

## Introduction to mass transfer in staged processes

- **mass exchange:**
  - **mass transfer** – from within the phase to the interface
  - **overall mass transfer** – from within the phase to the other phase across the interface
- **diffusion:** relative motion of a component with respect to the mixture (within one phase)
- **permeation:** transport from one phase to the second across a membrane

### Purpose of mass exchange:

- removal of unwanted components from a product
- removal of impurities from raw materials, waste water or polluted air

### Basic processes of mass exchange (= separation processes)

**extraction** – separation of a liquid mixture by adding another liquid-**solvent** so that two liquid phases are formed

**distillation** – separation of a liquid mixture by partial vaporization (i.e. by adding heat); reverse process is partial condensation

**rectification** – distillation in a staged or packed column with reflux

**absorption** – separation of a gaseous mixture by dissolving some component(s) in a liquid; reverse process is **desorption**

**adsorption** – separation of either gaseous or liquid mixture by binding some component(s) on a solid surface; reverse process is **desorption**

**drying** – evaporation of liquids from a mixture with a solid

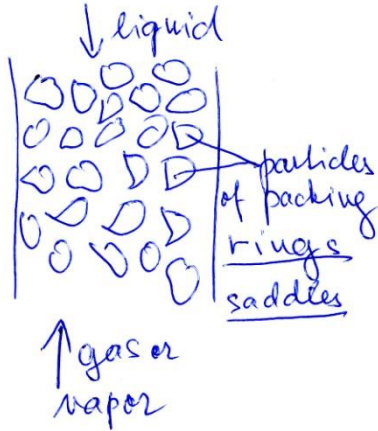
**leaching** – separation of a solid mixture by adding a liquid solvent (analogous to extraction)

**crystallization** – formation of crystals from a solution or a melt

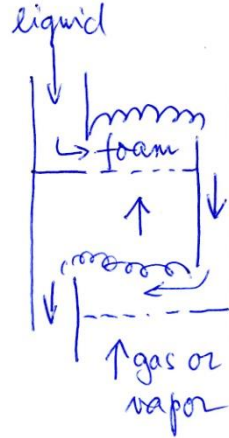
**membrane separations** – separation of homogeneous (single-phase) systems by using a membrane

### Types of mass exchangers

- contact of phases
  - **continuous:** column with a film, column with a packing, spray column, bubbled column
  - **staged:** column with stages (= plates), cascade of stages



Scheme of packed column



Staged column

**Amount of transferred component is proportional to:**

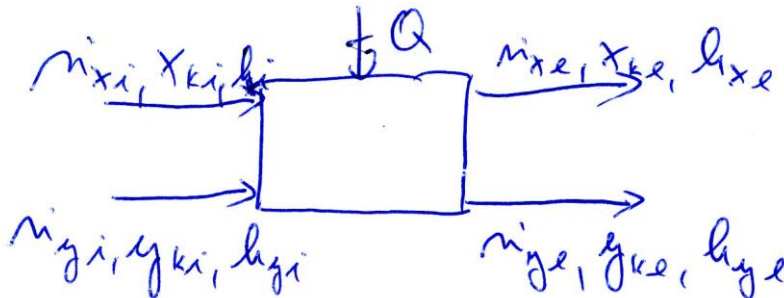
- the interface area (enhanced by packing, foam or bubbles)
- rate of interface transport
- contact time of the phases

**Basic equations form mass exchange**

- 1) material balances:  $\sum \text{inputs} + \underbrace{\text{source}}_{\substack{\text{normally} \\ \text{zero}}} = \sum \text{outputs} + \text{accumulation}$   
 $\text{accumulation} = 0$  at steady state
- 2) energy (enthalpy) balances
- 3) equilibrium condition – relation between composition in both phases
- 4) kinetic equation – rate of mass transfer
- 5) additional equations:  $pV = nRT, \sum x_i = 1$ , etc.

**Equilibrium stage**

- streams leaving are at equilibrium and phases are separated



- $i$  ... inlet
- $e$  ... outlet
- $x$  ... “heavier” phase
- $y$  ... “lighter” phase
- $\dot{n}$  ... molar flow
- $x, y$  ... molar fractions
- $h$  ... molar enthalpy

**Balance equations for flow system (differential time period)**

- moles of component k

$$\dot{n}_{xi}x_{ki} + \dot{n}_{yi}y_{ki} + \frac{dn_{kr}}{d\tau} = \dot{n}_{xe}x_{ke} + \dot{n}_{ye}y_{ke} + \frac{dn_{kS}}{d\tau}, \quad k = 1, \dots, K$$

no chemical reaction:  $\frac{dn_{kr}}{d\tau} = 0$

steady state:  $\frac{dn_{kS}}{d\tau} = 0$

enthalpy:

$$\dot{n}_{xi}h_{xi} + \dot{n}_{yi}h_{yi} + \underbrace{\dot{Q}}_{\text{heat flow}} = \dot{n}_{xe}h_{xe} + \dot{n}_{ye}h_{ye} + \frac{dH_S}{d\tau}$$

equilibrium relations:

$$p_{xe} = p_{ye} = p_e \quad \dots \text{ pressure}$$

$$T_{xe} = T_{ye} = T_e \quad \dots \text{ temperature}$$

$$y_{ke} = f(x_{1e}, \dots, x_{ke}, p_e, T_e) = \psi_k x_{ke}, \quad k = 1, \dots, K$$

In general,  $\psi_k$  is a function of  $x_{1e}, \dots, x_{ke}, p_e, T_e$

### Real (nonequilibrium) stage

Kinetic equations should be used. but often this is avoided (too difficult) and replaced by an empirical relation called **efficiency**.

$$\text{Efficiency} = \frac{\text{difference of input/output composition}}{\text{maximum such difference}}$$

$$E_{xk} = E_{yk} = E_k = \frac{x_{ki} - x_{ke}}{x_{ki} - x_{ke}^*} = \frac{y_{ke} - y_{ki}}{y_{ke}^* - y_{ki}}$$

(transport of component k from phase x to phase y is assumed). Here  $y_{ke}^* = \psi_k x_{ke}^*$

Remark: for counter-current cascade of stages or for a counter-current column a different efficiency is defined (Murphree eq., see later)

### Examples of equilibrium relations

**distillation:**

$$\underbrace{p_k}_{\text{partial pressure}} = \underbrace{y_k p}_{\text{Dalton's law}} = \underbrace{p_k^0 x_k}_{\text{Raoult's law}} \quad (\text{holds for ideal mixtures})$$

$x, y \dots$  molar fractions !

$$\text{thus } y_k = \frac{p_k^0}{p} x_k = \psi_k x_k$$

$p$  ... overall pressure

$p_k^0$  ... vapor pressure of pure component  $k$  (from Antoine equation  $p_k^0 = \exp\left(A - \frac{B}{C+T}\right)$ )

**absorption:**  $y_k = \frac{H_k}{p} x_k$  Henry's law,  $H_k$  is found in tables (empirical)

**extraction:** non-ideal behavior

$a_{kx} = a_{ky}$  activities in both phases

$$\gamma_{kx} x_k = \gamma_{ky} y_k \rightarrow y_k = \frac{\gamma_{kx}}{\gamma_{ky}} x_k = \psi_k x_k$$

Activity coefficients  $\gamma_{kx}, \gamma_{ky}$  depend on composition and so equilibrium relation is nonlinear often in form of a graph

