Evaporation Problems

Question 1: Mass and energy balances on a single stage evaporator.

A 10wt% aqueous lactic acid solution (470 kg/hr) at 36°C is concentrated to 30wt% solution in a steam heated evaporator. Solvent vapour (steam) and concentrated solution leave the evaporator at 46°C and 10 kPa absolute. The steam heat source is at -61 kPa gauge. Assume c_p liq = 4 kJ/(kg.K).

(a) Calculate the amount of concentrated lactic acid produced, the amount of solvent (steam) vaporised and the amount of heat supplied in the evaporator heat exchanger.

(b) What size heat exchanger would be required if the overall heat transfer coefficient is 2000 W/(m^2.K) ?

(c) How much -61 kPa gauge steam was consumed to provide the necessary heat? What is the energy efficiency and steam economy?

(d) How much heat must be removed to condense the solvent vapour produced at 10 kPa ? How much 25°C water would need to be injected into a direct contact heat exchanger (at 10 kPa absolute) to condense the steam ?

Question 2: Mass and energy balances on a single stage evaporator.

A 50 m^2 heat exchanger is currently used in an evaporator to concentrate 0.72 kg/s of waste slurry from 20 wt% to 50wt% solids. The feed enters at its boiling point of 80°C and is heated with 20 kPa gauge steam .

(a) Calculate the amount of concentrated waste produced, the amount of steam vaporised and the amount of heat supplied in the evaporator heat exchanger. What is the overall heat transfer coefficient of the heat exchanger ?

(b) It is desired to process 20% more feed. What will be the new outlet solids concentration if the pressures are unchanged ? What pressure steam would be required to keep the outlet solids concentration at 50wt% ?

Question 3: Evaporator selection

What evaporator components would you consider using for the following tasks and why?

(a) Concentrating a low viscosity, corrosive salt solution to give a crystalline product.
(b) Concentrating a fruit juice.
(c) Concentrating a non-corrosive, non-heat sensitive liquid solution.
(d) Concentrating a corrosive liquid solution inside a building with a low ceiling.

Boiling point elevation: Iterative Solution Procedure (for calculating solution temperature from solute conc)

Step 1 Determine the pure component boiling point

Step 2 Assume a boiling point rise

Step 3 Calculate the solution temperature

Step 4 Use the chart to obtain the boiling point rise for that solution temperature

Step 5 Compare the assumed boiling point rise with that obtained from the graph. If not the same assume a new boiling point rise and return to step 3

Question 4: Using the chart and steam tables (not iterative)

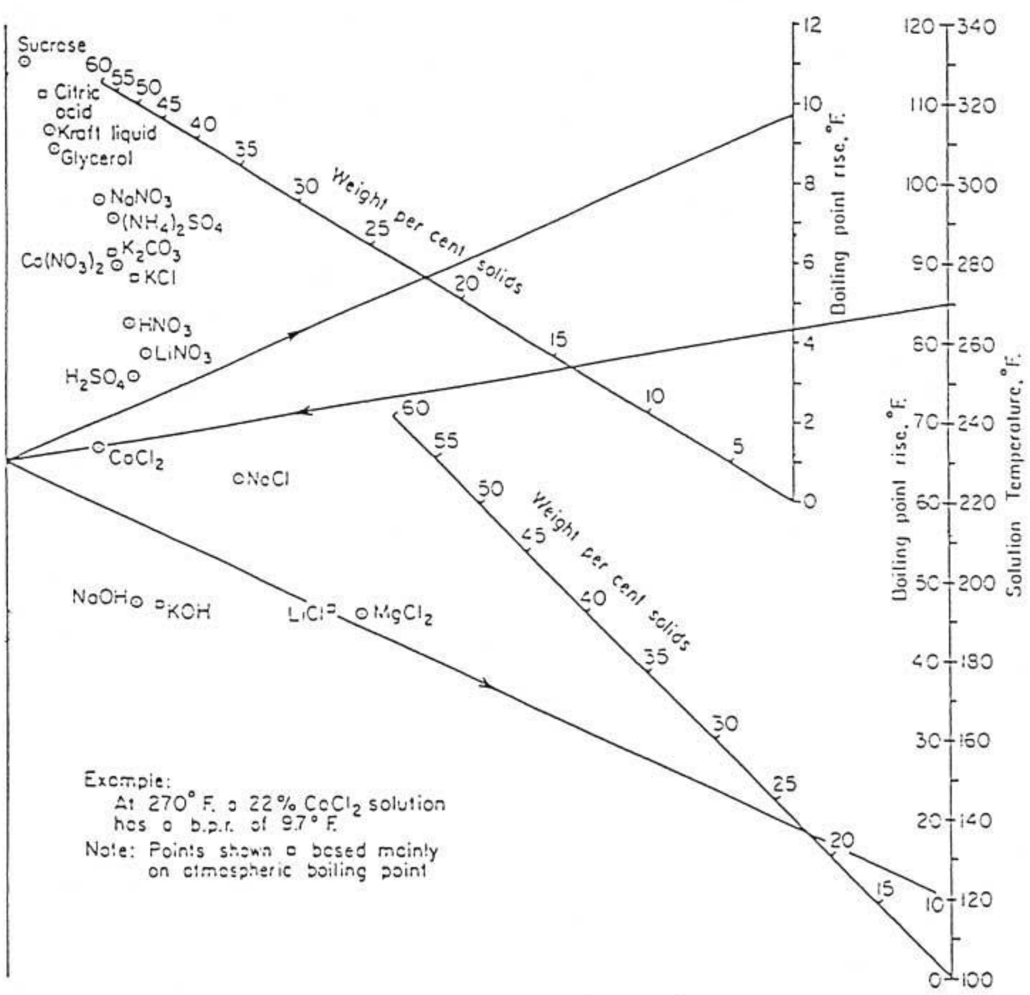
(a) What concentration of NaCl is required to give a boiling point rise of 9°F at atmospheric pressure ?

(b) What will be
- The solution temperature?
- The vapour enthalpy (c_{pg} = 1.88 kJ/kg°C)?
- The liquid enthalpy assuming that the specific heat of the salt solution is 4 kJ/kg°C?

Question 5: Using the chart and steam tables (iterative).

(a) What is the solution boiling point of 40wt% LiCl solution at 50 kPa absolute.

(b) What will be
- The boiling point rise?
- The vapour enthalpy (c_{pg} = 1.88 kJ/kg°C)?
- The liquid enthalpy assuming that the specific heat of the salt solution is 3.5 kJ/kg°C?



Boiling-point rise of aqueous solutions. $\quad {}^{\circ}C = \frac{5}{9}({}^{\circ}F - 32)$

During chart

Conversion factor:

Absolute temperature $\quad {}^{o}F = ({}^{o}C \times 1.8) + 32$

$${}^{o}C = \frac{({}^{o}F - 32)}{1.8}$$

Temperature interval ($\Delta\theta$) $\quad 1^{o}C = 1.8^{o}F$ and $\quad 1^{o}F = 0.555^{o}C$

Multi-stage evaporator - General Solution Procedure

Step 1 Solve equations mass balance equations to determine the amount of water evaporated $(m_{V1} + m_{V2} + m_{V3})$ and the missing solution flow rate or composition.

Step 2 Determine the steam heat source temperature (θ_s) and allowable last stage condensate temperature and pressure.

Step 3 Determine the boiling point elevation in the last stage and hence determine the last stage solution temperature (θ_3)

Step 3 Determine the temperature difference across the heat exchanger for each stage

Step 5 Determine the amount of water evaporated in each stage

Step 6 Determine the area of the heat exchanger

Question 6: Three stage feed forward evaporator

10 kg/s of 2 wt% NaCl is being concentrated to 20wt% NaCl in a three effect feed forward evaporator. Steam is available at 150 kPa abs and a vacuum of 500 mmHg (below atmospheric) is being pulled by the vacuum pump. The overall heat transfer coefficients for the first, second and third heat exchangers are 1000 W/m^{2}K, 900 W/m^{2}K and 800 W/m^{2}K respectively and the area of the three heat exchangers are identical.

(a) Determine the size of the heat exchangers.

(b) What increase in production would be expected if the steam pressure was increased to 200kPa.a?

Question 7: Three stage feed forward evaporator

A 5 wt% citric acid solution is concentrated in a triple effect feed forward evaporator to 60 wt% using steam at 20 kPa gauge. 10 kg/s of cooling water at 20°C is injected into the final stage condenser of operating at 10 kPa absolute.

(a) Calculate the amount of water evaporated in the final stage and hence the production rate of 60wt% citric acid.

(b) Both the overall heat transfer coefficient and the temperature difference across each heat exchanger is identical. Determine the size of each heat exchanger if the overall heat transfer coefficient is 1000 W/m^{2}K.

Question 8.

(a) Using a diagram, identify the major characteristics of a forced circulation evaporator utilising an external heat exchanger and comment on the types of products that this type of evaporator is well suited for.

(b) A seasoned meat broth is concentrated in a single stage vacuum evaporator to a final concentration of 25 wt % solids. The feed flowrate is 8,333 $l.h^{-1}$ and it has a density of 1040 $kg.m^{3}$ The feed concentration is 4 wt % solids and the area available for heat transfer is 68 m^2 . The average specific heat capacity across the concentration range is estimated to be 3,800 $J.kg^{-1}\cdot.K^{-1}$. The feed material enters preheated to 70°C. The evaporation pressure is 50 kPa.a and the evaporator is heated by steam which enters at 200 kPa.a. The boiling point elevation is proportional to the concentration:

$\Delta\theta_{BPR} = 0.25x$ where $\Delta\theta_{BPR}$ is in °C, x is

w/w Calculate:

(i) The product and vapour flowrates.
(ii) The boiling temperature of the mixture at its exit concentration and the enthalpy of the vapour produced (note C_{pg} = 1.88 $kJ.kg^{-1}.K^{-1}$).
(iii) The heat flow that must be supplied by the condensing steam and the required mass flowrate of steam.
(iv) The required overall heat transfer coefficient and the steam economy for the system.

Question 9

A three effect feed forward evaporator is used to concentrate a protein solution from 0.08 kg protein $(kg\ total)^{-1}$ to 0.45 kg protein $(kg\ total)^{-1}$ prior to spray-drying. The feed enters the first stage at 5,000 kg h^{-1} preheated to its boiling point. The boiling point elevation is negligible. The heat transfer areas are the same and the overall heat transfer in the first stage is estimated to be 3,000 W m^{-2} K^{-1}. The first effect is heated by steam which enters at a pressure of 80 kPa (absolute). The stages operate at evaporation pressures of 60, 50, 40 kPa (absolute) respectively. The vapour from the final stage is condensed at 40 kPa by using water at 10 ºC. A direct contact heat exchanger is used.

(a) Calculate the final product flow rate (kg h^{-1}), total vapour flow rate (kg h^{-1}) and the exact vapour flow (kg h^{-1}) off each stage.

(b) Calculate the steam flow rate (kg h^{-1}) and area (m^2) required in the first stage.

(c) Calculate the overall heat transfer coefficient (W m^{-2} $^oC^{-1}$) implied for each of the second and third stages.

(d) Calculate the amount of water (kg h^{-1}) that has to be injected in the direct contact heat exchanger to condense all the vapour.

Question 10

(i) In an effort to move towards zero discharge operation it is proposed to recover a NaOH solution that has been used for cleaning operations in a fermentation plant. The cleaning solution is recovered at a concentration of 0.5 % w/v and must be concentrated to 15 % w/v prior to reuse. The feed can be preheated to its boiling point using waste heat from elsewhere in the factory. The initial volume of recovered cleaning solution is 20 m^3 and this must be concentrated within 16 hours.

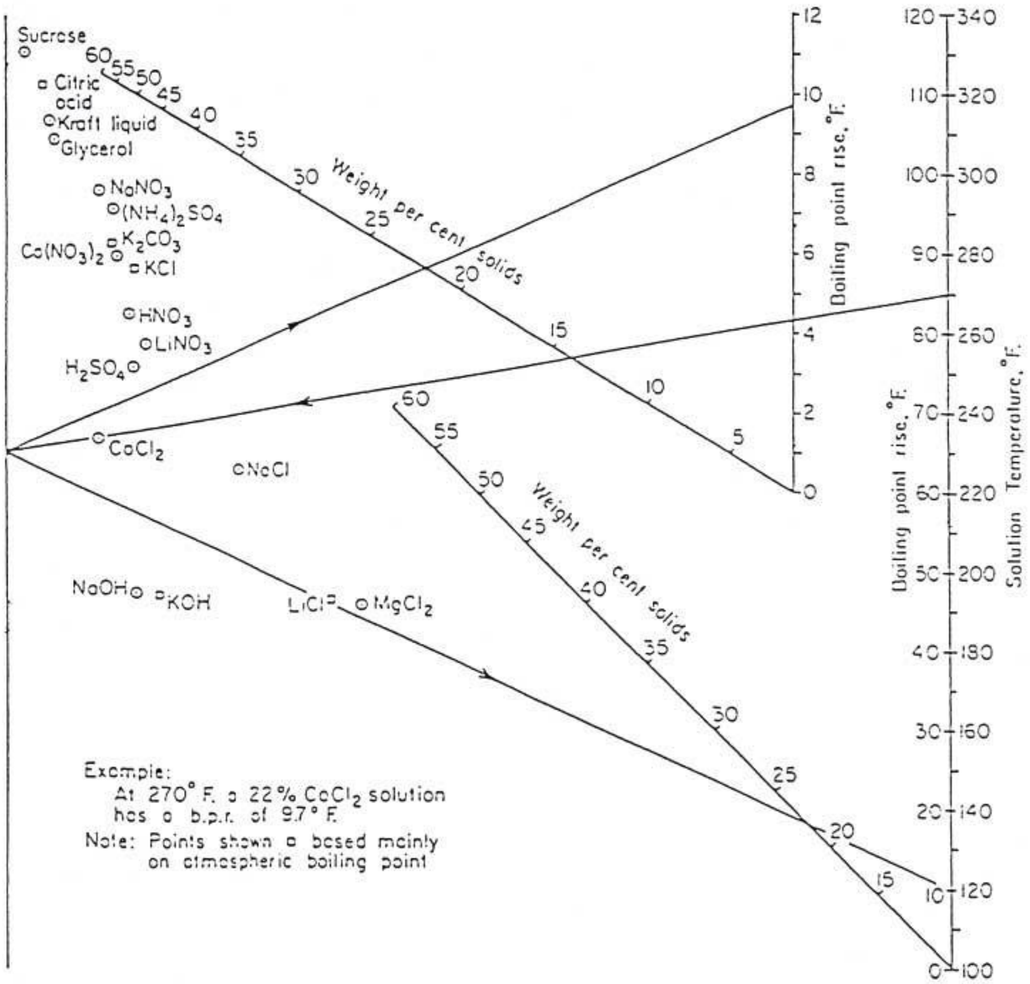
A single effect evaporator is being considered for this duty. The evaporator has a heat transfer area of 20 m^2 and was previously used to concentrate thin stillage, a waste stream with a tendency to be fouling. In this prior duty, 1500 kg.h^{-1} of vapour was evaporated at 100°C using dry steam supplied at 100 kPa.g. The feed (cp = 4200 J.kg^{-1}.°C^{-1}) was supplied to the evaporator at 60°C and boiling point elevation was negligible.

(a) Calculate the overall heat transfer coefficient (OHTC) for the prior evaporator application.

(b) Assuming the OHTC can be maintained at the same value, can the existing evaporator be used to process the recovered NaOH solution in the maximum time allowed using the existing steam supply? **Note that boiling point elevation cannot be considered negligible for the NaOH solution.** Show all calculations used to arrive at your answer and clearly state any assumptions made.

(c) What was the thermal efficiency of the evaporator in the thin stillage concentration system if the initial and final solids concentrations were 10 and 20% w/v, respectively?

(ii) Briefly describe what type(s) of evaporator you would expect to be used for these duties and explain which characteristics would be important to the success of both the prior and proposed duties.



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3 Saturated Data

P	θ_{sat}	v_l	v_v	u_l	u_v	h_l	$\Delta(h_{vap})$	h_v	s_l	s_v
MPa	°C	m^3/Mg		kJ/kg		kJ/kg			kJ/(kgK)	
0.0010	6.970	1.000	129178	29.30	2384	29.30	2484	2514	0.106	8.975
0.0015	13.02	1.001	87959	54.68	2393	54.68	2470	2525	0.196	8.827
0.0020	17.49	1.001	66987	73.43	2399	73.43	2459	2533	0.261	8.723
0.0025	21.08	1.002	54240	88.42	2404	88.42	2451	2539	0.312	8.642
0.0030	24.08	1.003	45653	101.0	2408	101.0	2444	2545	0.354	8.576
0.0035	26.67	1.003	39466	111.8	2411	111.8	2438	2550	0.391	8.521
0.0040	28.96	1.004	34791	121.4	2415	121.4	2432	2554	0.422	8.473
0.0045	31.01	1.005	31131	130.0	2417	130.0	2427	2557	0.451	8.431
0.0050	32.87	1.005	28185	137.7	2420	137.7	2423	2561	0.476	8.394
0.0060	36.16	1.006	23733	151.5	2424	151.5	2415	2567	0.521	8.329
0.0070	39.00	1.008	20524	163.3	2428	163.4	2408	2572	0.559	8.274
0.0080	41.51	1.008	18099	173.8	2431	173.8	2402	2576	0.592	8.227
0.0090	43.76	1.009	16199	183.2	2434	183.3	2397	2580	0.622	8.186
0.010	45.81	1.010	14670	191.8	2437	191.8	2392	2584	0.649	8.149
0.011	47.68	1.011	13412	199.6	2440	199.7	2388	2587	0.674	8.115
0.012	49.42	1.012	12358	206.9	2442	206.9	2383	2590	0.696	8.085
0.013	51.03	1.013	11462	213.7	2444	213.7	2379	2593	0.717	8.057
0.014	52.55	1.013	10691	220.0	2446	220.0	2376	2596	0.737	8.031
0.015	53.97	1.014	10020	225.9	2448	225.9	2372	2598	0.755	8.007
0.016	55.31	1.015	9431	231.5	2450	231.6	2369	2601	0.772	7.985
0.018	57.80	1.016	8443	241.9	2453	242.0	2363	2605	0.804	7.944
0.020	60.06	1.017	7648	251.4	2456	251.4	2358	2609	0.832	7.907
0.022	62.13	1.018	6994	260.1	2459	260.1	2352	2613	0.858	7.874
0.024	64.05	1.019	6445	268.1	2461	268.2	2348	2616	0.882	7.844
0.025	64.96	1.020	6203	271.9	2462	272.0	2345	2617	0.893	7.830
0.030	69.10	1.022	5228	289.2	2468	289.3	2335	2625	0.944	7.767
0.035	72.68	1.024	4525	304.3	2472	304.3	2326	2631	0.988	7.715
0.040	75.86	1.026	3993	317.6	2476	317.6	2318	2636	1.026	7.669
0.045	78.71	1.028	3576	329.6	2480	329.6	2311	2641	1.060	7.629
0.050	81.32	1.030	3240	340.5	2483	340.5	2305	2645	1.091	7.593
0.055	83.71	1.032	2963	350.5	2486	350.6	2299	2649	1.119	7.561
0.060	85.93	1.033	2732	359.8	2489	359.9	2293	2653	1.145	7.531
0.065	87.99	1.035	2535	368.5	2492	368.6	2288	2656	1.170	7.504
0.070	89.93	1.036	2365	376.7	2494	376.8	2283	2659	1.192	7.479
0.075	91.76	1.037	2217	384.4	2496	384.4	2278	2662	1.213	7.456
0.080	93.49	1.039	2087	391.6	2498	391.7	2273	2665	1.233	7.434
0.085	95.13	1.040	1972	398.5	2500	398.6	2269	2668	1.252	7.414
0.090	96.69	1.041	1869	405.1	2502	405.2	2265	2670	1.270	7.394
0.095	98.18	1.042	1777	411.4	2504	411.5	2261	2673	1.287	7.376
0.100	99.61	1.043	1694	417.4	2506	417.5	2257	2675	1.303	7.359
0.120	104.8	1.047	1428	439.2	2512	439.4	2244	2683	1.361	7.298
0.140	109.3	1.051	1237	458.3	2517	458.4	2232	2690	1.411	7.246
0.160	113.3	1.054	1091	475.2	2521	475.4	2221	2696	1.455	7.201
0.180	116.9	1.058	977.5	490.5	2525	490.7	2211	2701	1.494	7.162
0.200	120.2	1.061	885.7	504.5	2529	504.7	2202	2706	1.530	7.127
0.220	123.2	1.063	810.1	517.4	2532	517.6	2193	2711	1.563	7.095
0.240	126.1	1.066	746.7	529.4	2535	529.6	2185	2715	1.593	7.066
0.260	128.7	1.068	692.7	540.6	2538	540.9	2177	2718	1.621	7.039
0.280	131.2	1.071	646.2	551.1	2541	551.4	2170	2722	1.647	7.015
0.300	133.5	1.073	605.8	561.1	2543	561.4	2163	2725	1.672	6.992
0.320	135.7	1.075	570.2	570.6	2545	570.9	2157	2728	1.695	6.970
0.340	137.8	1.078	538.6	579.5	2547	579.9	2151	2731	1.717	6.950
0.360	139.8	1.080	510.5	588.1	2549	588.5	2145	2733	1.738	6.931
0.380	141.8	1.082	485.2	596.3	2551	596.8	2139	2736	1.758	6.913
0.400	143.6	1.084	462.4	604.2	2553	604.7	2133	2738	1.776	6.895
0.420	145.4	1.085	441.7	611.8	2555	612.3	2128	2740	1.795	6.879
0.440	147.1	1.087	422.7	619.1	2556	619.6	2123	2742	1.812	6.864
0.460	148.7	1.089	405.4	626.1	2558	626.6	2118	2744	1.829	6.849
0.480	150.3	1.091	389.5	632.9	2559	633.5	2113	2746	1.845	6.834
0.500	151.8	1.093	374.8	639.5	2561	640.1	2108	2748	1.860	6.821