Evaporation

Boiling point elevation

- The feed to an evaporator is often so dilute that the properties of the solution can be assumed to be same as that of water
- However, if the *solution is concentrated* enough or during the process of evaporation when solution becomes concentrated, then the *thermal properties of the solution being evaporated may differ considerably from that of water*
- *Boiling point is the temperature at which vapor pressure of liquid equals surrounding pressure*
- It is known that boiling point depends on the following factors –

    a) External pressure – lower the pressure, lower the boiling point

    b) Presence of dissolved solute – increase in boiling point is proportional to amount of solute

    c) Hydrostatic head – boiling point increase with depth

- As the addition of solute increases the boiling point of the solution, the *boiling point of the concentrated solutions in the evaporator is substantially higher than the boiling point of water at the pressure* maintained in the vapour space of the evaporator
- The difference in the boiling point of water and the concentrated solution at any pressure is called the ***boiling point elevation*** or the ***boiling point rise***
- A strong solution of NaOH boils at 115°C at atmospheric pressure whereas the boiling point of water at atmospheric pressure is 100°C – the boiling point elevation in this case is (115-100) = 15°C

What happens during evaporation ?

- Boiling point of solution rises – due to increase in solid content
- The rate of heat transfer in an evaporator is given by $Q = UA(T_s - T_b)$
- The *rise in boiling point gives rise to decrease in effective driving force*, ΔT $(= T_s - T_b)$ between steam and product – as the steam temperature remains constant and product temperature (boiling temperature) increases
- Rate of heat transfer decreases – due to decrease in ΔT between steam and product

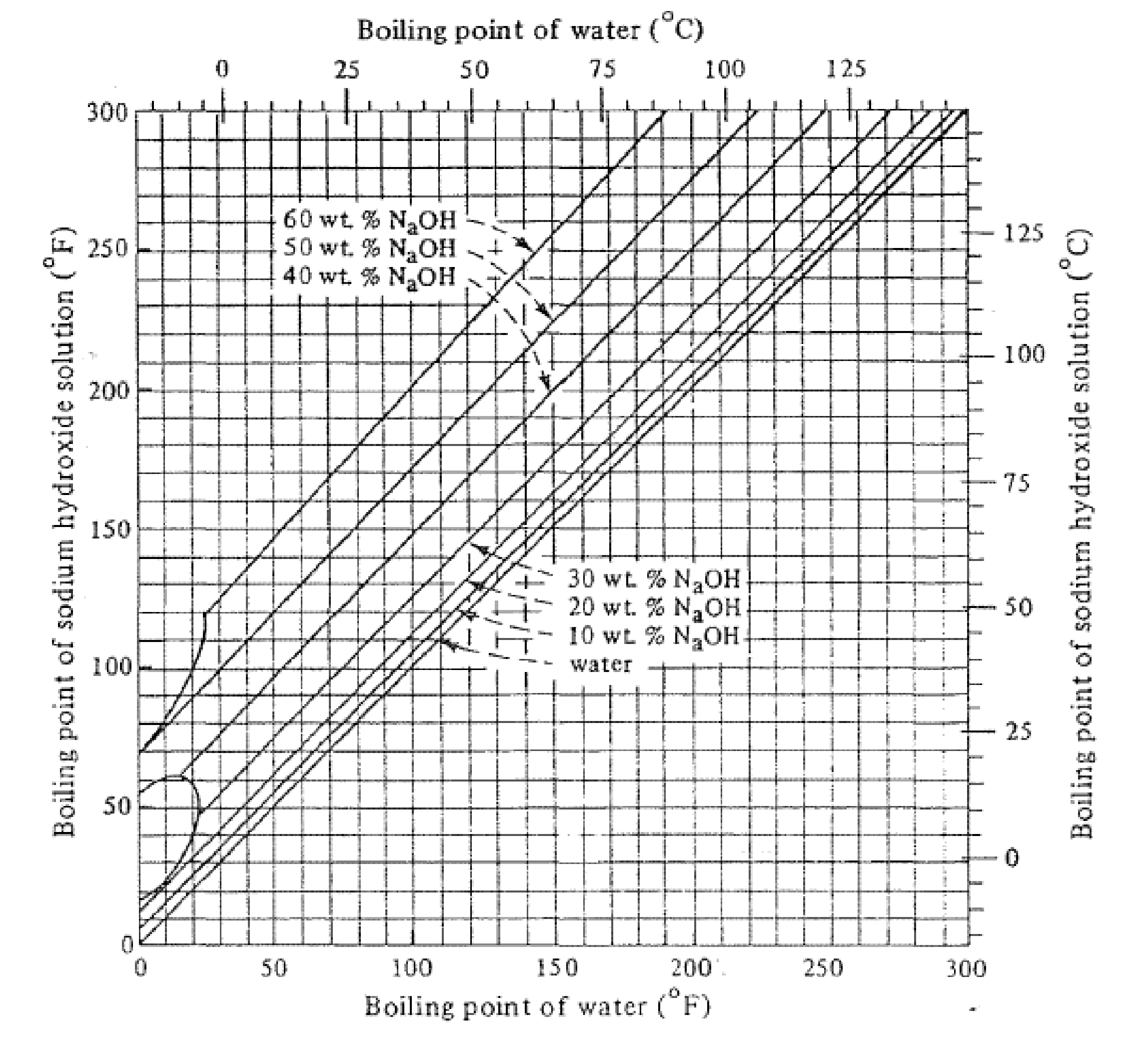
If steam temperature (T_s) is 120°C, and the boiling points of pure water and NaOH solution is 100°C and 115°C, respectively, then

$$\Delta T = T_s - T_b = 120 - 100 = 20\text{°C}$$ (no boiling point rise)

$$\Delta T = T_s - T_b = 120 - 115 = 5\text{°C}$$ (with boiling point rise)

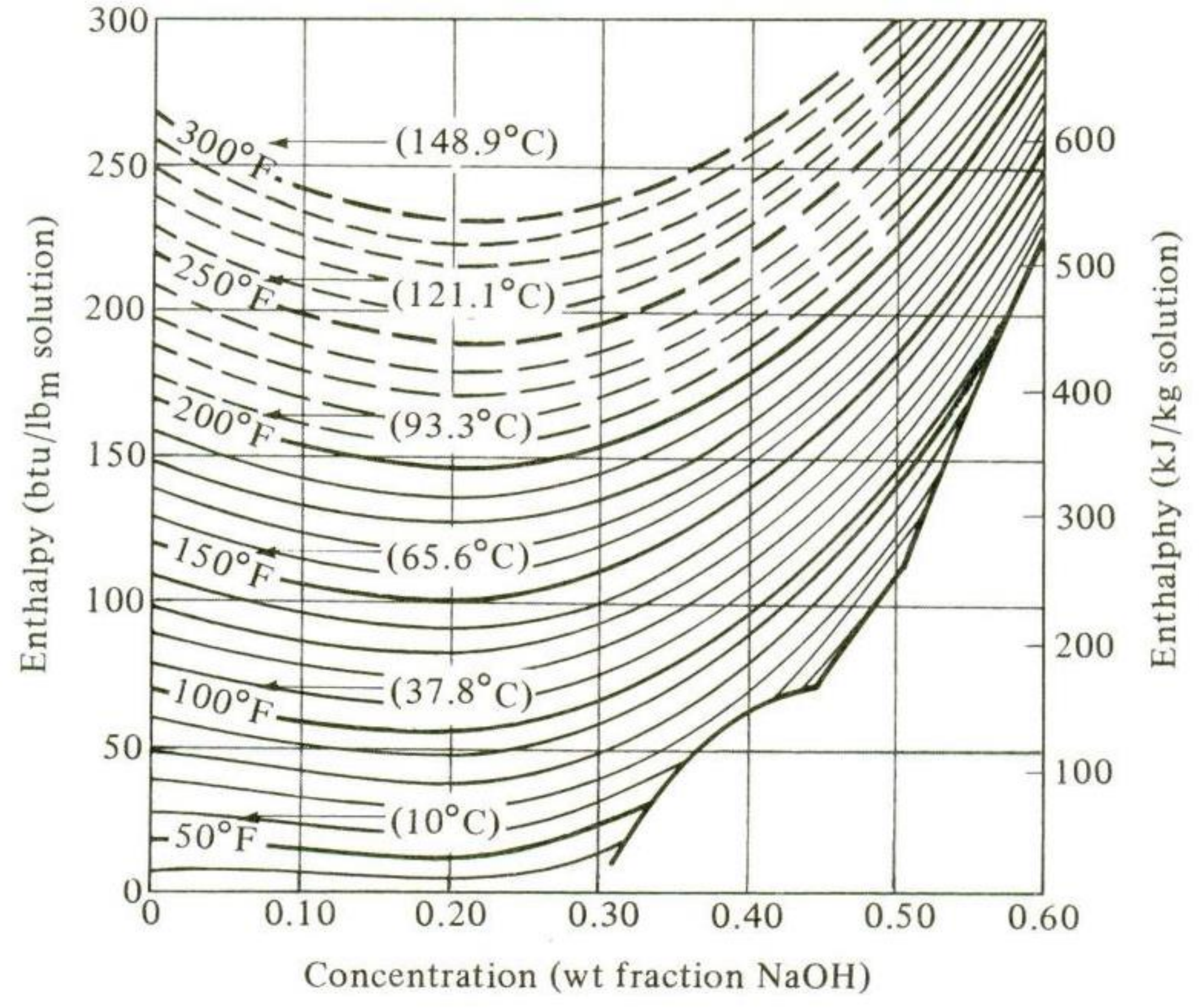
Prediction of Boiling point elevation

- It is often difficult to **predict the elevation of boiling point of the solution** and experimental data is often required
- An useful empirical law known as the ***Duhring's rule*** can be used for this
- The rule states that the *boiling point of a solution of given concentration is a linear function of the boiling point of water*
- If the boiling points of a solution at two different pressures are known, and the corresponding boiling points of water are read from steam tables, a line known as the Duhring line can be drawn through them
- This line can be used to predict the boiling point of a solution at any other pressure



Enthalpy – concentration charts of solutions

- If the *heat of solution of the aqueous solution being concentrated in the evaporator is large*, then its effect should be included while doing the heat balance
- For solutions having negligible heats of solution, the heat capacities can be used to calculate enthalpies
- For solutions with high heats of solution, the enthalpies are estimated from the figure given



Overall heat transfer coefficient in evaporators

- The *overall heat transfer coefficient* in a evaporator is composed of the *steam side condensing coefficient, the metal wall (usually negligible resistance) and liquid film resistance inside the tube*
- The *steam condensing coefficient outside the tube* is calculated by the equations mentioned earlier in the condensation section (see next slide)
- In case no data is available for calculations, steam condensing coefficient can be taken to be 5700 W/m^{2}K
- The *heat transfer coefficient inside the tubes* can be predicted if little or no vaporization takes place inside the tubes
- The heat transfer coefficient can be calculated from

$$\frac{h_i d}{k} = 0.0278(Re)^{0.8}(Pr)^{0.4}$$

- Velocities inside the tube range from 2 to 5 m/s
- However, if there is boiling inside the tubes, there is no practically useful method to estimate the tube side coefficient
- Design calculations are done on the basis of data obtained from an operating evaporator
- Typical overall coefficients for evaporators depend on the type of evaporator and are available in the form of tables

*Typical Heat-Transfer Coefficients for Various Evaporators**

Type of Evaporator	*Overall U* $W/m^2 \cdot K$	*Overall U* $btu/h \cdot ft^2 \cdot {}^\circ F$
Short-tube vertical, natural circulation	1100–2800	200–500
Horizontal-tube, natural circulation	1100–2800	200–500
Long-tube vertical, natural circulation	1100–4000	200–700
Long-tube vertical, forced circulation	2300–11 000	400–2000
Agitated film	680–2300	120–400

*Generally, nonviscous liquids have the higher coefficients and viscous liquids the lower coefficients in the ranges given.

Steam-side condensation coefficient

- For ***laminar flow*** (Re_{film} < 1800), the steam-side condensation coefficient for ***vertical tube surfaces*** can be calculated by the following equation:

$$Nu = 1.13\left[\frac{g\lambda\rho_l(\rho_l - \rho_v)L^3}{\mu k_l(T_v - T_w)}\right]^{1/4}$$

All physical properties of the liquid are evaluated at the film temperature, $T_{film} = \frac{T_{sat}+T_{wall}}{2}$

λ (latent heat of condensation) is evaluated at T_{sat}

- For ***laminar flow*** (Re_{film} < 1800), the steam-side condensation coefficient for ***horizontal surfaces*** can be calculated by the following equation:

$$Nu = \frac{hD}{k} = 0.725\left[\frac{g\lambda\rho_l(\rho_l - \rho_v)D^3}{N\mu k(T_v - T_w)}\right]^{1/4}$$

- For ***turbulent flow*** (Re_{film} > 1800), the steam-side condensation coefficient for ***vertical surfaces*** can be calculated by the following equation:

$$Nu = \frac{hL}{k} = 0.0077\left(\frac{g\rho_l^2 L^3}{\mu^2}\right)^{1/3}(Re)^{0.4}$$