# (905212)Chemical Engineering Principles (2)

## CHAPTER 8:
## Balances on Nonreactive Processes

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# Adiabatic Cooling

- In adiabatic cooling: a warm gas is brought into contact with a cold liquid to evaporate. Heat is transferred from liquid to gas, BUT no heat transfer from systems to its surrounding.
- Examples:

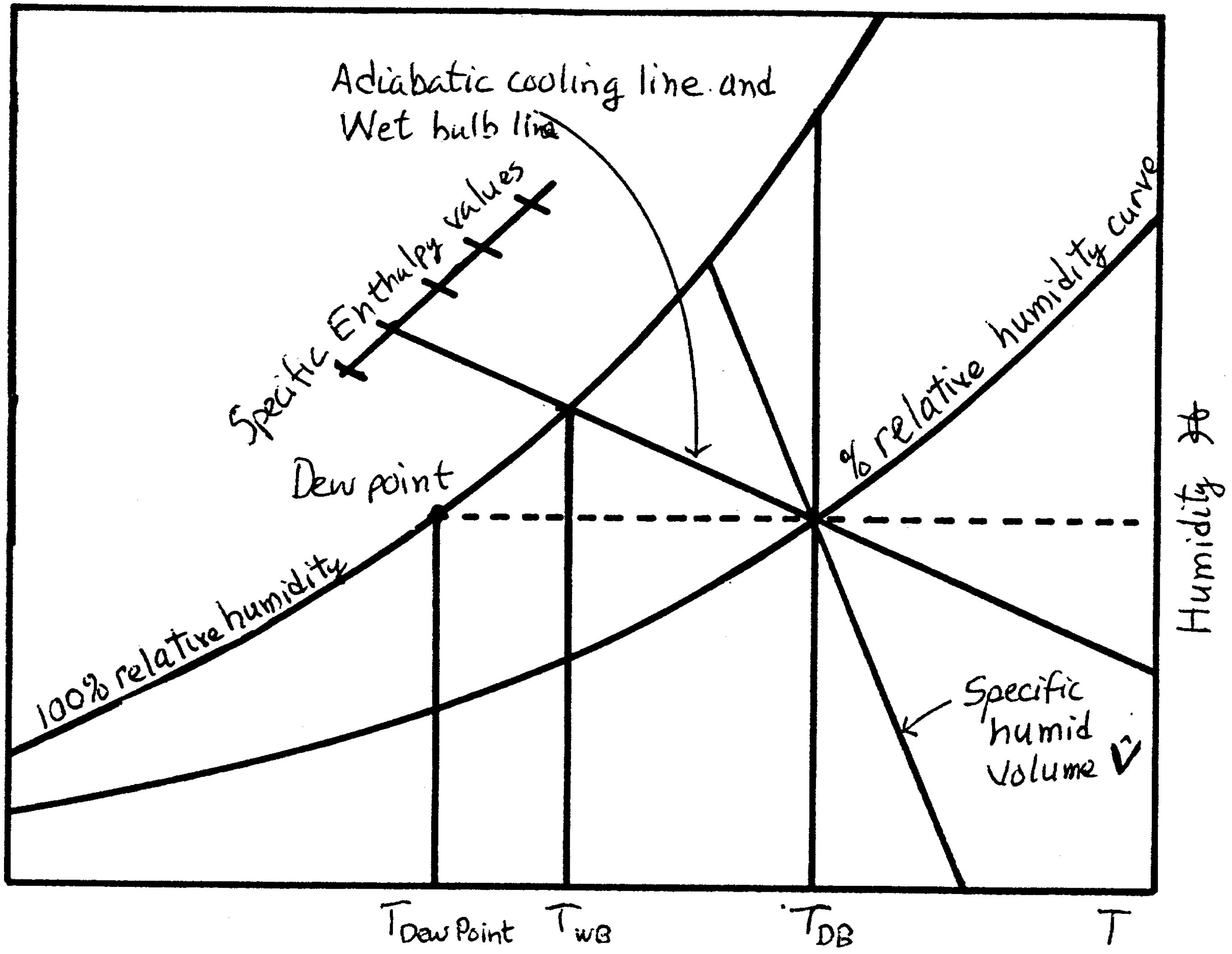
❖ Spray cooling, spray humidification.

❖ Spray dehumidification.

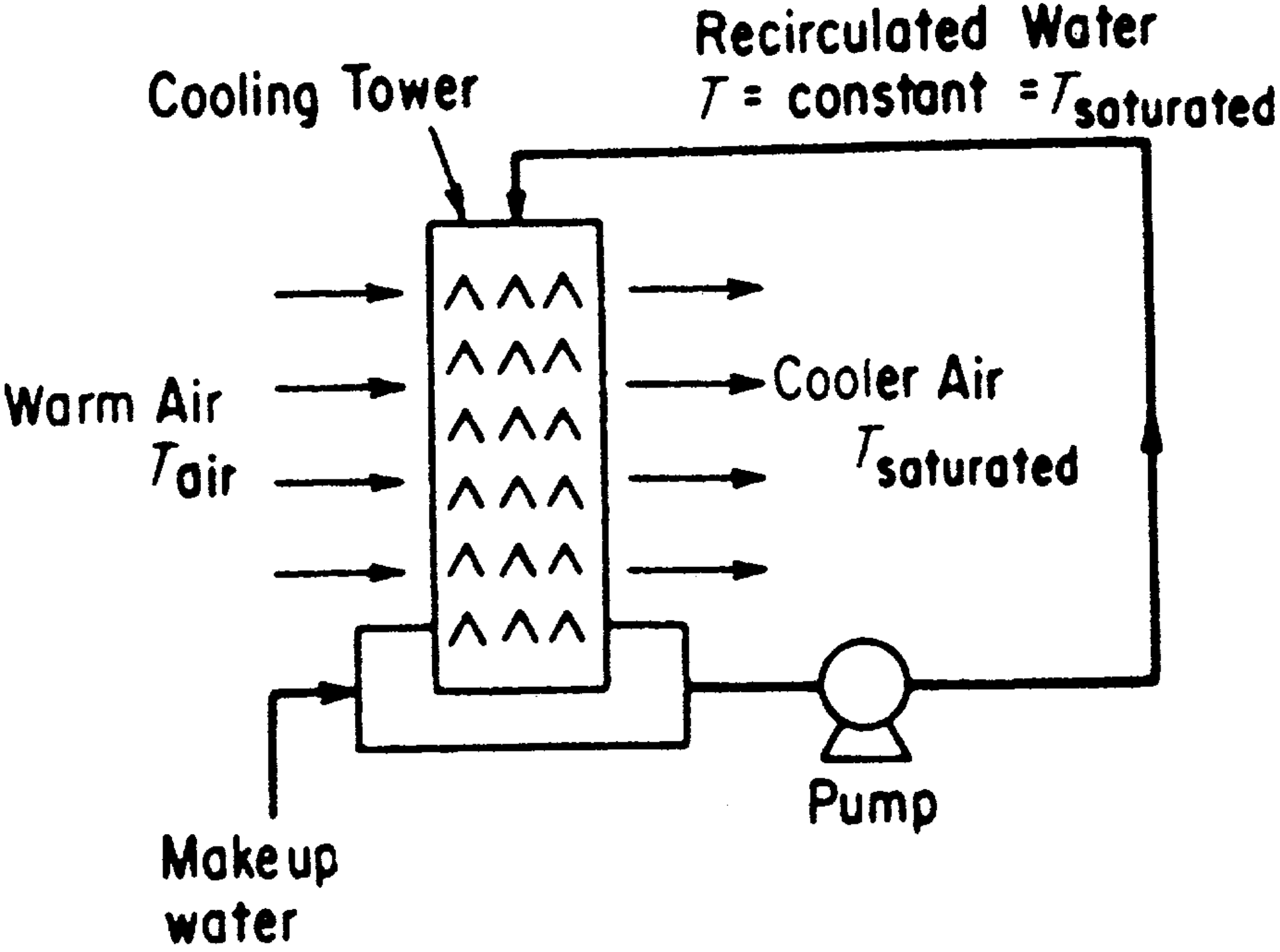
❖ Drying

❖ Spray drying.

# Adiabatic Cooling (Same as Wet Bulb Line)

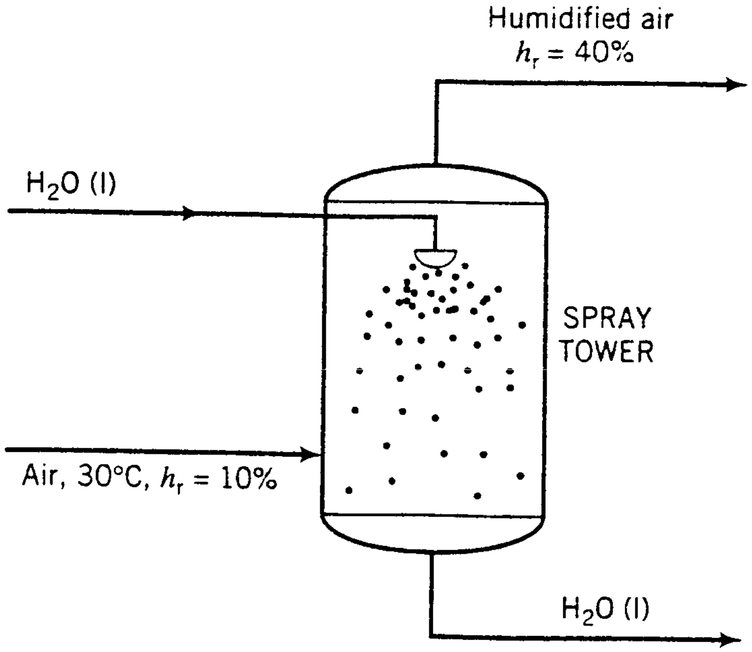


# A Cooling Tower and Swamp Coolers- Adiabatic Humidification



# Example 8.4.7 Adiabatic Humidification

A stream of air at 30°C and 10% relative humidity is humidified in an adiabatic spray tower operating at $P \approx 1$ atm. The emerging air is to have a relative humidity of 40%.



1. Determine the absolute humidity and the adiabatic saturation temperature of the entering air.
2. Use the psychrometric chart to calculate (i) the rate at which water must be added to humidify 1000 kg/h of the entering air, and (ii) the temperature of the exiting air.

# Example 8.4.7 Solution

**1.** Air at 30°C, 10% relative humidity

$$\Big\Downarrow \text{Figure 8.4-1}$$

$$\begin{aligned} h_a &= 0.0026 \text{ kg } H_2O/\text{kg DA} \\ T_{wb} &= T_{as} = 13.2°\text{C} \end{aligned}$$

**2.** The state of the outlet air must lie on the $T_{wb} = 13.2°\text{C}$ line. From the intersection of this line with the curve for $h_r = 40\%$, the absolute humidity of the exit gas is determined to be 0.0063 kg $H_2O$/kg DA. The inlet (and outlet) flow rate of dry air, $\dot{m}_{DA}$, is

$$\dot{m}_{DA} = (1000 \text{ kg air/h})(1 \text{ kg DA}/1.0026 \text{ kg air}) = 997.4 \text{ kg DA/h}$$

The amount of water that must be evaporated, $\dot{m}_{H_20}$, may be calculated as the difference between the outlet and inlet water flow rates in the air stream.

$$\begin{aligned} \dot{m}_{H_2O} &= (997.4 \text{ kg DA/h})(0.0063 - 0.0026) \frac{\text{kg } H_2O}{\text{kg DA}} \\ &= \boxed{3.7 \text{ kg } H_2O/\text{h}} \end{aligned}$$

From Figure 8.4-1 the temperature of the exiting air is $\boxed{21.2°\text{C}}$.

# Mixing and Solutions

- **Heats of solution :** enthalpy change when **1** mol of solute is dissolved in ***r*** mol of a liquid solvent at temperature T. Some values are given in Table B.11, p.653. (Note: The last column in Table B.11 is a heat of solution, not a heat of mixing as defined below.)

In general, the enthalpy of a solution containing *r* moles $H_2O$/mole solute is for reference states of pure solute and solvent at 25°C and 1 atm

$$\hat{H} = \Delta\hat{H}_s(r) \qquad \textbf{(8.5.1)}$$

$$\Delta\hat{H}_s(T,r) \longrightarrow$$

**(See Table B.11 for some data.)**

Reference is at 25 $^0$C and 1 atm
Water (liquid)
The solute (gas or solid)

# Mixing and Solutions

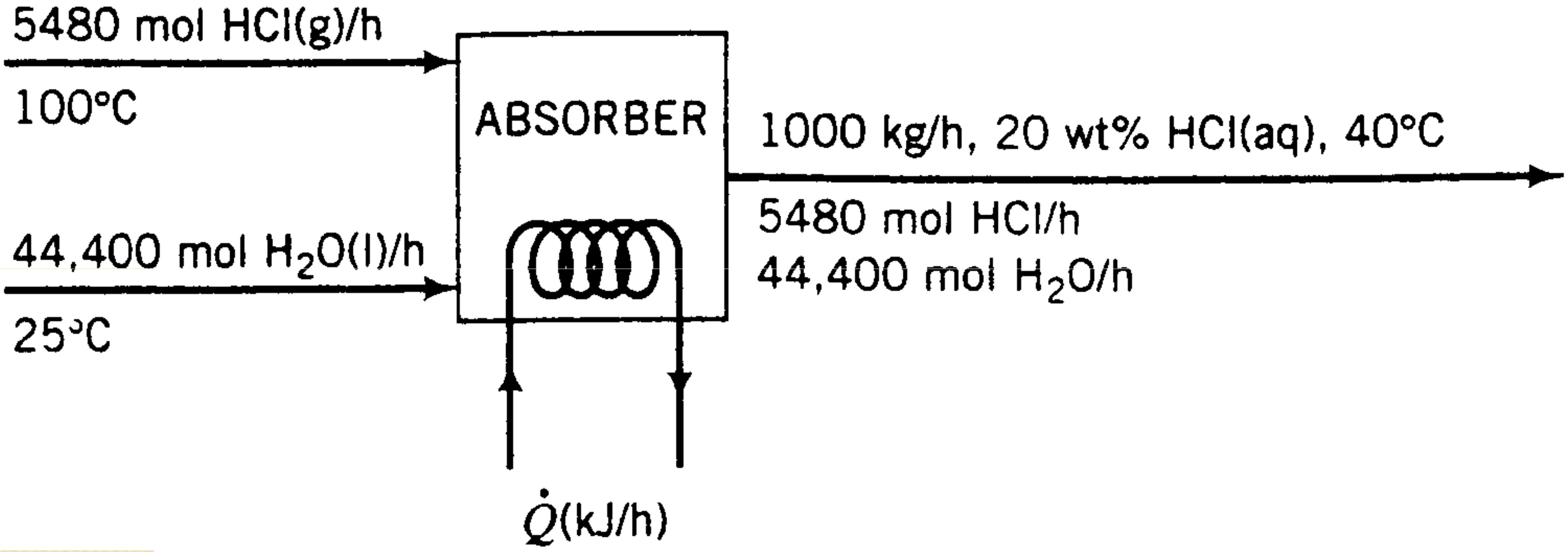
- Heats of mixing - enthalpy change when one mol of mixture is formed from the pure components at temperature T:

$$\Delta\hat{H}_m = \hat{H} - \sum x_i \hat{H}_i = \hat{H}^E$$

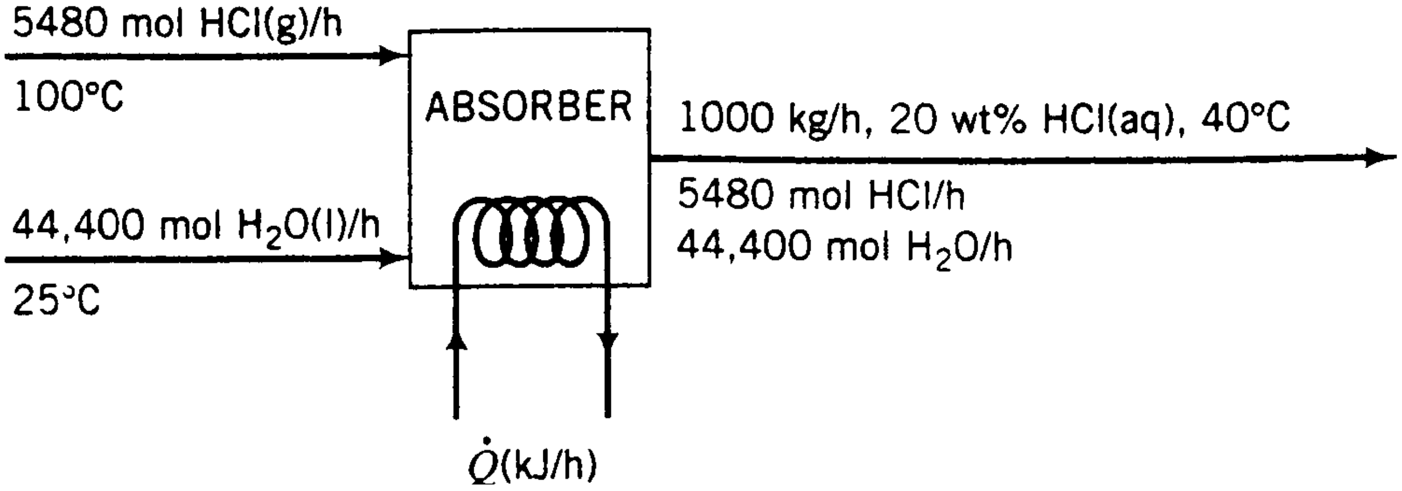
The heat of mixing is also called the excess enthalpy

# Example 8.5.1 Production of HCl Acid

Hydrochloric acid is produced by absorbing gaseous HCl (hydrogen chloride) in water. Calculate the heat that must be transferred to or from an absorption unit if HCl(g) at 100°C and $H_2O(l)$ at 25°C are fed to produce 1000 kg/h of 20.0 wt% HCl(aq) at 40°C.



# Example 8.5.1 Production of HCl Acid



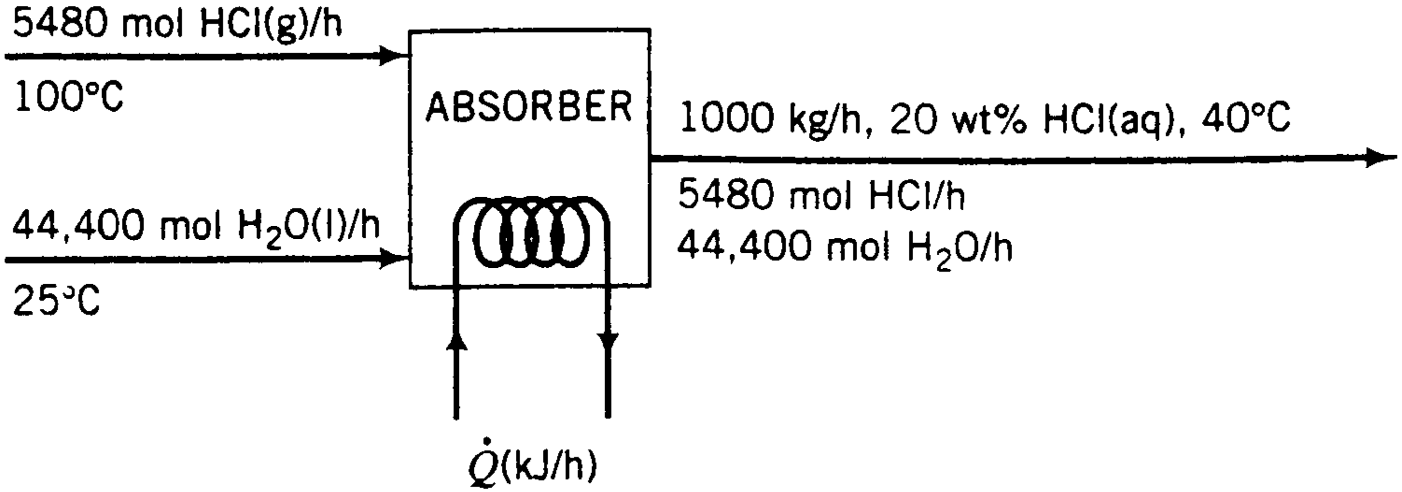
1000 kg/h of 20.0 wt% HCl(aq)

$$\Downarrow$$

$$\dot{n}_{\mathrm{HCl}} = \frac{1000\ \mathrm{kg}}{\mathrm{h}} \left| \frac{0.200\ \mathrm{kg\ HCl}}{\mathrm{kg}} \right| \frac{10^3\ \mathrm{mol}}{36.5\ \mathrm{kg\ HCl}} = 5480\ \mathrm{mol\ HCl/h}$$

$$\dot{n}_{\mathrm{H_2O}} = \frac{1000\ \mathrm{kg}}{\mathrm{h}} \left| \frac{0.800\ \mathrm{kg\ H_2O}}{\mathrm{kg}} \right| \frac{10^3\ \mathrm{mol}}{18.0\ \mathrm{kg\ H_2O}} = 44{,}400\ \mathrm{mol\ H_2O/h}$$

# Example 8.5.1 Production of HCl Acid



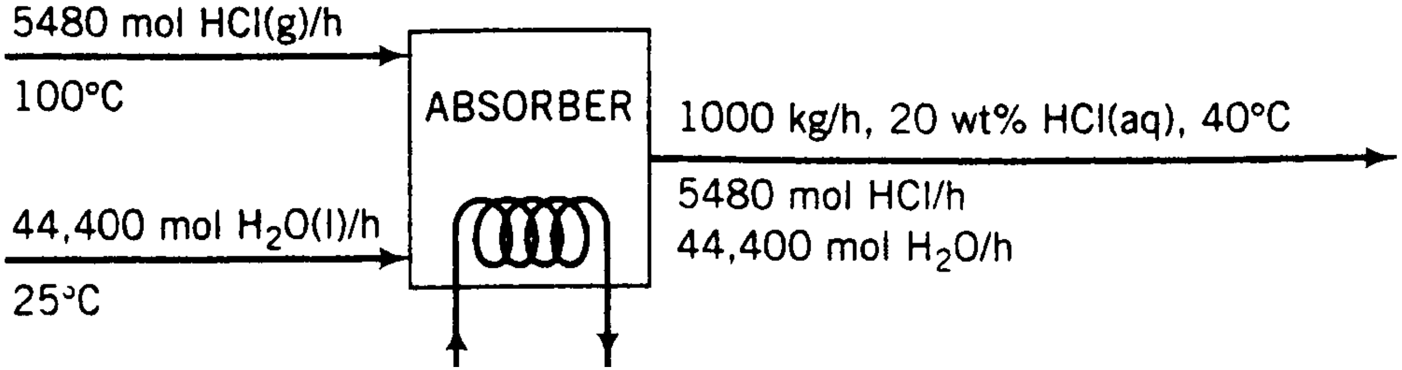
*References:* $HCl(g)$, $H_2O(l)$ at 25°C and 1 atm

| Substance | $\dot{n}_{in}$ | $\hat{H}_{in}$ | $\dot{n}_{out}$ | $\hat{H}_{out}$ |
|---|---|---|---|---|
| $HCl(g)$ | 5480 mol HCl | $\hat{H}_1$ (kJ/mol HCl) | — | — |
| $H_2O(l)$ | 44,400 mol $H_2O$ | 0 | — | — |
| $HCl(aq)$ | — | — | 5480 mol HCl | $\hat{H}_2$(kJ/mol HCl) |

***Energy Balance***

$$\dot{Q} = \Delta \dot{H} = \sum_{\text{out}} \dot{n}_i \hat{H}_i - \sum_{\text{in}} \dot{n}_i \hat{H}_i$$

# Example 8.5.1 Production of HCl Acid



*References:* $HCl(g)$, $H_2O(l)$ at 25°C and 1 atm

| Substance | $\dot{n}_{in}$ | $\hat{H}_{in}$ | $\dot{n}_{out}$ | $\hat{H}_{out}$ |
|---|---|---|---|---|
| $HCl(g)$ | 5480 mol HCl | $\hat{H}_1$ (kJ/mol HCl) | — | — |
| $H_2O(l)$ | 44,400 mol $H_2O$ | 0 | — | — |
| $HCl(aq)$ | — | — | 5480 mol HCl | $\hat{H}_2$(kJ/mol HCl) |

***Calculate $\hat{H}_1$***

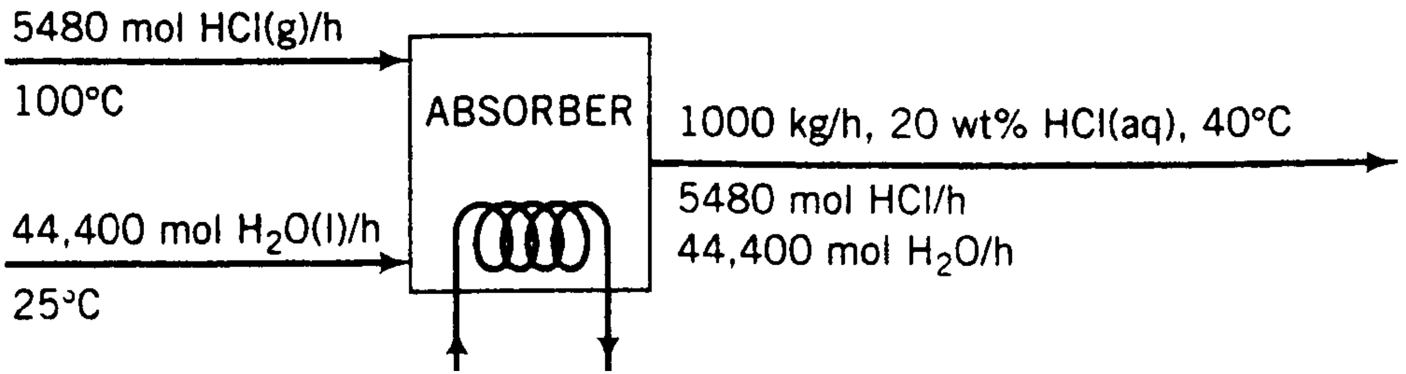
$$HCl(g, 25°C) \rightarrow HCl(g, 100°C)$$

$$\hat{H}_1 = \Delta\hat{H} = \int_{25°C}^{100°C} C_p \, dT$$

$\Downarrow$ $C_p$ for $HCl(g)$ from Table B.2

$$\hat{H}_1 = 2.178 \text{ kJ/mol}$$

# Example 8.5.1 Production of HCl Acid



*References:* HCl(g), $H_2O$(l) at 25°C and 1 atm

| Substance | $\dot{n}_{\text{in}}$ | $\hat{H}_{\text{in}}$ | $\dot{n}_{\text{out}}$ | $\hat{H}_{\text{out}}$ |
|---|---|---|---|---|
| HCl(g) | 5480 mol HCl | $\hat{H}_1$ (kJ/mol HCl) | — | — |
| $H_2O$(l) | 44,400 mol $H_2O$ | 0 | — | — |
| HCl(aq) | — | — | 5480 mol HCl | $\hat{H}_2$(kJ/mol HCl) |

***Calculate $\hat{H}_2$***

For the product solution,

$$r = (44{,}400 \text{ mol } H_2O)/(5480 \text{ mol HCl}) = 8.10$$

$$\text{HCl(g, 25°C)} + 8.10\ H_2O\text{(l, 25°C)} \xrightarrow{\Delta\hat{H}_a} \text{HCl(aq, 25°C)} \xrightarrow{\Delta\hat{H}_b} \text{HCl(aq, 40°C)}$$

$$\Delta\hat{H}_a = \Delta\hat{H}_s(25°\text{C}, r = 8.1) \xRightarrow{\text{Table B.11}} -67.4 \text{ kJ/mol HCl}$$

# Example 8.5.1 Production of HCl Acid

***Calculate $\hat{H}_2$***

The heat capacities of aqueous hydrochloric acid solutions are listed on p. 2-184 of *Perry's Chemical Engineers' Handbook* (see footnote 5) as a function of the mole fraction of HCl in the solution, which in our problem is

$$\frac{5480 \text{ mol HCl/h}}{(5480 + 44{,}400) \text{ mol/h}} = 0.110 \text{ mol HCl/mol}$$

$$\Downarrow$$

$$C_p = \frac{0.73 \text{ kcal}}{\text{kg}\cdot{}^\circ\text{C}} \left| \frac{1000 \text{ kg solution}}{5480 \text{ mol HCl}} \right| \frac{4.184 \text{ kJ}}{\text{kcal}} = 0.557 \frac{\text{kJ}}{\text{mol HCl}\cdot{}^\circ\text{C}}$$

$$\Delta\hat{H}_b = \int_{25^\circ\text{C}}^{40^\circ\text{C}} C_p\, dT = 8.36 \text{ kJ/mol HCl}$$

$$\Downarrow$$

$$\hat{H}_2 = \Delta\hat{H}_a + \Delta\hat{H}_b = (-67.4 + 8.36) \text{ kJ/mol HCl} = -59.0 \text{ kJ/mol HCl}$$

$$\dot{Q} = \Delta\dot{H} = \sum_{\text{out}} \dot{n}_i\hat{H}_i - \sum_{\text{in}} \dot{n}_i\hat{H}_i$$

$$= (5480 \text{ mol HCl/h})(-59.0 \text{ kJ/mol HCl}) - (5480 \text{ mol HCl/h})(2.178 \text{ kJ/mol HCl})$$

$$= \boxed{-3.35 \times 10^5 \text{ kJ/h}}$$

# Enthalpy-concentration diagrams: Single Liquid phase

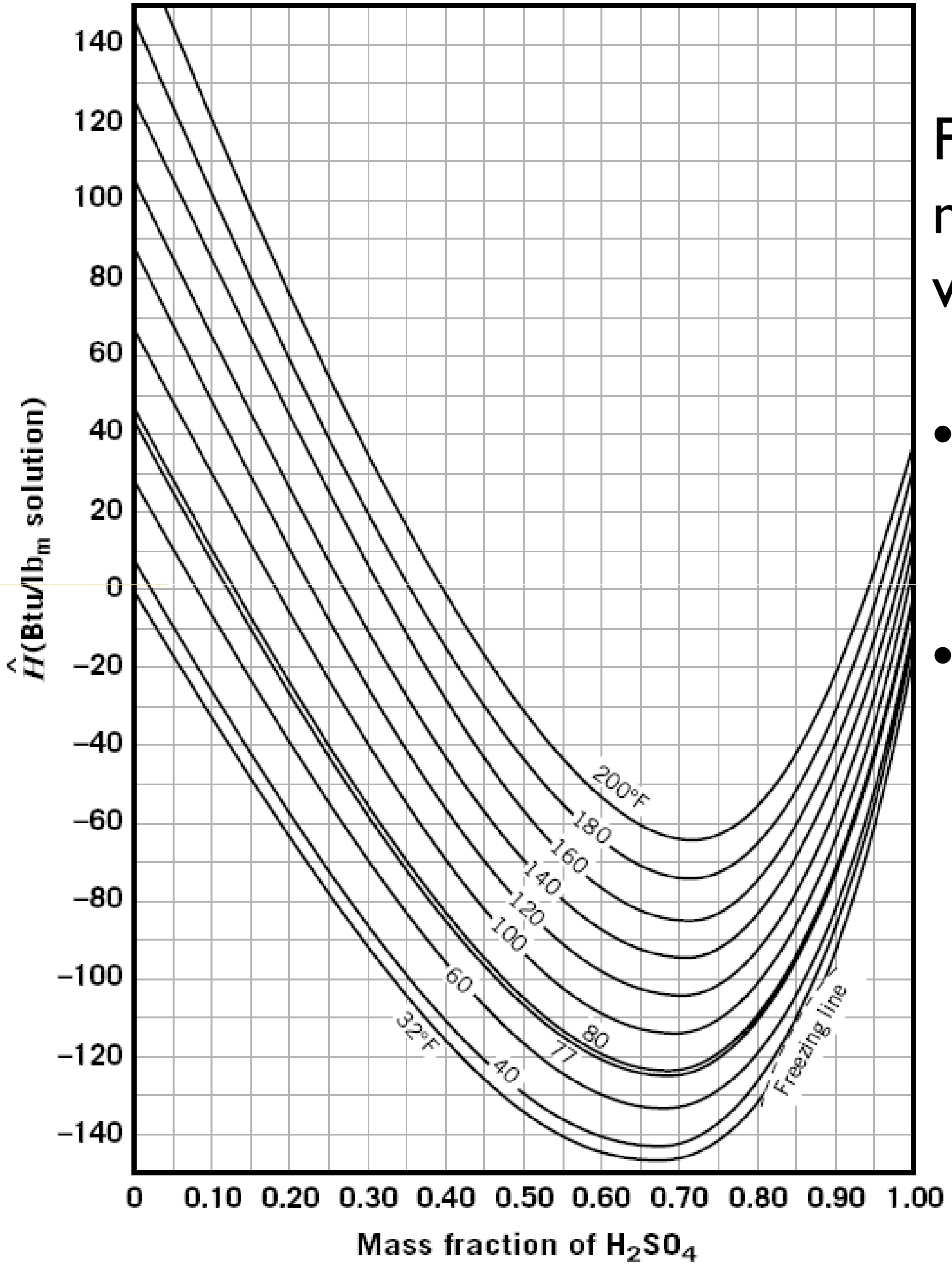


Fig. 8.5-1, p. 399, for liquid mixtures of sulfuric acid and water

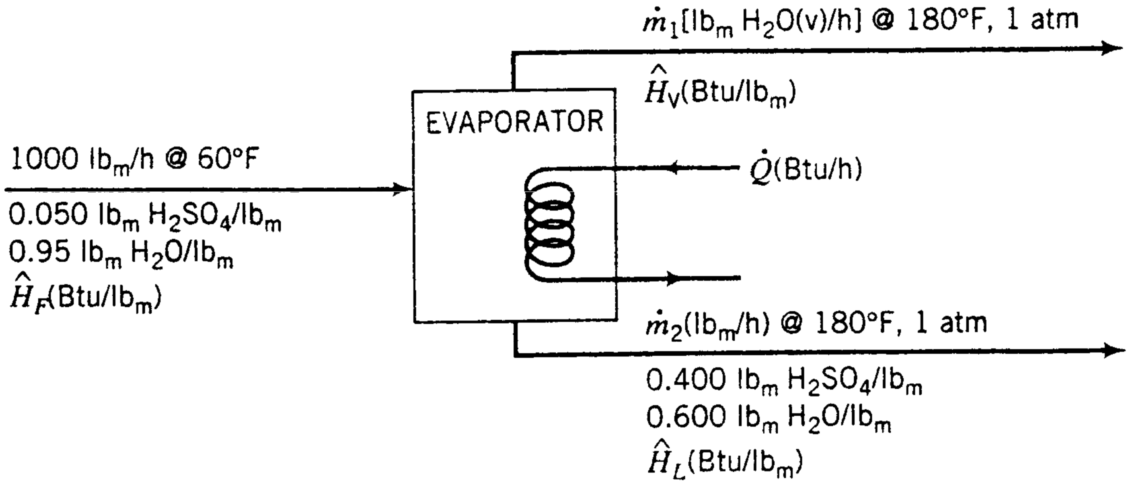
- equivalent to heat of mixing or heat of solution data
- can be used to solve energy balance problems for mixing or separation of aqueous sulfuric acid streams

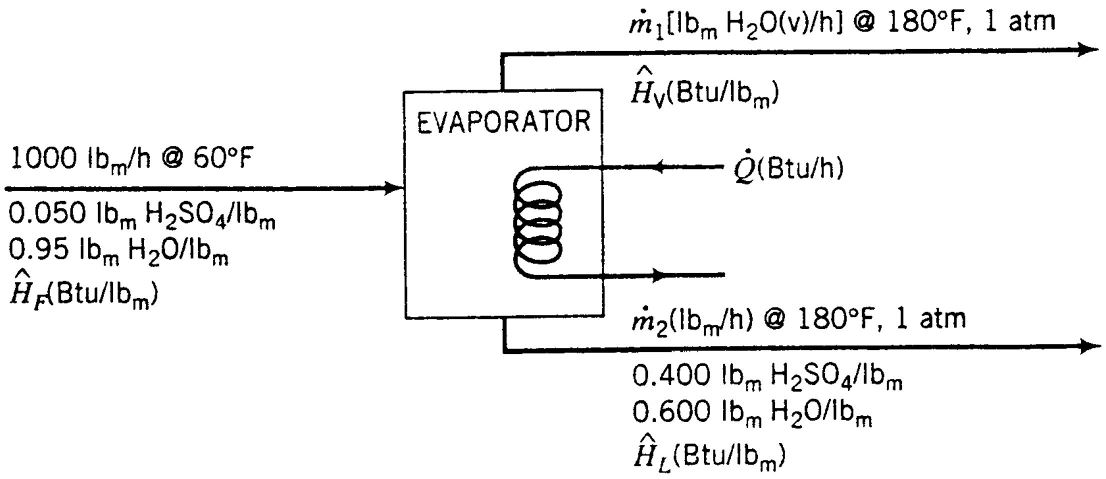
# Enthalpy-concentration diagrams: Single Liquid phase

## Example 8.5.2: *Concentration of an Aqueous $H_2SO_4$ Solution*

A 5.0 wt% $H_2SO_4$ solution at 60°F is to be concentrated to 40.0 wt% by evaporation of water. The concentrated solution and water vapor emerge from the evaporator at 180°F and 1 atm. Calculate the rate at which heat must be transferred to the evaporator to process 1000 $lb_m/h$ of the feed solution.

***Basis: Given Feed Rate of 5% Solution***





***$H_2SO_4$ Balance*** $\quad (0.050)(1000)\ \mathrm{lb_m/h} = 0.400\dot{m}_2 \Longrightarrow \dot{m}_2 = 125\ \mathrm{lb_m/h}$

***Total Mass Balance*** $\quad 1000\ \mathrm{lb_m/h} = \dot{m}_1 + \dot{m}_2 \xRightarrow{\dot{m}_2 = 125\ \mathrm{lb_m/h}} \dot{m}_1 = 875\ \mathrm{lb_m/h}$

***Reference States for Energy Balance*** $\quad H_2O(l, 32°F), H_2SO_4(l, 77°F)$

From Figure 8.5-1:

$$\hat{H}_F = 10\ \mathrm{Btu/lb_m} \qquad (5\%\ H_2SO_4 \text{ at } 60°F)$$
$$\hat{H}_L = -17\ \mathrm{Btu/lb_m} \qquad (40\%\ H_2SO_4 \text{ at } 180°F)$$

The enthalpy of water vapor at 180°F and 1 atm relative to liquid water at 32°F may be obtained from the steam tables in *Perry's Chemical Engineers' Handbook* (see footnote 5) as

$$\hat{H}_V = 1138\ \mathrm{Btu/lb_m}$$

***Energy Balance***

$$\begin{aligned}\dot{Q} &= \Delta\dot{H} = \dot{m}_1\hat{H}_V + \dot{m}_2\hat{H}_L - (1000\mathrm{lb}_m/h)\hat{H}_F \\ &= [(875)(1138) + (125)(-17) - (1000)(10)]\ \mathrm{Btu/h} \\ &= \boxed{984{,}000\ \mathrm{Btu/h}}\end{aligned}$$

# Enthalpy-concentration diagrams: vapor-liquid Equilibrium Calculations

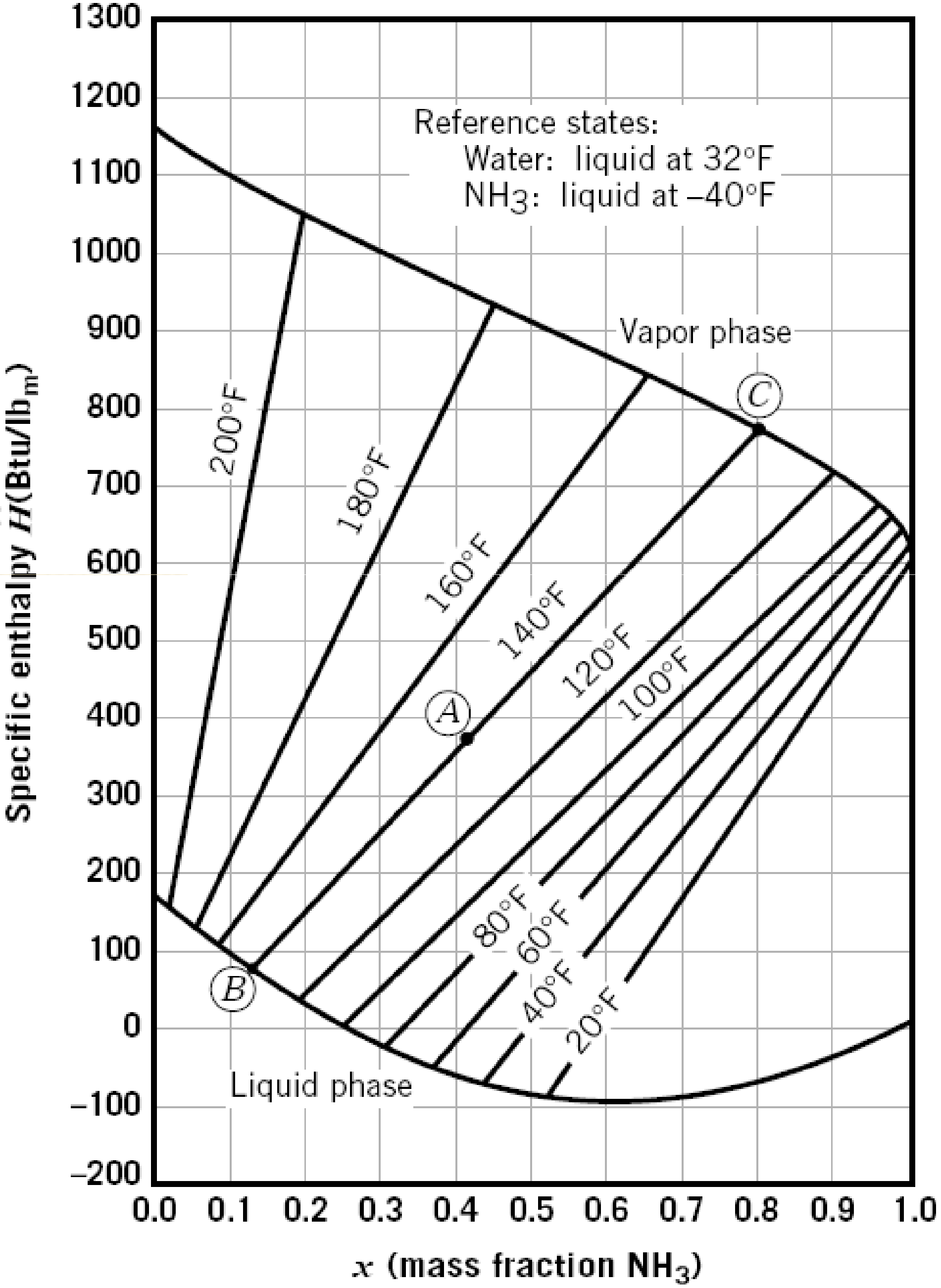


Fig. 8.5-2, p. 403, for liquid-vapor equilibria in the ammonia + water system at 1 atm pressure

- has saturated liquid and vapor curves plus tie lines in the two-phase region
- can be used to solve energy balance problems, such as the flash vaporization of ammonia + water mixtures (see Example 8.5-5, p. 405)