

# Evaporation

# Calculation for Single Effect Evaporator

- The basic equation for solving for the capacity of a single effect evaporator is  $Q = UA\Delta T = UA(T_s - T_b)$  where  $\Delta T$  is the difference between the temperature of condensing steam ( $T_s$ ) and the temperature of the boiling liquid ( $T_b$ ) in the evaporator
- The value of  $Q$  is determined by making mass and energy balances on the evaporator

If,

$F$  = feed to the evaporator, kg/h

$x_F$  = mass fraction of solids in feed

$T_F$  = temperature of feed, K or °C

$h_F$  = enthalpy of feed, J/kg

$L$  = flow rate of concentrated liquor

$x_L$  = solid content in concentrated liquor

$T_1$  = temperature in the evaporator at  $P_1$

$h_L$  = enthalpy of concentrated liquor, J/kg

$V$  = flow rate of vapour

$y_V$  = solid content in vapour = 0

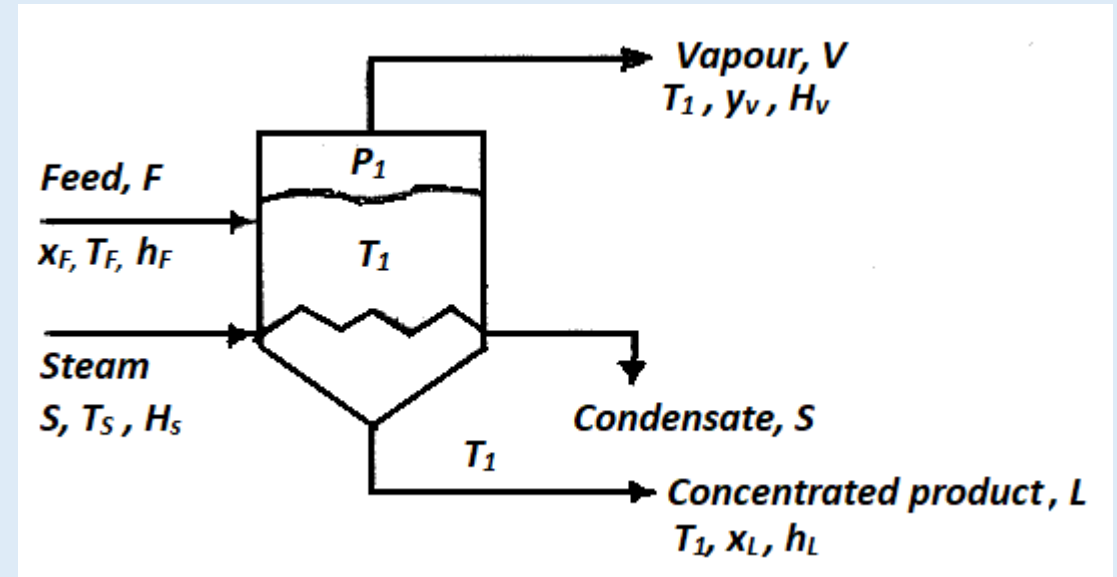
$H_v$  = enthalpy of vapour, J/kg

$S$  = flow rate of steam, kg/h

$T_s$  = saturation temperature of steam

$H_s$  = enthalpy of steam, J/kg

$h_s$  = enthalpy of condensed steam, J/kg



**Mass balance** at steady state,

$$F = L + V \quad (\text{Total balance})$$

$$x_F F = x_L L \quad (\text{Solute balance})$$

**Energy balance** at steady state,

*Heat in feed + Heat in steam = Heat in conc. product  
+ Heat in vapour  
+ Heat in condensate*

$$Fh_F + SH_S = Lh_L + VH_V + Sh_S$$

$$Fh_F + S(H_S - h_S) = Lh_L + VH_V$$

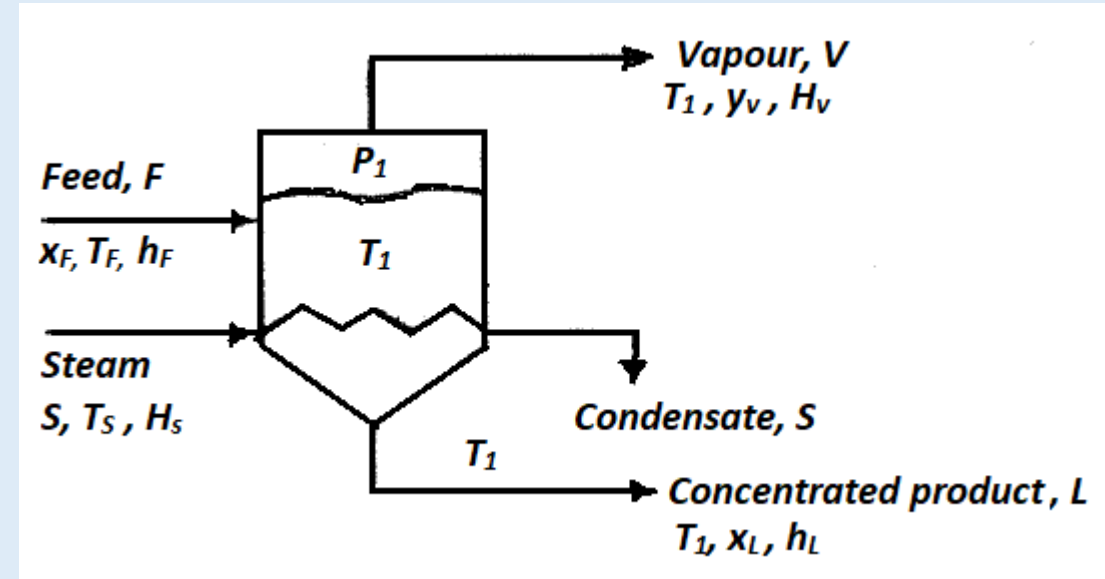
$$Fh_F + S\lambda = Lh_L + VH_V$$

- Energy balance for the steam side,  $Q_S = S(H_S - h_S) = S\lambda$
- Energy balance liquor side,  $Fh_F + Q = Lh_L + VH_V \quad \Rightarrow \quad Q = Lh_L + VH_V - Fh_F$

In the absence of heat losses, heat transferred from the steam to the tubes equals that transferred to the liquor

$$Q_S = Q$$

The values of  $h_F$  and  $h_L$  can be obtained from specific heat capacity values or enthalpy-concentration charts (for cases having high heat of solution values), the values of  $H_V$  and  $\lambda$  are obtained from steam tables



## Problem (for dilute solution, no boiling point rise)

A continuous single effect evaporator is to be fed with 5000 kg/h of solution containing 1 wt% solute. The feed is at a temperature of 303K. It is to be concentrated to a solution of 2 wt% solute. The evaporator is at atmospheric pressure (101.3 kPa) and the area of the evaporator is 69.7 m<sup>2</sup>. Saturated steam is supplied at 143.3 kPa for heating. Calculate the amounts of vapour and liquid and the overall heat transfer coefficient.

$$F = L + V \quad (\text{Total balance})$$

$$5000 = L + V$$

$$x_F F = x_L L \quad (\text{Solute balance})$$

$$0.01 \times 5000 = 0.02 \times L$$

$$L = 2500 \text{ kg/h} \quad \text{and} \quad V = 2500 \text{ kg/h}$$

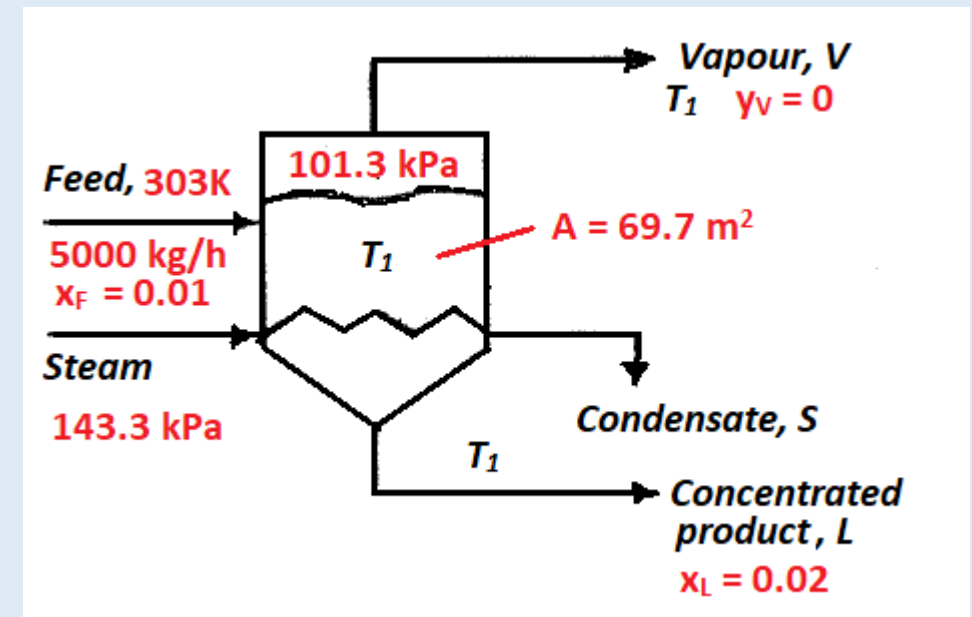
Now,  $T_F = 303\text{K}$ ,

At this temperature  $h_F = 125.79 \frac{\text{kJ}}{\text{kg}}$  (from steam tables), as the solution is considered to be dilute

The evaporator is at atmospheric pressure, boiling point of water at 101.3 kPa is = **373 K**

This is the temperature maintained inside the evaporator ( $T_1$ ) and is also the temperature of the vapour

From steam tables,  $H_V = 2676.1 \frac{\text{kJ}}{\text{kg}}$  at 373 K



The temperature of the liquid and the vapour in the evaporator is the same

From the steam tables, enthalpy of liquid (2% solution),  $h_L = 419.04 \text{ kJ/kg}$

From steam tables, enthalpy of steam at 143.3 kPa,  $H_S$  is  $= 2691.5 \frac{\text{kJ}}{\text{kg}}$  and saturation temperature ( $T_S$ ) is 383K

From steam tables, enthalpy of condensate at 143.3 kPa,  $h_S$  is  $= 461.3 \frac{\text{kJ}}{\text{kg}}$

Now,

$$Fh_F + S(H_S - h_S) = Lh_L + VH_V$$
$$5000 \times 125.79 + S(2691.5 - 461.3) = 2500 \times 419.04 + 2500 \times 2676.1$$
$$S = 3187.56 \frac{\text{kg}}{\text{h}}$$

Also,

$$Q_S = S(H_S - h_S) = S\lambda$$
$$Q_S = 3187.56(2691.5 - 461.3) = 7108900 \frac{\text{kJ}}{\text{h}} = 1974694.44 \text{ W}$$

Design equation for evaporator is,  $Q = UA\Delta T = UA(T_S - T_b)$

$$1974694.44 = U \times 69.7 \times (383 - 373)$$

$$U = 2833.13 \frac{\text{W}}{\text{m}^2\text{K}}$$

# Steam table

Temp. $T^{\circ}\text{C}$	Sat. Press. $P_{\text{sat}}$ kPa	Specific volume $\text{m}^3/\text{kg}$		Internal energy $\text{kJ}/\text{kg}$			Enthalpy $\text{kJ}/\text{kg}$			Entropy $\text{kJ}/\text{kg}\cdot\text{K}$		
		Sat. Liquid $v_f$	Sat. Vapor $v_g$	Sat. Liquid $u_f$	Evap. $u_{fg}$	Sat. Vapor $u_g$	Sat. Liquid $h_f$	Evap. $h_{fg}$	Sat. Vapor $h_g$	Sat. Liquid $s_f$	Evap. $s_{fg}$	Sat. Vapor $s_g$
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1	0.0763	8.9487	9.0249
10	1.2281	0.001000	106.32	42.020	2346.6	2388.7	42.022	2477.2	2519.2	0.1511	8.7488	8.8999
15	1.7057	0.001001	77.885	62.980	2332.5	2395.5	62.982	2465.4	2528.3	0.2245	8.5559	8.7803
20	2.3392	0.001002	57.762	83.913	2318.4	2402.3	83.915	2453.5	2537.4	0.2965	8.3696	8.6661
25	3.1698	0.001003	43.340	104.83	2304.3	2409.1	104.83	2441.7	2546.5	0.3672	8.1895	8.5567
30	4.2469	0.001004	32.879	125.73	2290.2	2415.9	125.74	2429.8	2555.6	0.4368	8.0152	8.4520
35	5.6291	0.001006	25.205	146.63	2276.0	2422.7	146.64	2417.9	2564.6	0.5051	7.8466	8.3517
40	7.3851	0.001008	19.515	167.53	2261.9	2429.4	167.53	2406.0	2573.5	0.5724	7.6832	8.2556
45	9.5953	0.001010	15.251	188.43	2247.7	2436.1	188.44	2394.0	2582.4	0.6386	7.5247	8.1633
50	12.352	0.001012	12.026	209.33	2233.4	2442.7	209.34	2382.0	2591.3	0.7038	7.3710	8.0748
55	15.763	0.001015	9.5639	230.24	2219.1	2449.3	230.26	2369.8	2600.1	0.7680	7.2218	7.9898
60	19.947	0.001017	7.6670	251.16	2204.7	2455.9	251.18	2357.7	2608.8	0.8313	7.0769	7.9082
65	25.043	0.001020	6.1935	272.09	2190.3	2462.4	272.12	2345.4	2617.5	0.8937	6.9360	7.8296
70	31.202	0.001023	5.0396	293.04	2175.8	2468.9	293.07	2333.0	2626.1	0.9551	6.7989	7.7540
75	38.597	0.001026	4.1291	313.99	2161.3	2475.3	314.03	2320.6	2634.6	1.0158	6.6655	7.6812
80	47.416	0.001029	3.4053	334.97	2146.6	2481.6	335.02	2308.0	2643.0	1.0756	6.5355	7.6111
85	57.868	0.001032	2.8261	355.96	2131.9	2487.8	356.02	2295.3	2651.4	1.1346	6.4089	7.5435
90	70.183	0.001036	2.3593	376.97	2117.0	2494.0	377.04	2282.5	2659.6	1.1929	6.2853	7.4782
95	84.609	0.001040	1.9808	398.00	2102.0	2500.1	398.09	2269.6	2667.6	1.2504	6.1647	7.4151
100	101.42	0.001043	1.6720	419.06	2087.0	2506.0	419.17	2256.4	2675.6	1.3072	6.0470	7.3542
105	120.90	0.001047	1.4186	440.15	2071.8	2511.9	440.28	2243.1	2683.4	1.3634	5.9319	7.2952
110	143.38	0.001052	1.2094	461.27	2056.4	2517.7	461.42	2229.7	2691.1	1.4188	5.8193	7.2382
115	169.18	0.001056	1.0360	482.42	2040.9	2523.3	482.59	2216.0	2698.6	1.4737	5.7092	7.1829
120	198.67	0.001060	0.89133	503.60	2025.3	2528.9	503.81	2202.1	2706.0	1.5279	5.6013	7.1292

## Problem (for concentrated solution, boiling point rise, inclusion of heat of solution)

An evaporator is used to concentrate 4536 kg/h of a 20% solution of NaOH in water entering at 60°C to a product having 50% solids. The pressure of saturated steam used is 172.4 kPa and the pressure in the vapour space of the evaporator is 11.7 kPa. The overall heat transfer coefficient is 1560 W/m<sup>2</sup>K. Calculate the steam used, the steam economy in kg vaporized/kg steam used, and the heating surface area in m<sup>2</sup>

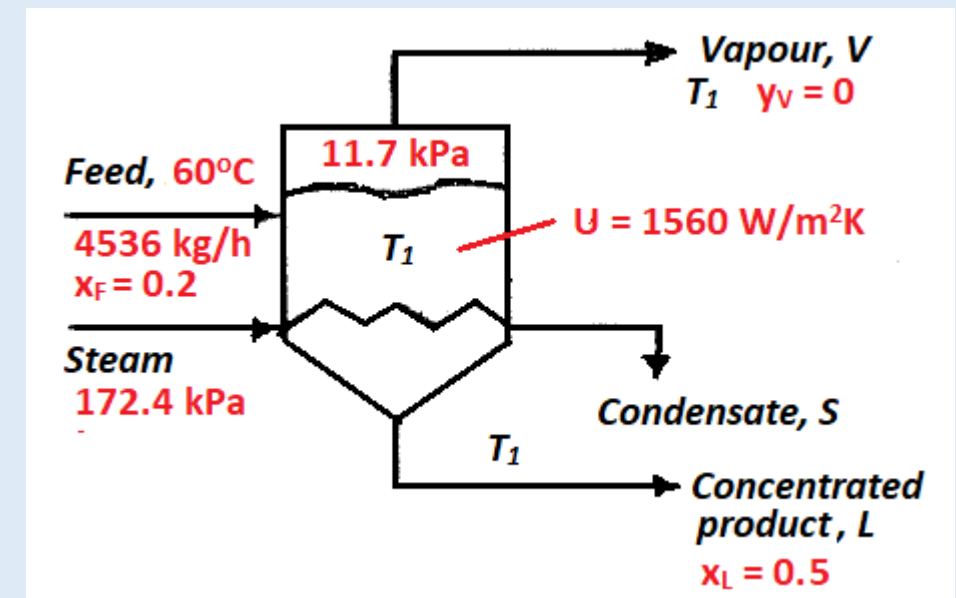
$$F = L + V \quad (\text{Total balance})$$

$$4536 = L + V$$

$$x_F F = x_L L \quad (\text{Solute balance})$$

$$0.2 \times 4536 = 0.5 \times L$$

$$L = 1814.4 \text{ kg/h} \quad \text{and} \quad V = 2721.6 \text{ kg/h}$$



From steam tables, for **saturated steam** at **172.4 kPa**, the saturation temperature ( $T_S$ ) is **115.6°C**

and heat of vaporization,  $\lambda = 2214.8 \frac{\text{kJ}}{\text{kg}}$

**The evaporator is operated at 11.7 kPa**

The boiling point of pure water at **11.7 kPa** is = **48.82°C**

The concentration of the solution inside the evaporator is fairly high at 50% and therefore it is essential to determine the boiling point rise in this case

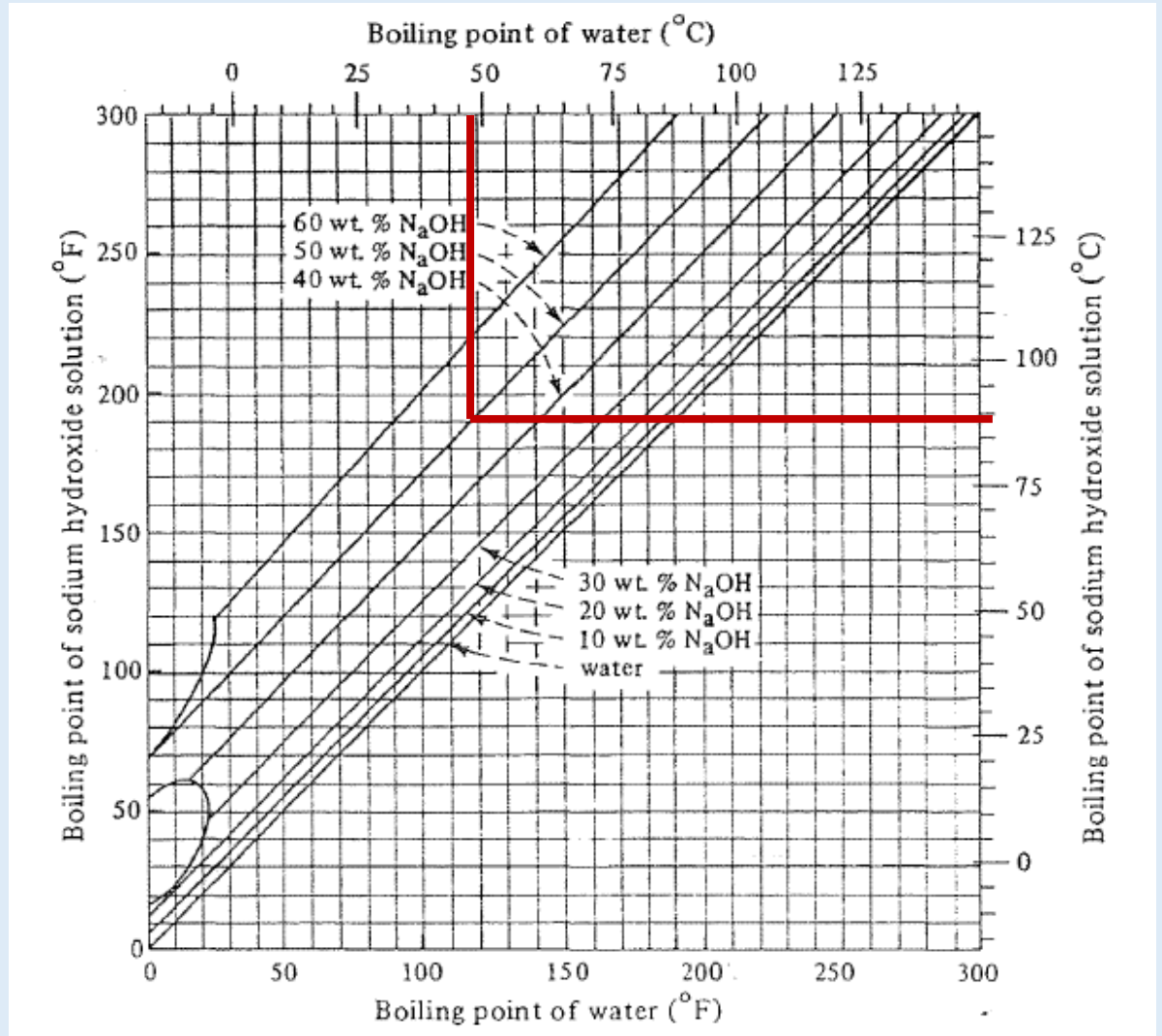
From the Dühring plot shown alongside, for the boiling point of water = 48.82°C and solution of NaOH having 50% concentration,

the boiling point of the solution ( $T_1$ ) is 89.4 °C

Therefore,

The boiling point rise =  $89.4 - 48.82 = 40.58$  °C

Thus, **the temperature inside the evaporator is 89.4 °C instead of 48.82 °C**





The enthalpies of the feed and concentrated liquor is determined from the enthalpy – concentration diagram

For 20% NaOH solution at 60°C,  $h_F = 214 \frac{kJ}{kg}$

For 50% NaOH solution at 89.4°C,  $h_L = 505 \frac{kJ}{kg}$

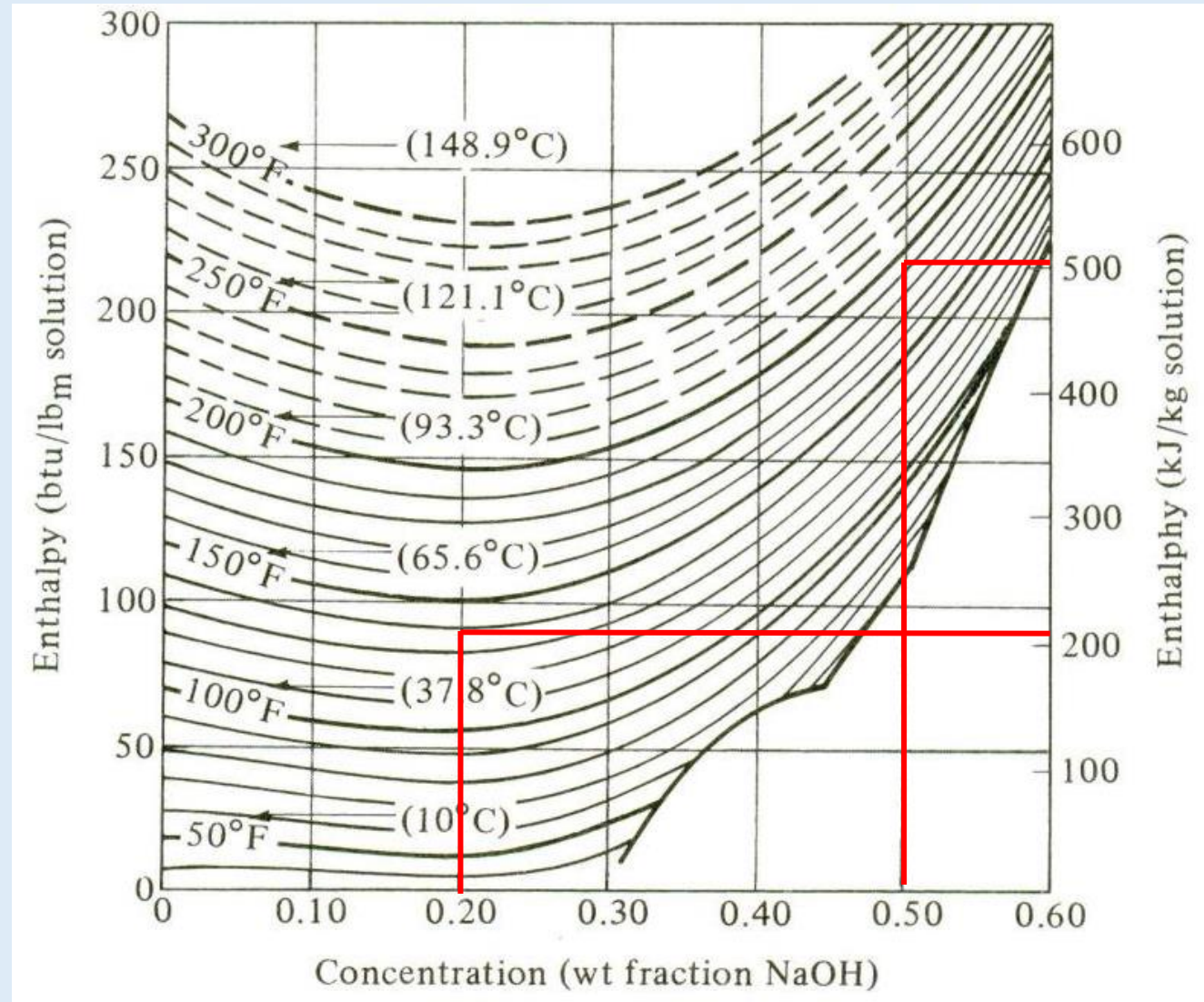
In order to calculate the enthalpy of the vapour,  $H_V$ , it is necessary to find the enthalpy of saturated steam at 48.82°C and 11.7 kPa.

Steam tables gives a value of  $2590 \frac{kJ}{kg}$

The degree of superheat is then added to it to get  $H_V$ ,

$$H_V = 2590 + 1.884 (89.4 - 48.82) = 2666.53 \frac{kJ}{kg}$$

where  $C_p$  of superheated steam = 1.884 kJ/kgK



Now,

$$Fh_F + S(H_S - h_S) = Lh_L + VH_V$$

$$Fh_F + S\lambda = Lh_L + VH_V$$

$$4536 \times 214 + S \times 2214.8 = 1814.4 \times 505 + 2721.6 \times 2666.53$$

$$S = 3252.12 \frac{kg}{h} = 0.903 \frac{kg}{s}$$

Also,

$$Q_S = S(H_S - h_S) = S\lambda$$

$$Q_S = 0.903 \times 2214.8 = 2000.78 \text{ kW}$$

Design equation for evaporator is,  $Q = UA\Delta T = UA(T_s - T_b)$

$$2000.78 \times 1000 = 1560 \times A \times (115.6 - 89.4)$$

$$A = 49.03 \text{ m}^2$$

$$\text{Steam economy} = \frac{2721.6}{3252.12} = 0.837$$