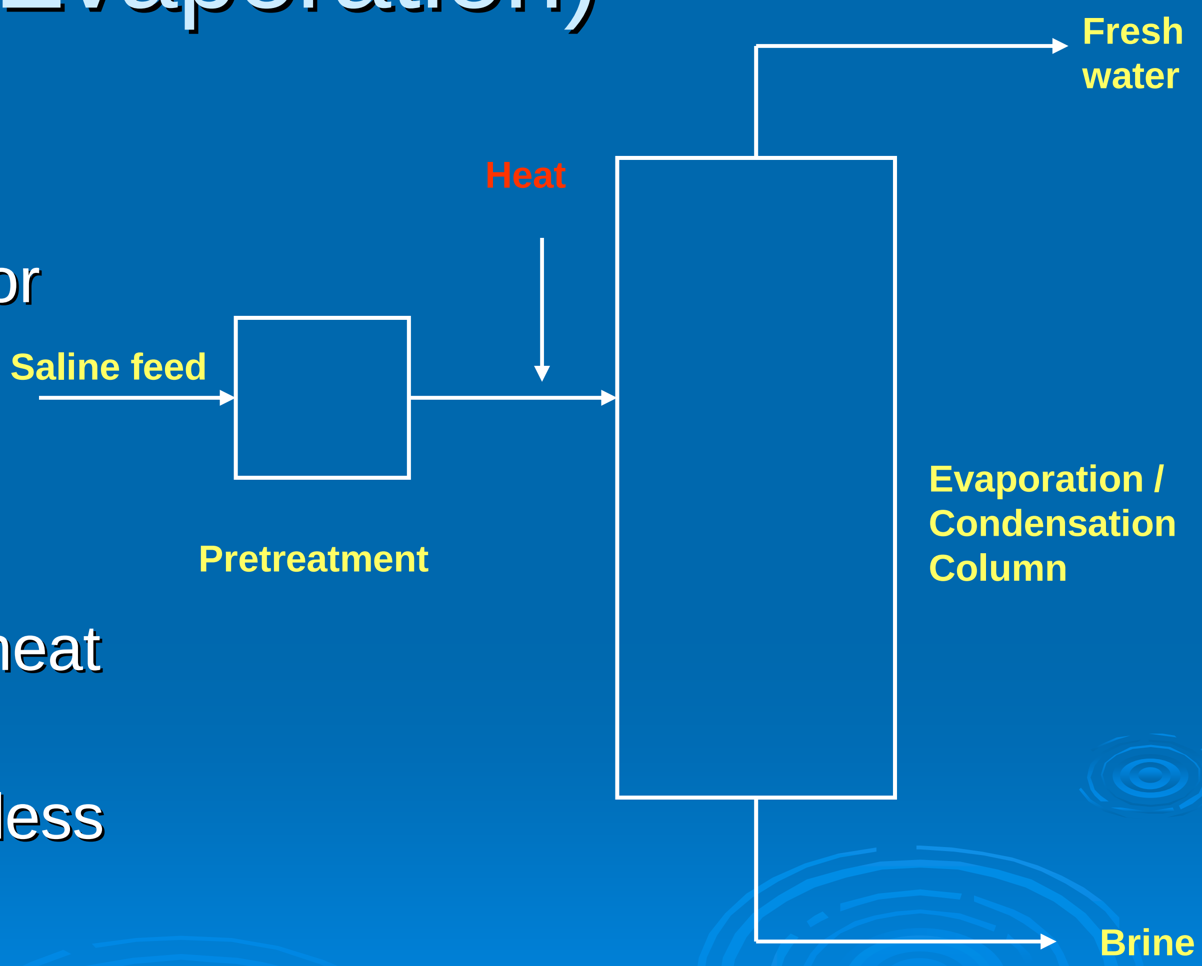
- Membrane fouling
  - Caused by micro organisms and particles
  - Reduce water quality
  - Add chemical e.g. chlorine
  - Ultra-filtration of suspended solids
- Scaling
  - Formation of salt precipitate e.g. $CaCO_3$
  - Reduces efficiency
  - Add anti-scalant e.g. H_2SO_4

RO Statistics

- Operating costs
  - 2.50 – 4.00 $/1000gal of product[2]
- Energy requirements
  - 26 KWh/1000gal of product[2]
- Capital cost for sea water desalination
  - 4.00 - 10.00 $/gal-day[2]

Thermal Process (Evaporation)

- Phase separation
- Heat saline water/condense vapor
- Reduce pressure
- Energy required for heat of vaporization
- Large energy costs, less common in USA

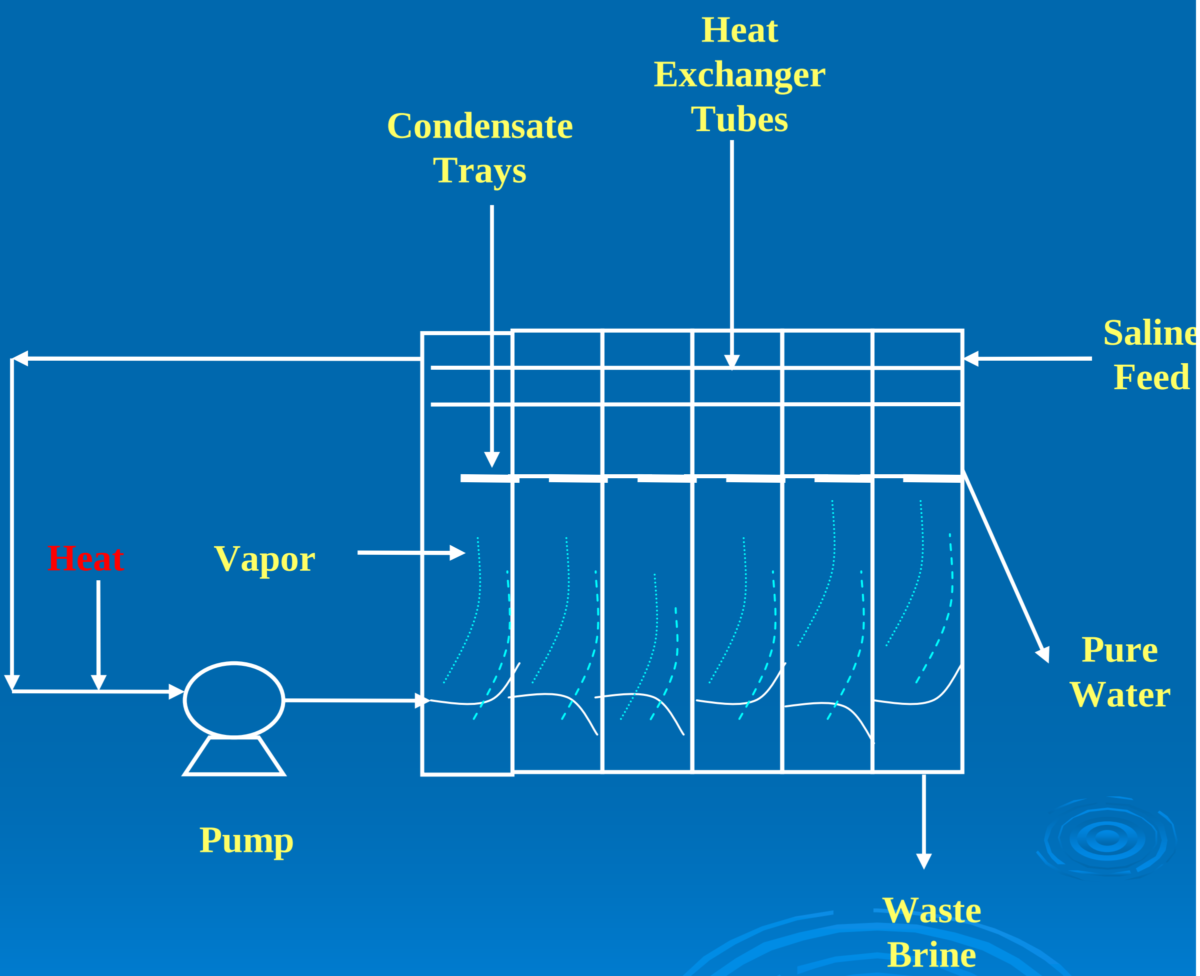


Multi Stage Flash Distillation

- 80% of world's thermal desalination product
- Energy needed for heat
- Recycles heat
- Two heat sources for incoming saline feed
  - External
  - Heat of vaporization

Schematic of MSF

- Additional heat
- Pressure released in first chamber
- Water boils quickly
- Evaporation and condensation



Problems

- Scale formation
  - Extra heat transfer layer
  - Reduces heat transferred
  - Reduces efficiency
- Erosion and Corrosion
  - Use stainless steel

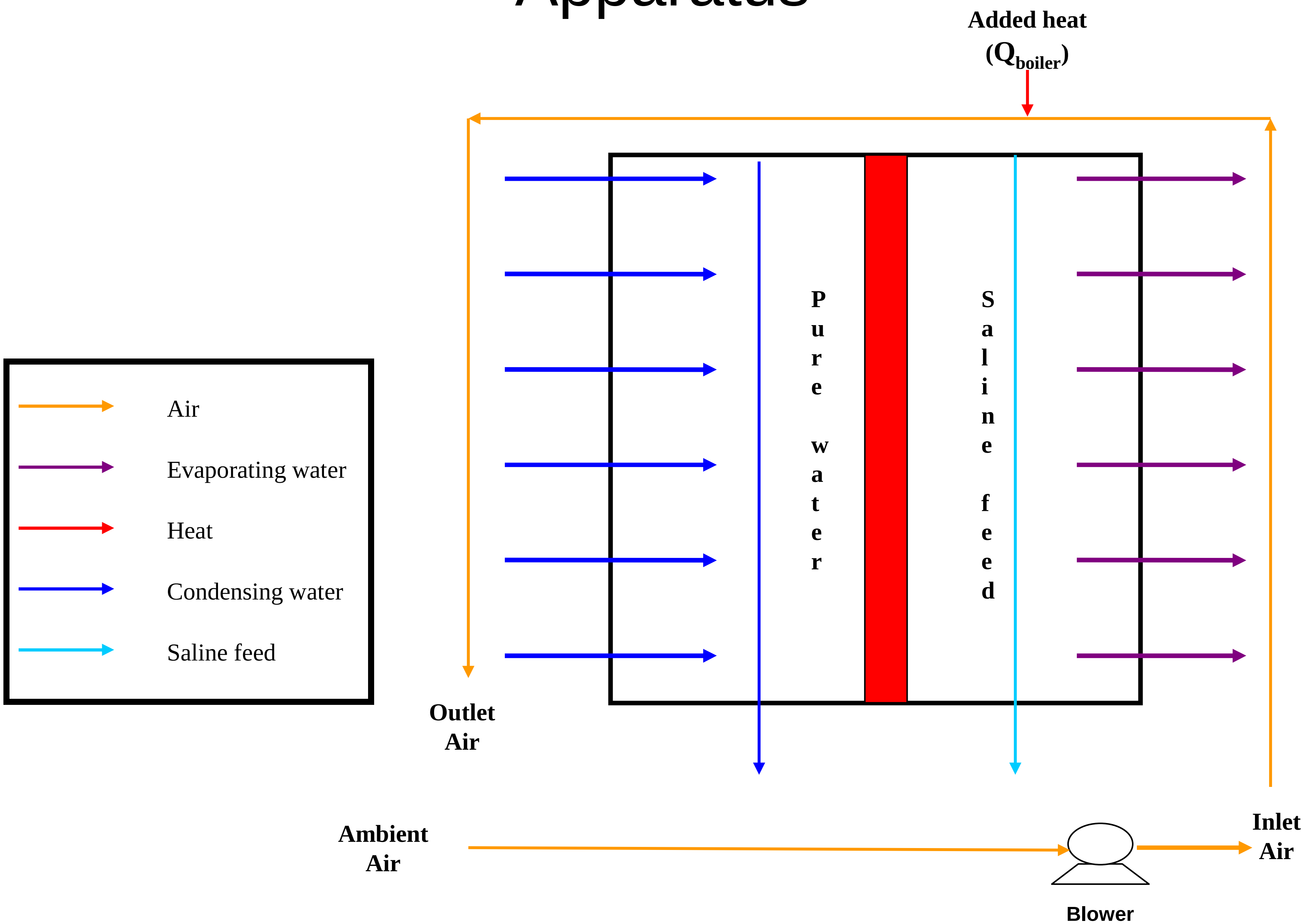
Evaporation Statistics

- Energy requirements
  - 56 KWh/1000gal of product[2]
- Costs are very high
  - Because of expensive energy, prices are in the range of $12 to $14 per 1000 gallons[5] in USA
  - Only economically feasible in regions like the Middle East, where fuel is cheap and water is scarce

Dewvaporation

- Developed by James Beckman
- Arizona State University
- Relies on air circulation
  - Air moves in a cycle
  - Works to recycle heat
- Waste heat
- Atmospheric pressure

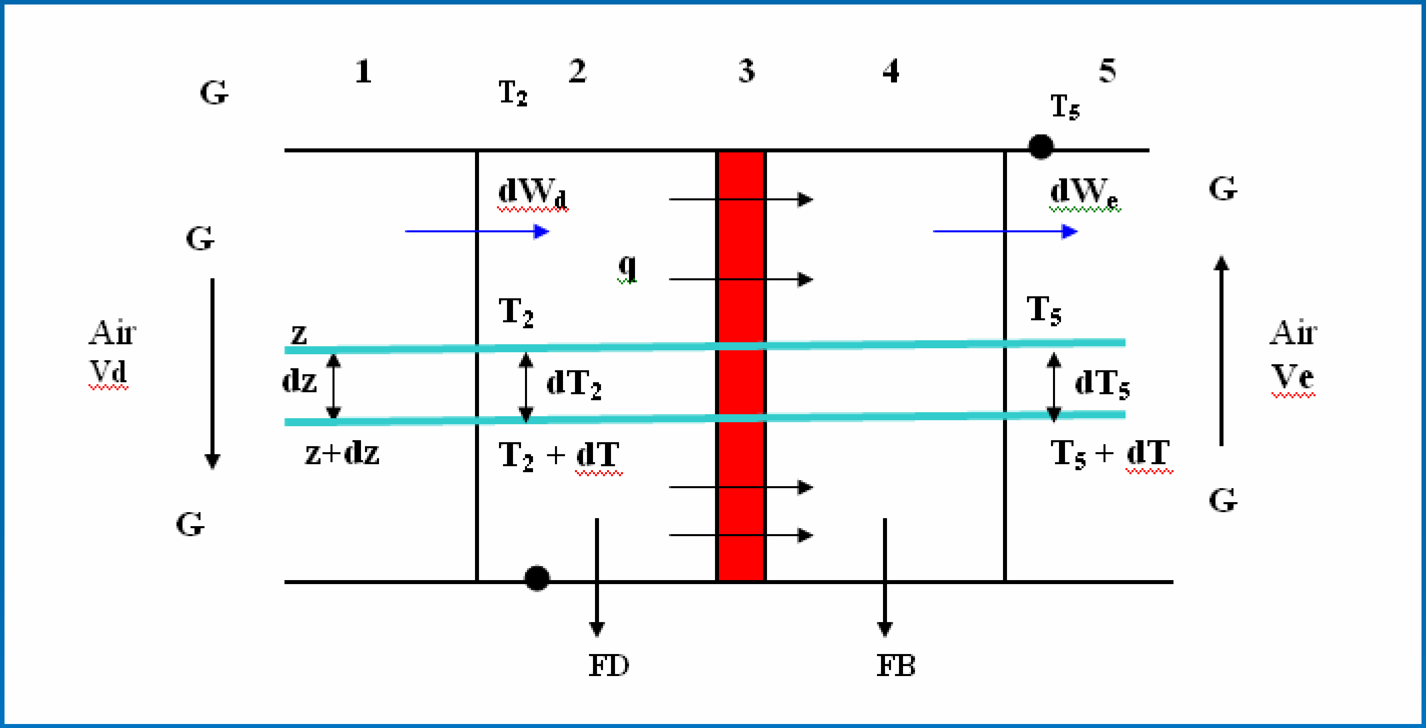
Dewvaporation Apparatus



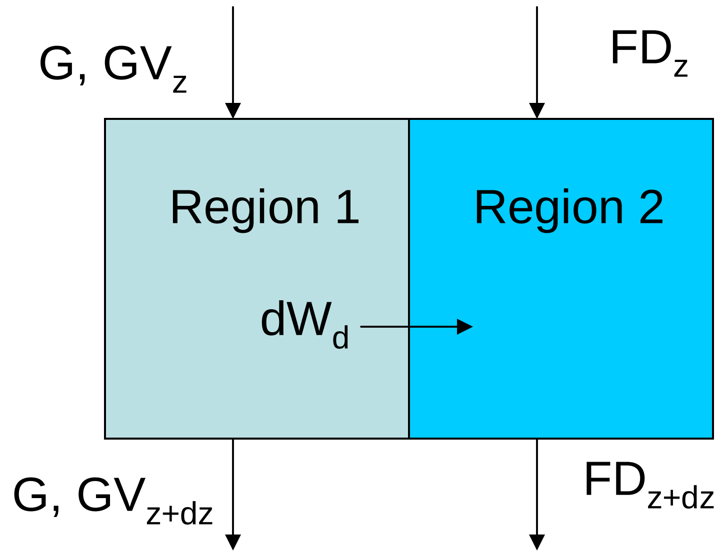
Economic Analysis

- The cost has two main components
- Operational costs associated with the heat added
  - Heat required to created a larger temperature difference from dew formation to evaporation side
- Cost associated with equipment
  - Modeled as a heat exchanger

Differential Analysis



Heat Transfer Model Region 1



Mass Balance:

$$GV_z = GV_{z+dz} + dW_d$$

Heat Balance:

$$Gh_a(T_1) + GVh_v(T_1) = Gh_a(T + dT_1) + GVh_V(T + dT_1) + \Delta h_{vap} dW_d + hL(T_1 - T_2)dz$$

Heat Transfer Model

Region	Mass balance	Heat balance
1	$GV_z = GV_{z+dz} + dW_d$	$Gh_a(T_1) + GVh_v(T_1) = Gh_a(T + dT_1) + GVh_v(T + dT_1) + \Delta h_{vap} dW_d + hL(T_1 - T_2)dz$
2	$FD_z + dW_d = FD_{z+dz}$	$FD_z h_w(T_2) + \Delta h_v dW_d + hL(T_1 - T_2)dz = FD_{z+dz} h_w(T_2 - dT_2) + q$
3	0	$q = UL(T_2 - T_4)dz$
4	$FB_z = FB_{z+dz} + dW_e$	$FB_z h_w(T_4) + q = FB_{z+dz} h_w(T - dT_4) + \Delta h_v dW_e + hL(T_4 - T_5)$
5	$GV_z = GV_{z+dz} + dW_e$	$Gh_a(T_5 + dT_5) + GVh_v(T_5 + dT_5) + \Delta h_{vap} dW_e + hL(T_4 - T_5)dz = Gh_a(T_5) + GVh_v(T_5)$

Deriving Differential Equations

Region 1

Mass balance

$$GV_Z = GV_{Z+D} + dW_d$$

$$dW_d = GV_z - GV_{z+dz} = GV - G(V_z + \frac{\partial V}{\partial T}\frac{\partial T}{\partial Z}\partial Z$$

$$dW_d = G\left.\frac{dV^s}{dT_1}\right)_{T1} dT_1$$

Heat balance

$$Gh_a(T_1) + GVh_v(T_1) = Gh_a(T - dT_1) + GVh_V(T - dT_1) + \Delta h_{vap} dW_d + hL(T_1 - T_2)dz$$

$$Gh_a(T_1) - Gh_a(T - dT_1) + GVh_v(T_1) - GVh_V(T - dT_1) = \Delta h_{vap} dW_d + hL(T_1 - T_2)dz$$

Deriving Differential Equations (Continued)

$$-GCp_{air1} - GV^{s}Cp_{v}dT_{1} = \Delta h_{vap}dW_{d} + hL(T_{1} - T_{2})dz$$

Substituting the equation for dW_d

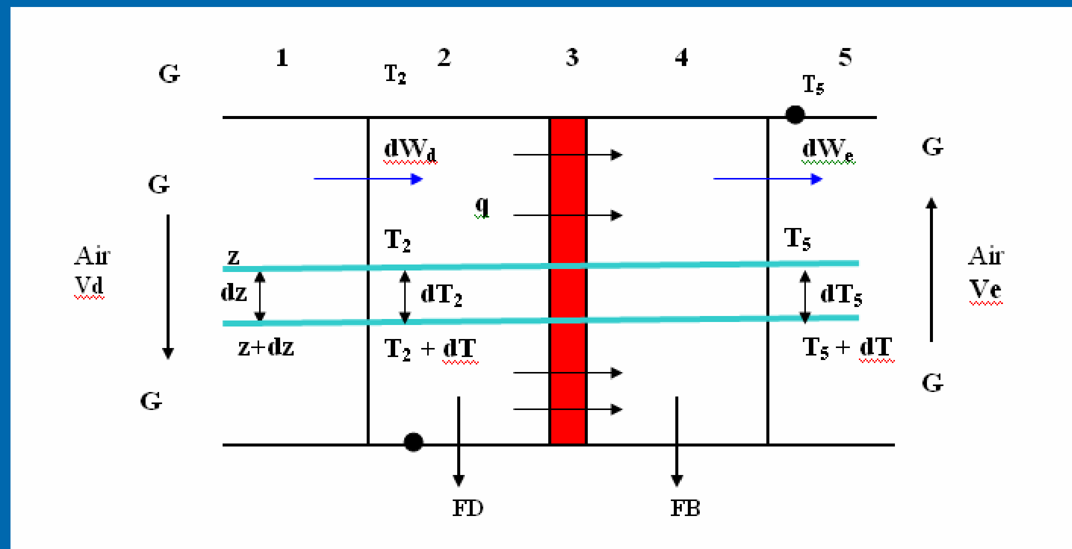
$$-(GCp_{air} + GV^{s}Cp_{v})dT_{1} = \Delta h_{vap}G\left.\frac{dV^{s}}{dT_{1}}\right)_{T1} dT_{1} + hL(T_{1} - T_{2})dz$$

$$dT_{1} = \frac{-hL(T_{1} - T_{2})dz}{(GCp_{air} + GV^{s}Cp_{v}) - \Delta h_{vap}G\frac{dV^{s}}{dT_{1}}}$$

Note that when: $V < V^{s}$, no condensation takes place and $dW_d = 0$.

$$dT_{1} = \frac{-hL(T_{1} - T_{2})dz}{GCp_{air} + GV^{s}Cp_{v}}$$

Equations Used



$$dT_1 = \frac{-hL(T_1 - T_2)dz}{GCp_{air} + GV^s Cp_v}$$

$$dW_d = G\frac{dV^s}{dT_1}\Bigg)_{T1} dT_1$$

$$dT_2 = \frac{dW_d(h_w(T_2 - dT_2) + \Delta h_{vap})}{FD_z Cp_w} + \left[\frac{UL(T_2 - T_4)}{FD_z Cp_w} - \frac{hL(T_1 - T_2)}{FD_z Cp_w}\right]dz$$

$$dT_3 = \frac{h_{45}L(T_4 - T_5)dz - h_{24}L(T_2 - T_4)dz + \Delta h_v dW_e - dW_e h_w(T + dT_3)}{FB_z Cp_w}$$

$$dT_5 = \frac{-hL(T_4 - T_5)dz}{GCp_{air} + GV^s Cp_v + \Delta h_{vap} G\frac{dV^s}{dT_5}}$$

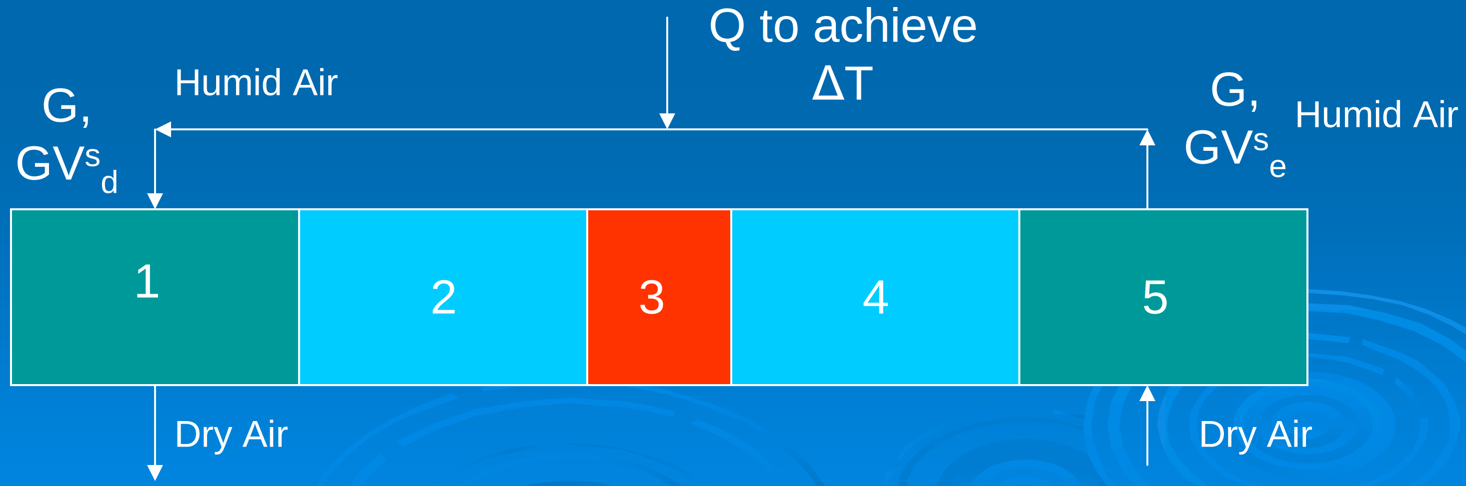
$$dW_e = G\frac{dV^s}{dT_5} dT_5$$

Solving Differential Equation in Spreadsheet

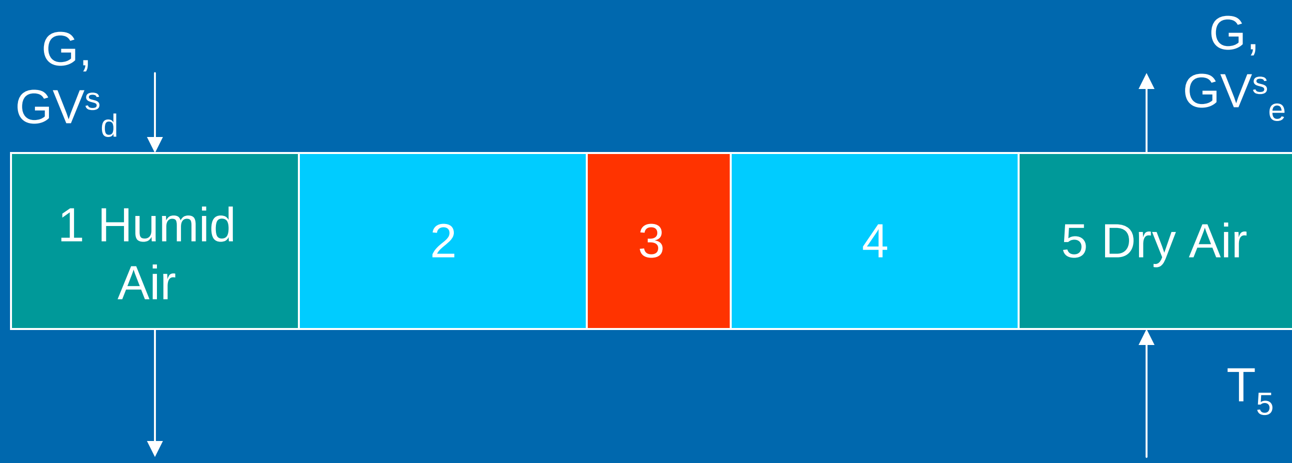
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1																	
2	C_{pair}	29.07	J/mol/k				Heat Transfer Coefficients						Region 1	Dewformation Air Stream			
3	$C_{pwater\ vapor}$	37.08	J/mol/K				h12	6.09E-05	$J/cm^2/s/K$	(from moheat book equation 19-25)			Region 2	Pure Water Stream			
4	C_{pwater}	74.54	J/mol/K				h14	6.09E-05	$J/cm^2/s/K$				Region 3	Wall			
5	Δh_{vap}	40600	J/mol				h24	0.000842	$J/cm^2/s/K$				Region 4	Seawater/Brine			
6	Δz	1	cm				h45	0.001191	$J/cm^2/s/K$				Region 5	Evaporation Air Stream			
7	L	100	cm														
8	G	4000	mol/h														
9	G	1.11	mol/s														
10	delT	10.00	C														
11	hw	1892.00	J/mol					FD final	1.821575	mol/s	Q	323	W	A	67100	cm^2	
12	FB top	7000.00	mol/h						6557.67	mol/hr		1162800	J/hour		6.71	m^2	
13	FB top	1.94	mol/s						31.2204	gal/hr							
14	FB top	33.32629	gal/hr						749.2895	gal/day							
15																	
16	z	T1	T2	T4	T5	dT1	dT2	dT4	dT5	dWd	dVs/dT1	dWe	dVs/dT5	Vsd	Vd	Vse	Ve
17	0	75.00		20	65	0.017529	0	-0.05136	-0.15134	1.82100668	0.0001382	-1.0348E-05	6.838E-05	0.001094	1.64	0.000585	1.6
18	1	74.98	75.00	19.94864	64.84866	-4.1E-06	0.06288	-0.00764	-0.15114	1.33309E-06	0.0001381	-1.02251E-05	6.765E-05	0.0010928	0.001094	0.000579	1.63999
19	2	74.98	74.94	19.94101	64.69752	0.010366	0.062873	-0.00752	-0.1508	1.43134E-06	0.0001381	-1.00938E-05	6.694E-05	0.0010928	0.0010928	0.000574	1.63998
20	3	74.97	74.87	19.93349	64.54672	0.010366	0.062815	-0.0074	-0.15045	1.43022E-06	0.000138	-9.96429E-06	6.623E-05	0.0010921	0.0010915	0.000569	1.63997
21	4	74.96	74.81	19.92609	64.39626	0.010365	0.062756	-0.00728	-0.15011	1.4291E-06	0.0001379	-9.83652E-06	6.553E-05	0.0010914	0.0010902	0.000563	1.63996
22	5	74.95	74.75	19.91881	64.24616	0.010365	0.062697	-0.00716	-0.14976	1.42798E-06	0.0001378	-9.71048E-06	6.484E-05	0.0010907	0.0010889	0.000558	1.63995
23	6	74.94	74.69	19.91166	64.0964	0.010364	0.062638	-0.00704	-0.14941	1.42686E-06	0.0001377	-9.58613E-06	6.416E-05	0.00109	0.0010876	0.000553	1.63994
24	7	74.93	74.62	19.90461	63.947	0.010364	0.062578	-0.00692	-0.14905	1.42573E-06	0.0001376	-9.46346E-06	6.349E-05	0.0010892	0.0010864	0.000548	1.63993
25	8	74.92	74.56	19.89769	63.79795	0.010363	0.062519	-0.00681	-0.1487	1.4246E-06	0.0001375	-9.34245E-06	6.283E-05	0.0010885	0.0010851	0.000543	1.63992
26	9	74.91	74.50	19.89088	63.64925	0.010362	0.06246	-0.00669	-0.14834	1.42347E-06	0.0001374	-9.22307E-06	6.217E-05	0.0010878	0.0010838	0.000538	1.6399
27	10	74.90	74.44	19.88419	63.5009	0.010362	0.062401	-0.00658	-0.14799	1.42234E-06	0.0001373	-9.10532E-06	6.153E-05	0.0010871	0.0010825	0.000533	1.63991
28	11	74.89	74.37	19.87762	63.35291	0.010361	0.062341	-0.00646	-0.14763	1.42121E-06	0.0001372	-8.98915E-06	6.089E-05	0.0010864	0.0010812	0.000528	1.63990
29	12	74.88	74.31	19.87116	63.20529	0.01036	0.062282	-0.00635	-0.14727	1.42007E-06	0.0001371	-8.87456E-06	6.026E-05	0.0010857	0.00108	0.000523	1.63989
30	13	74.87	74.25	19.86481	63.05802	0.010359	0.062222	-0.00623	-0.14691	1.41894E-06	0.000137	-8.76152E-06	5.964E-05	0.001085	0.0010787	0.000518	1.63988
31	14	74.86	74.19	19.85858	62.91111	0.010359	0.062163	-0.00612	-0.14655	1.4178E-06	0.0001369	-8.65002E-06	5.903E-05	0.0010843	0.0010774	0.000513	1.6398
32	15	74.85	74.12	19.85246	62.76456	0.010358	0.062103	-0.00601	-0.14618	1.41666E-06	0.0001368	-8.54003E-06	5.842E-05	0.0010836	0.0010761	0.000509	1.63987
33	16	74.84	74.06	19.84645	62.61837	0.010357	0.062043	-0.0059	-0.14582	1.41551E-06	0.0001367	-8.43154E-06	5.782E-05	0.0010829	0.0010748	0.000504	1.63986
34	17	74.83	74.00	19.84055	62.47255	0.010356	0.061984	-0.00579	-0.14546	1.41437E-06	0.0001366	-8.32451E-06	5.723E-05	0.0010822	0.0010736	0.000499	1.63985
35	18	74.82	73.94	19.83477	62.3271	0.010355	0.061924	-0.00568	-0.14509	1.41322E-06	0.0001365	-8.21895E-06	5.665E-05	0.0010815	0.0010723	0.000495	1.63984
36	19	74.81	73.88	19.82909	62.18201	0.010355	0.061864	-0.00557	-0.14472	1.41207E-06	0.0001364	-8.11482E-06	5.607E-05	0.0010808	0.001071	0.00049	1.63984
37	20	74.80	73.81	19.82353	62.03729	0.010354	0.061804	-0.00546	-0.14435	1.41092E-06	0.0001363	-8.01211E-06	5.55E-05	0.0010801	0.0010698	0.000486	1.63983
38	21	74.79	73.75	19.81807	61.89293	0.010353	0.061744	-0.00535	-0.14398	1.40977E-06	0.0001362	-7.91079E-06	5.494E-05	0.0010794	0.0010685	0.000482	1.63982
39	22	74.78	73.69	19.81272	61.74895	0.010352	0.061684	-0.00524	-0.14361	1.40861E-06	0.0001361	-7.81086E-06	5.439E-05	0.0010787	0.0010672	0.000477	1.6398
40	23	74.76	73.63	19.80748	61.60534	0.010351	0.061623	-0.00513	-0.14324	1.40746E-06	0.000136	-7.71229E-06	5.384E-05	0.001078	0.0010659	0.000473	1.63981
41	24	74.75	73.57	19.80235	61.4621	0.01035	0.061563	-0.00503	-0.14287	1.4063E-06	0.0001359	-7.61506E-06	5.33E-05	0.0010773	0.0010647	0.000469	1.63980
42	25	74.74	73.51	19.79732	61.31923	0.010349	0.061503	-0.00492	-0.1425	1.40514E-06	0.0001358	-7.51915E-06	5.277E-05	0.0010766	0.0010634	0.000465	1.63979

Heating the Air

- Heat needs to be added to achieve a temperature difference from dewvaporation to evaporation side
  - Can be added as steam
  - Adding steam keeps air saturated
- This made ΔT and G of the air stream above the tower design parameters

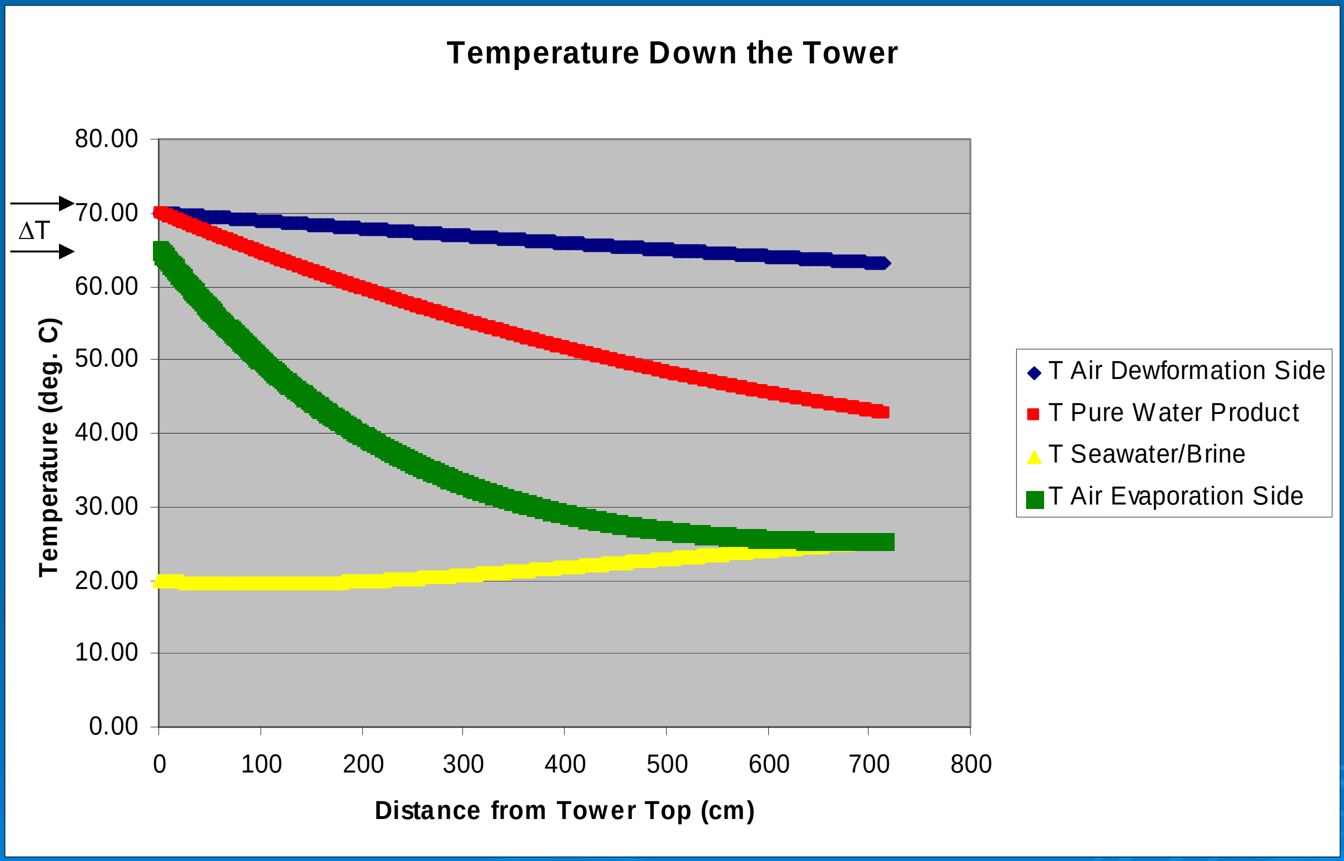


Results of Model



- Model considered credible if temperature profile was appropriate
  - Temperature of evaporation side air had to reach ambient air temperature (25ºC) at bottom of column
- Air flow rate (G) had the most dramatic effect on product flow and heating requirements

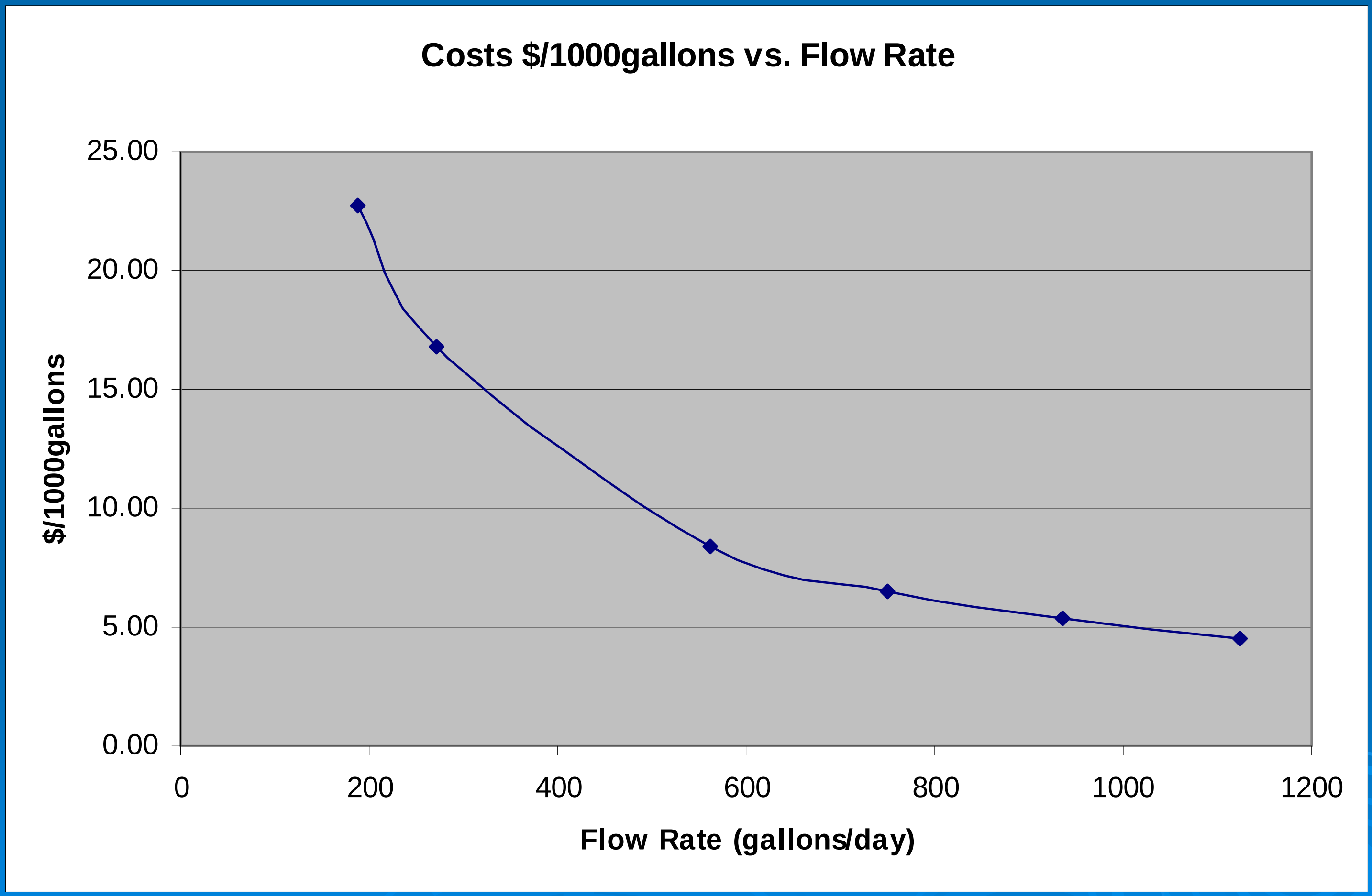
Temperature Profile



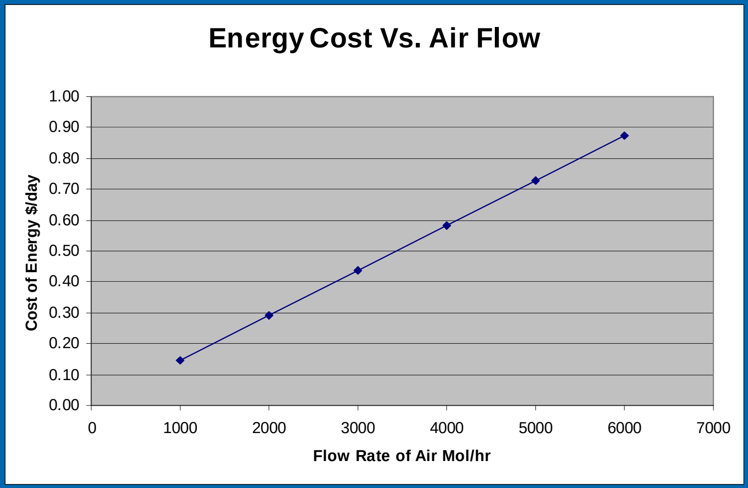
Equipment Cost and Energy Cost Calculations

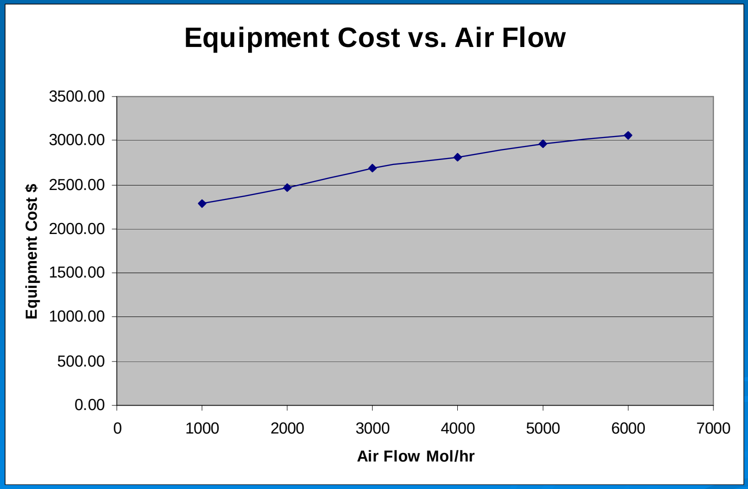
Design	G mol/h	Qboiler J/hour	FD gal/day	FB gal/day	FAC $	Operating Cost $/1000gallons
1	1000	290700	187.85	954.77	$1,557.14	$5.86
2	2000	581400	272.06	870.56	$1,665.91	$4.27
3	3000	872100	562.05	580.56	$1,725.26	$1.81
4	4000	1162800	749.33	393.29	$1,773.35	$1.30
5	5000	1453500	936.60	206.01	$1,830.24	$1.00
6	6000	1744200	1123.76	18.85	$1,867.10	$0.79

Cost $/1000gallons



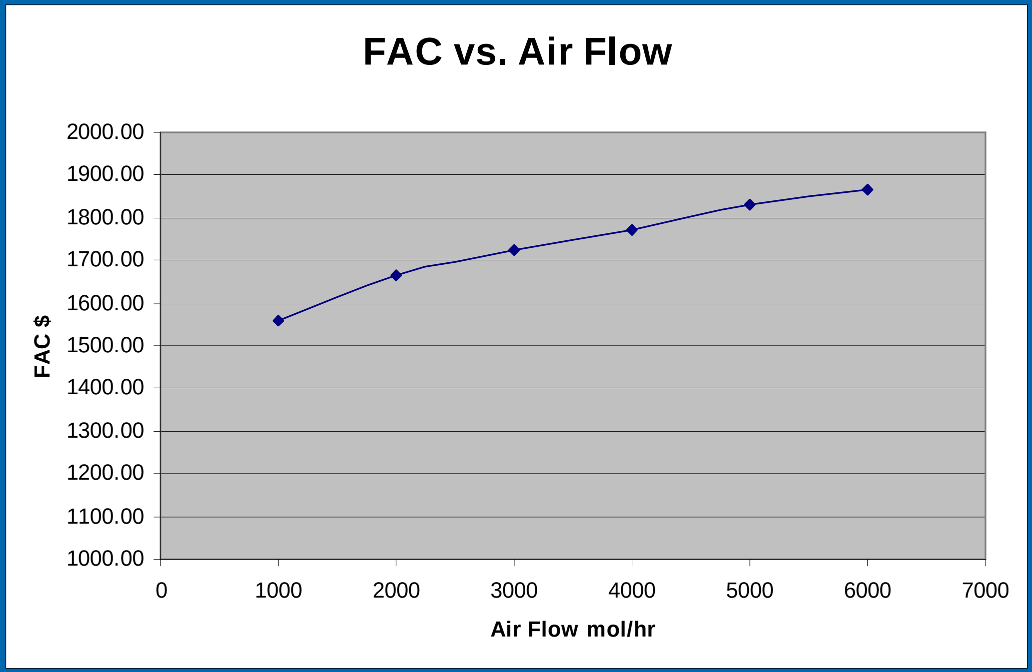
Equipment Cost and Energy Cost vs. Air Flow





- Energy cost goes up sharply
  - More air to heat
- Equipment cost increases
  - More expensive blower
  - Slightly higher tower

Fixed Annualized Cost



- 10 years of operation
- Production of 200 to 1200 gal/day

Conclusions

- Dewvaporation is on the low end of costs for current desalination technologies
  - Flow rates similar to Beckman's had similar costs
  - This is in the $1.70 to $3.70/1000gallon range
- Most effective in places like Arizona where the air is dry