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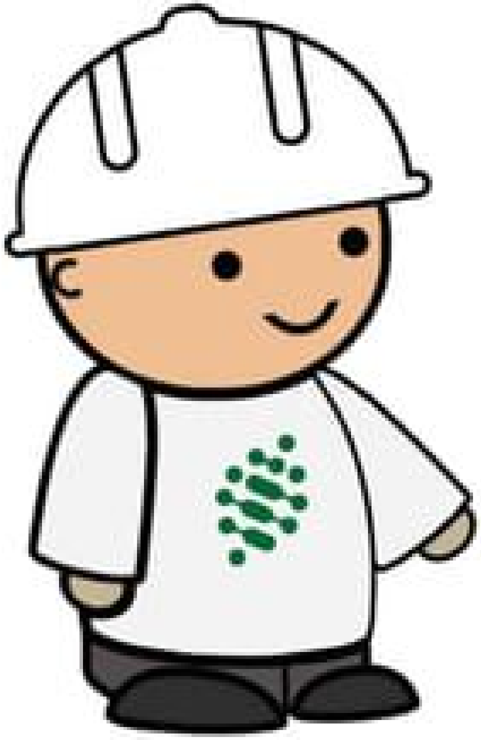

# What is mass transfer?

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869993.

# Transport processes

- **Mass transfer** is one of the three major transport processes in chemical engineering. The other two are **momentum transport** and **heat transport**. They have **many analogies** and they often **occur simultaneously**.
- All of these processes are **gradient driven**. They have a **driving force** which causes the transfer of mass, heat or momentum.

| Process | Driving force |
|---|---|
| Mass transfer | Concentration difference |
| Momentum transfer | Velocity gradient |
| Heat transfer | Difference in temperature |

# Occurence of mass transfer

- Mass transfer occurs **in everyday life**, e.g. in drying of clothes or dissolution of honey in tea.
- Many mass transfer processes occur also **in human body**, e.g. in the transport of oxygen and carbon dioxide.
- Mass transfer operations are widely used **in industry** in different **separation and purification** processes.
- However, not all separation processes are mass transfer operations. E.g. centrifugation and filtration are mechanical unit operations.

# Mass transfer process

- Mass transfer is the **net movement of species** in a mixture from one location to another.
- Chemical species move **from** areas of **high concentration to** areas of **low concentration**. This phenomenon is called **diffusion**.
- One typical example of diffusion is dropping food coloring into water.
- Diffusion **does not need external energy**. Molecules mix due to their random motion.
- Diffusion happens more rapidly in hot water.
- Stirring accelerates the diffusion.

# Basic mechanisms of mass transfer

- Molecules transfer randomly from higher concentration to lower concentration. This phenomenon is called **molecular diffusion**.
- In turbulent medium, phenomenon called **eddy diffusion also occurs**. Then a random, macroscopic fluid motion of eddies is also involved.
- When the motion in a fluid medium plays a significant role, the process is called **convective mass transfer**.
- Some **chemical reactions** might also occur, affecting the mass transfer process.

# Molecular diffusion and eddy diffusion

- **Molecular diffusion** is extremely slow.
- **Eddy diffusion** is more rapid.
- Both molecular and eddy diffusion may involve the movement of different species in opposing directions.
- When a **bulk flow** occurs, the total rate of mass transfer of individual species is increased or decreased by this bulk flow.
- In industrial separation processes, the fluids must be agitated and interfacial areas maximized to accelerate the process.

Stirring accelerates the diffusion.
(Screenshot from the video)

# References

Dutta, B. K. 2007. Principles of mass transfer and separation processes. New Delhi: Prentice-Hall, pp. xi-xii, 1-4, 74.

Lakhi, K. & Viswanathan. B. 2012. Chemical engineering: A comprehensive approach. Alpha Science International Ltd. pp. 153-154.

Seader, J. D., Roper, D. K. & Henley, E. J. 2011. Separation process principles: Chemical and biochemical operations. 3rd ed. Hoboken, NJ: Wiley, pp. 85-86.

**Videos:**

- An overview of the phenomenon of mass transfer: https://youtu.be/-YTC3A6dEGM
- Molecular diffusion and eddy diffusion: https://youtu.be/4Hy0aEwq6fk

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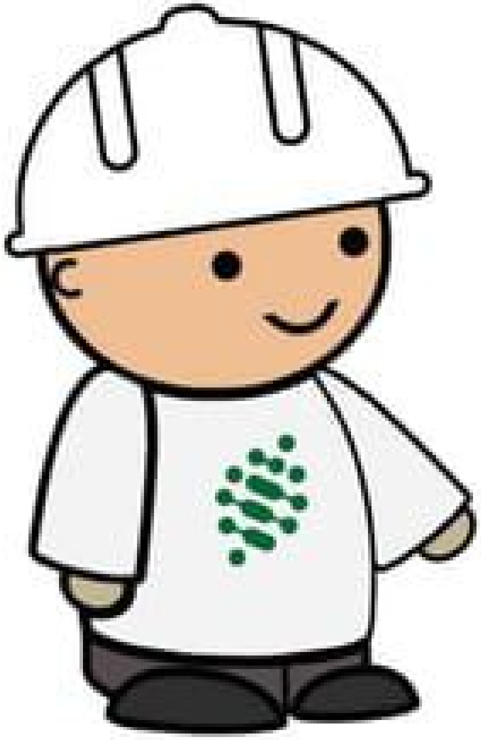

# Classification of mass transfer processes

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869993.

# Mass transfer separation processes

- In mass transfer separation processes, the **mixture of substances is transformed into two or more products** differing in composition.
- Core separation processes in chemical industry are:
  - distillation
  - gas absorption and stripping
  - liquid-liquid and liquid-solid extraction
  - drying of a wet solid
  - adsorption
  - crystallization
  - membrane separation
  - separation of multicomponent mixtures
- There are also several other processes that are not discussed in this course.

# Typical applications

| Separation process | Typical applications |
|---|---|
| Distillation | Fractionation of crude oil |
| Gas absorption | Removal of $CO_2$ from synthesis gas |
| Stripping (desorption) | Stripping volatile substances from wastewater by steam |
| Adsorption | Drying of air |
| Drying | Drying of fruits |
| Crystallization | Production of salt and sugar |
| Liquid-liquid extraction | Removal of benzene from gasoline |
| Membrane extraction | Concentration of milk |
| Solid-liquid extraction | Extraction of caffein from coffee |

# Principle mechanisms

- There are **three phases** encountered in practice: gas, liquid and solid. If mass transfer occurs between two phases, there are **total nine possible combinations** of operations. If the direction is not concidered, there are six combinations (**bolded** in the table).
- The mass transfer operations can also be classified in four mechanisms:
    1. Contact of two **immiscible** phases
    2. **Indirect** contact of **miscible** phases
    3. **Direct** contact of **miscible** phases
    4. Use of surface phenomena
- Let's take a closer look at these.

| | **Phase undergoing treatment** | **Phase performing treatment** |
|---|---|---|
| 1 | **Gas** | **Gas** |
| 2 | **Gas** | **Liquid** |
| 3 | **Gas** | **Solid** |
| 4 | Liquid | Gas |
| 5 | **Liquid** | **Liquid** |
| 6 | **Liquid** | **Solid** |
| 7 | Solid | Gas |
| 8 | Solid | Liquid |
| 9 | **Solid** | **Solid** |

# Contact of two immiscible phases

- When to **immiscible** phases are in contact, mass transfer or diffusion may occur through the **interphase between the phases**. Most of the real-world industrial mass transfer processes include in this category.

| Category | Examples of separation processes |
|---|---|
| Gas-gas | Cannot be realized, because all gases are soluble in each other. |
| Gas-liquid | Distillation, gas absorption, desorption/stripping, humidification |
| Gas-solid | Fractional sublimation, drying, desorption, adsorption |
| Liquid-liquid | Liquid-liquid extraction, fractional extraction |
| Liquid-solid | Fractional solidification, crystallization, leaching |
| Solid-solid | No industrial separation operations (so slow rate of diffusion) |

## Indirect contact of miscible phases

- In this category, the phases are separated with diffusion through a permeable or semi-permeable **membrane**. The membrane is necessary to prevent the mixing of the phases. It also selectively separates materials.
- Membranes can be organic or inorganic.
- There are three possible combinations within phases shown in the table below. There is no phase change associated with the separation.

| **Category** | **Examples of separation processes** |
|---|---|
| Gas-gas | Gaseous diffusion, gas permeation, effusion |
| Gas-liquid | Permeation separation |
| Liquid-liquid | Dialysis, electrodialysis, osmosis, reverse osmosis |
| Solid-solid | No practical applications in the chemical process industry |

# Others

- When **miscible phases** has a **direct contact**, it is difficult to maintain the concentration gradient.
- These operations have only a few industrial applications: Thermal diffusion, sweep diffusion, atmolysis and centrifugation of a gas mixture.
- **Foam separation** is an example of **use of surface phenomena**. It should not be confused with the flotation process, where insoluble soplid particles are removed from slurries.
- In foam separation, a foam is formed by bubbling air through the solution. The foam is collected and the solute can be concentrated.
- This classification into four groups categorizes all the major mass transfer operations. Although, new operations continue to be developed.

# References

Dutta, B. K. 2007. Principles of mass transfer and separation processes. New Delhi: Prentice-Hall, pp. 3-6.

Theodore, L. & Ricci, F. 2010. Mass Transfer Operations for the Practicing Engineer. John Wiley & Sons, Inc, pp. 43, 97-102

Treybal, R. E. 1980. Mass-transfer operations. 3rd ed. Auckland: McGraw-Hill, pp. 2-7.

**Videos:**

- Introduction to mass separation processes: https://youtu.be/YjuZs8PFIEU
- Liquid-liquid extraction in laboratory: https://youtu.be/8bZI7mcG0Ew
- Fractional distillation separates crude oil: https://youtu.be/PYMWUz7TC3A
- Overview of mass transfer operations: https://youtu.be/6wi2ReP2ezI

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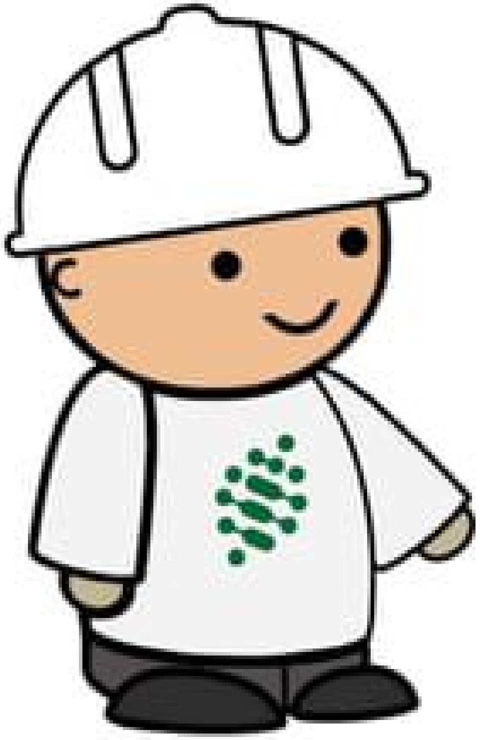


# Interphase mass transfer

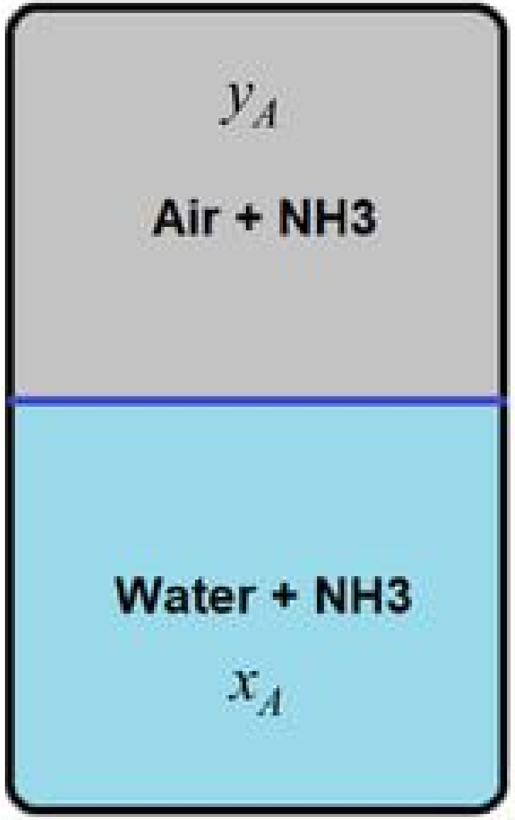
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869993.

# Interphase mass transfer

- Molecular diffusion and convective mass transfer concerned only the mass transfer within a single phase.
- In practical applications, there are usually **two insoluble phases** brought into contact to permit mass transfer between them.
- In one-phase system, the rate of diffusion is dependent upon concentration differences within the phase.
- In two-phase system, the driving force is measured by **how far the phases are away from equilibrium** which exists between the two phases.
- When the **equilibrium** is achieved, the **net rate** of diffusion will fall to **zero**.
- Molecules continue to transfer back and forward, but **concentrations** within each phase **no longer change**.

# Equilibrium

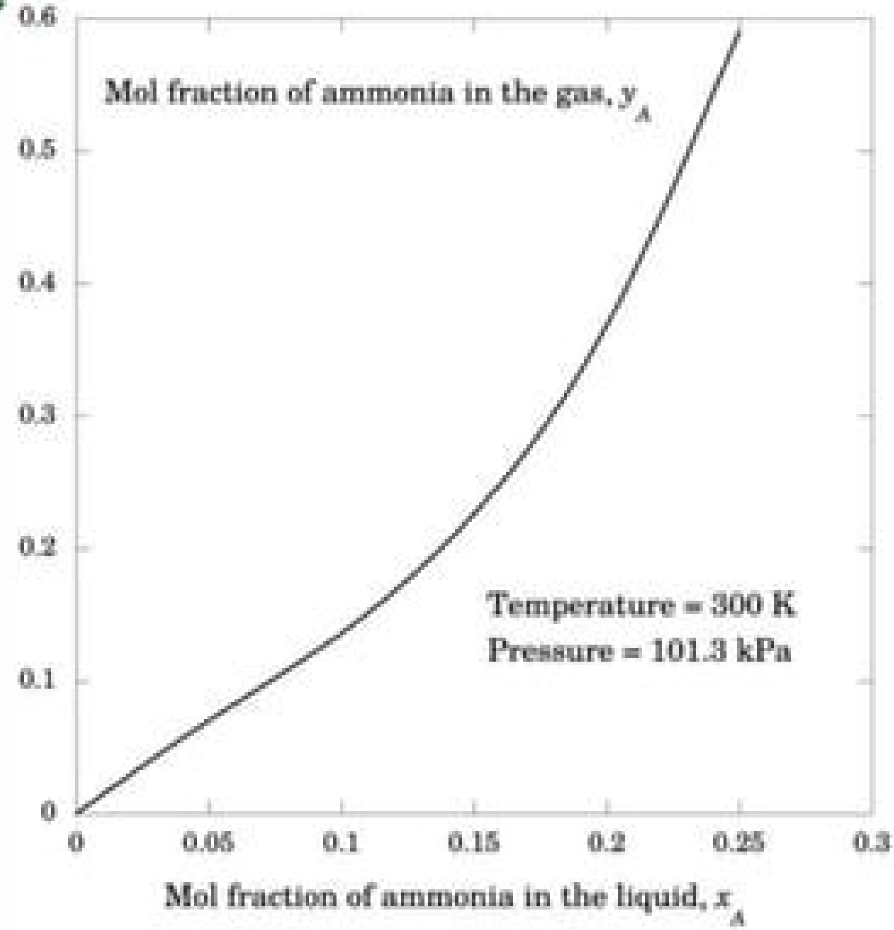
- Let's consider an example where ammonia ($NH_3$) is dissolved from ammonia-air mixture into liquid water.
- Fixed amount of water and ammonia-air mixture are placed in a closed container at constant temperature and pressure. Ammonia is very soluble in water and it starts to **transfer into water** through the interface.
- Part of ammonia molecules escapes back into the gas. This continues until the rates are equal and net transfer falls to zero.
- With time, concentrations throughout each phase become uniform by diffusion. **Equilibrium is achieved**.




$x_A$ = Mole fraction of ammonia in the liquid
$y_A$ = Mole fraction of ammonia in the gas

# Equilibrium-distribution curve

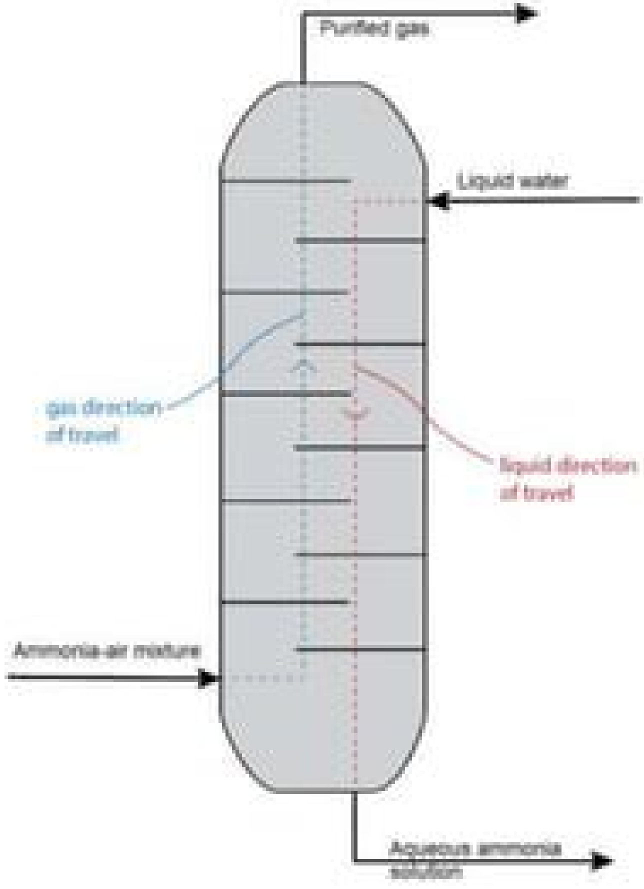
- If additional ammonia is injected into the container, a new set of equilibrium concentrations will be eventually established. Concentrations in both phases ($x_A$ and $y_A$) are now higher.
- This **equilibrium data** can be presented in **equilibrium curve**: mole fraction in the liquid on the x-axis and mole fraction in the gas on the y-axis.
- Pressure and temperature are fixed.




Picture: Benitez 2016, 160.

# Diffusion between phases

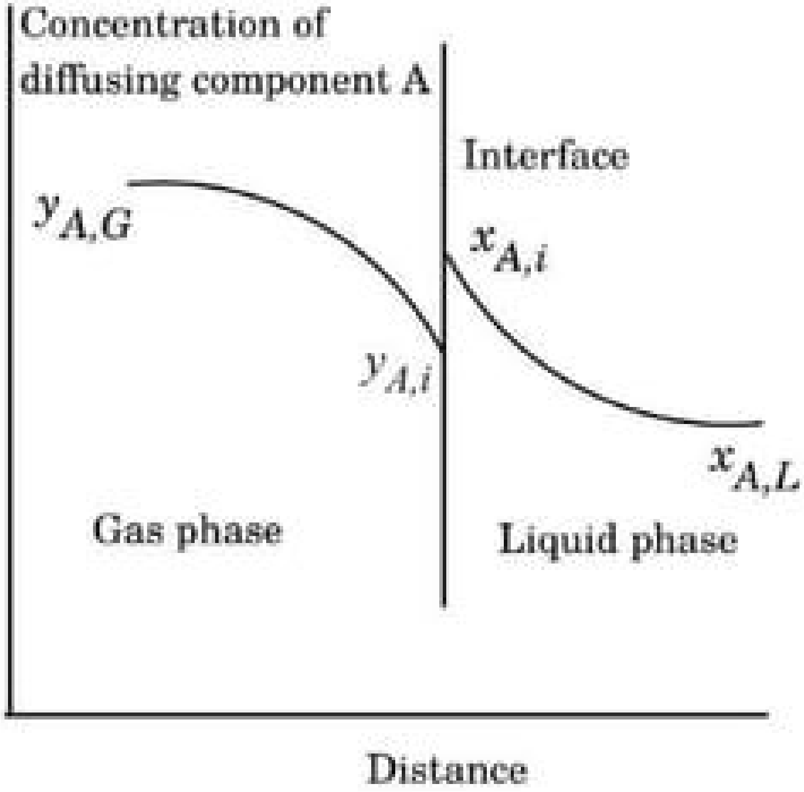
- Industrial mass transfer operations are usually carried out under **steady-state** conditions. It means that the **concentrations do not vary** with time at any position in the apparatus.
- Let's continue with the gas absorption example. Ammonia-air mixture is feeded from the bottom of the column and water is feeded from top.
- Water absorbs the ammonia as it flows downward and **the concentration of ammonia in gas decreases** as the gas flows upward.
- **The concentrations at any particular point** in the column **do not change** with time.




Simplified absorption column
Picture by Jocelynskim - 
remixed by Kati Jordan

# Two-resistance film theory

- Interphase mass transfer can be divided into **three steps**:
  1. Transfer of mass from bulk flow of one phase to the interfacial surface
  2. Transfer of mass across interface into the second phase
  3. Transfer of mass to the bulk flow of the second phase
- Situation in a particular level of the column can be visualized graphically.
- Concentrations $x_{A,i}$ and $y_{A,i}$ are the **equilibrium values** from the equilibrium curve.



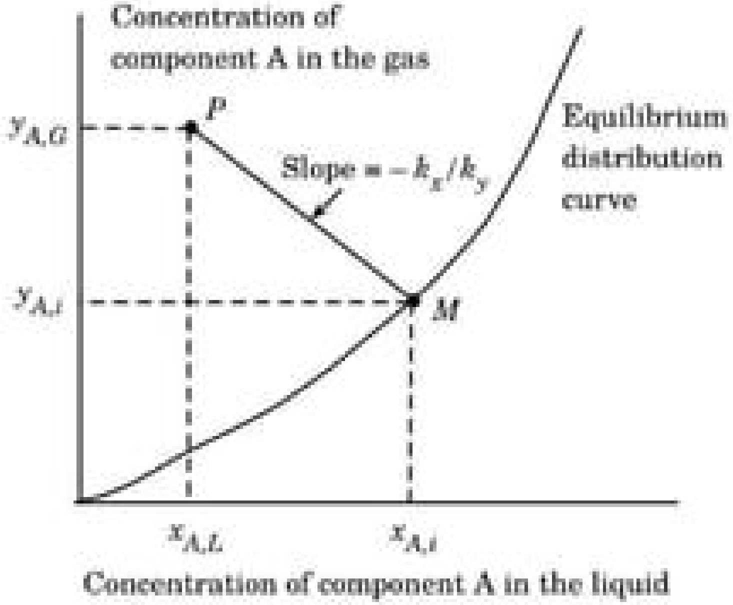

Picture: Benitez 2016, 165.

# Mass transfer coefficients and slope

- Let's put those values into the equilibrium diagram.
- Point P represents the concentrations in the bulk phases (gas and liquid), and point M presents the values in the interphase.
- Because we have a steady-state system, molar fluxes of ammonia are equal in both directions:

$$N_A = k_y(y_{A,G} - y_{A,i}) = k_x(x_{A,i} - x_{A,L})$$

- $k_y$ = local mass transfer coefficient in **gas** phase
  $k_x$ = local mass transfer coefficient in **liquid**
  $y_{A,G}$ and $x_{A,L}$ are **bulk** mole fractions
- $y_{A,i}$ and $x_{A,i}$ the mole fractions in the **interphase**

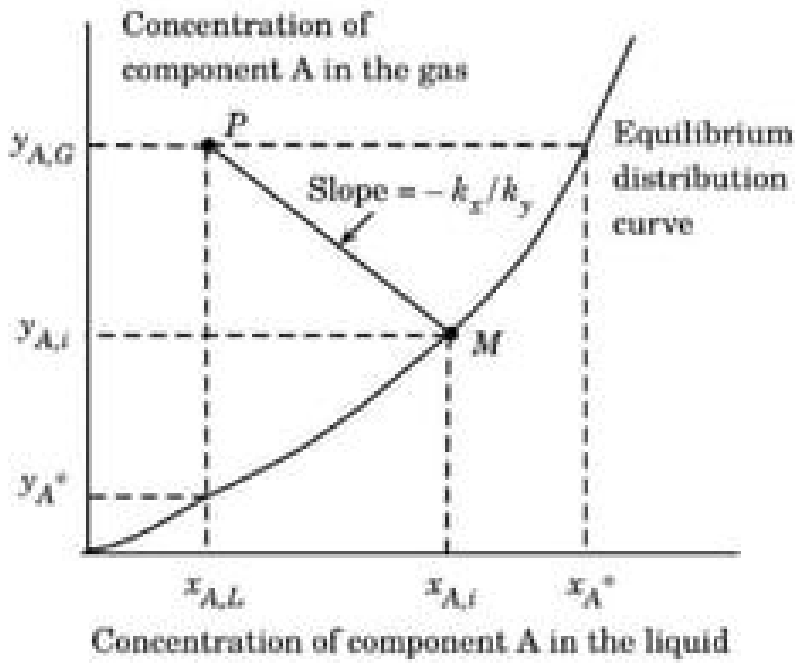



Slope of the line PM can be determined by the local mass transfer coefficients.
Picture: Benitez 2016, 166.

# Overall mass transfer coefficients

- It is usually hard to determine the interphase concentrations $y_{A,i}$ and $x_{A,i}$.
- Overall mass transfer coefficients can be determined by the **equilibrium concentrations $y_A$* and $x_A$*** with respective to bulk concentrations.

  $N_A = K_y(y_{A,G} - y_A^*) = K_x(x_A^* - x_{A,L})$
- Overall mass transfer coefficients are marked with **upper case $K$**.
- These overall coefficients are exactly valid only in those situations, **when the equilibrium-distribution line is straight**.




Picture: Benitez 2016, 167.

# Correlations between mass transfer coefficients

- When the equilibrium relation is linear, the relations between gas and liquid phase concentrations can be presented with proportionality constant $m$.
- $y_{A,i} = mx_{A,i}$ $\qquad$ $y_A^* = mx_{A,L}$ $\qquad$ $y_{A,G} = mx_A^*$
- On these circumstances, the following equations are valid:

$$\frac{1}{K_y} = \frac{1}{k_y} + \frac{m}{k_x} \qquad \frac{1}{K_x} = \frac{1}{mk_y} + \frac{1}{k_x}$$

- Many values for mass transfer coefficients have been determined by experimental studies. Values can be converted to other forms.
- Correlations between different types of mass transfer coefficients presented in *Chapter 2.3 Convective mass transfer* are valid also here. For example:

$$K_y = PK_G = \frac{PK_C}{RT}$$

# Example

- Absorption of ammonia by water in a wetted-wall column.

Temperature T = 300 K and pressure P = 1 atm = 101.325 kPa

Proportionality constant m = 1.64 at those circumstances and dilute solutions

At one point in the column $x_{A,L} = 0.00115$ and $y_{A,G} = 0.08$

Experimental value of $K_G = 2.75 \cdot 10^{-6}$ kmol/(m²·s·kPa)

Calculate the molar flux $N_A$.

Solution: $N_A = K_y(y_{A,G} - y_A{}^*)$

$$K_y = PK_G = 101.325\ \mathrm{kPa} \cdot 2.75 \cdot 10^{-6} \frac{\mathrm{kmol}}{\mathrm{m^2 \cdot s \cdot kPa}} = 2.7864 \ldots \cdot 10^{-4} \frac{\mathrm{kmol}}{\mathrm{m^2 \cdot s}}$$

$$y_A{}^* = mx_{A,L} = 1.64 \cdot 0.00115 = 1.886 \cdot 10^{-3}$$

$$N_A = 2.7864 \ldots \cdot 10^{-4} \frac{\mathrm{kmol}}{\mathrm{m^2 \cdot s}} \cdot (0.08 - 1.886 \cdot 10^{-3}) \approx 2.18 \cdot 10^{-5} \frac{\mathrm{kmol}}{\mathrm{m^2 \cdot s}}$$

# Summary

- Most of the industrial mass transfer processes are interphase mass transfer.
- Two phases are brought into contact to permit mass transfer between them.
- The driving force is measured by **how far the phases are away from equilibrium** which exists between the two phases.
- Equilibrium data can be expressed in **equilibrium curve**.
- Molar flux can be determined with mass transfer coefficients: local or overall.
- With **local** mass transfer **coefficients**: $N_A = \boldsymbol{k_y}(y_{A,G} - y_{A,i}) = \boldsymbol{k_x}(x_{A,i} - x_{A,L})$
- With **overall** mass transfer **coefficients**: $N_A = \boldsymbol{K_y}(y_{A,G} - y_A^*) = \boldsymbol{K_x}(x_A^* - x_{A,L})$
- Overall mass transfer coefficients can be used only when the equilbrium curve is straight or only slightly curved.
- Correlations between different types of mass transfer coefficients are valid also for overall mass transfer coefficients.

# References

Benitez, J. 2016. Principles and Modern Applications of Mass Transfer Operations. Wiley, pp. 158-167.

Dutta, B. K. 2007. Principles of mass transfer and separation processes. New Delhi: Prentice-Hall, pp. 122-138.

Treybal, R. E. 1980. Mass-transfer operations. 3rd ed. Auckland: McGraw-Hill, pp. 104-114.

**Videos:**

- Local vs. Overall coefficients: https://youtu.be/4AmIGiUxQ4o
- Two film theory: https://youtu.be/ydTo0SFTm2A

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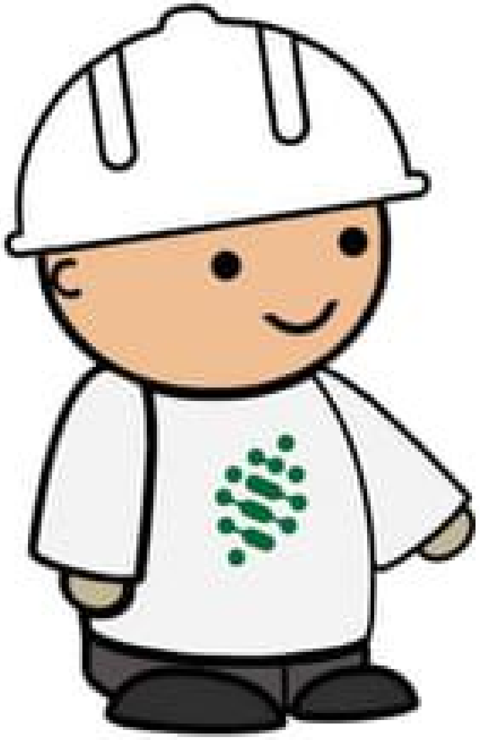

# Convective mass transfer

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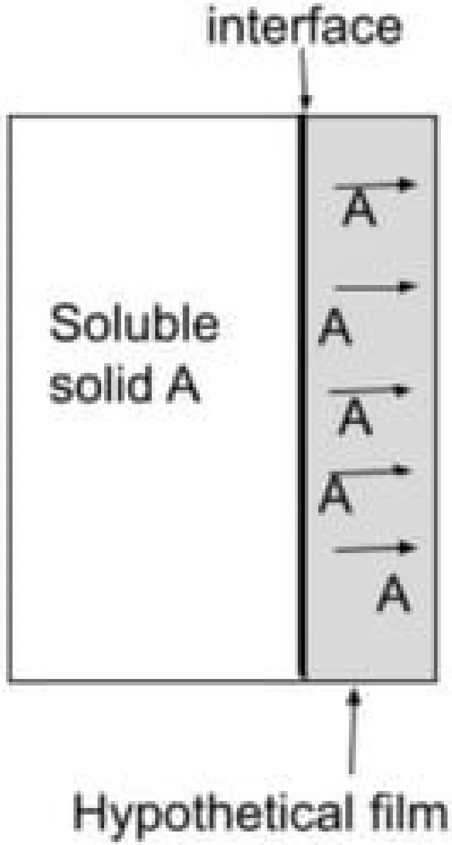
# Convective mass transfer

- Molecular diffusion has a major role in a stagnant medium. It is extremely slow process. If there is motion in the medium, the rate of mass transfer increases dramatically. This is called **convective mass transfer**.
- For example, if you add sugar in coffee, it will dissolve much more rapidly if you stir it with the spoon.
- There is a **'boundary layer'** or **'film'** surrounding the sugar crystal which get saturated instantly. Dissolved sugar diffuses from the interface to the bulk through this 'film'. **Stirring** decreases the thickness of the film and **accelerates the rate of mass transfer**.



# Mass transfer coefficients

- Theoretical calculations of the mass transfer rate in turbulent flow can become very complex. **Mass transfer coefficients** are here to simplify the calculations.
- The idea of mass transfer coefficient is similar to heat transfer coefficient, although there are different types of mass transfer coefficients.
  - mass transfer **in liquid or gas** phase
  - choice of the **driving force**
  - equimolar counterdiffusion or diffusion of A through stagnant B
- These are presented on the next slide.

| **Heat transfer coefficient** | **Mass transfer coefficient** |
| --- | --- |
| $h = \frac{q}{\Delta T}$ | $k_c = \frac{N_A}{\Delta C_A}$ |
| $q$ = heat flux<br><br>$\Delta T$ = difference in temperature between the solid surface and surrounding area | $N_A$ = molar flux<br><br>$\Delta C_A$ = difference in concentration **between the interface and the bulk fluid** |

Comparison of heat transfer coefficient and mass transfer coefficient

# Different types of mass transfer coefficients

| | Equimolar counter diffusion | Diffusion of A through non-diffusing B | |
|---|---|---|---|
| in GASES | In terms of partial pressures<br>$N_A = k'_G(p_{A1} - p_{A2})$ $\quad k'_G = \frac{D_{AB}}{RT\delta}$ | $N_A = k_G(p_{A1} - p_{A2})$ $\quad k_G = \frac{D_{AB}P}{RT\delta p_{BM}}$ | |
| | In terms of mole fractions<br>$N_A = k'_y(y_{A1} - y_{A2})$ $\quad k'_y = \frac{D_{AB}P}{RT\delta}$ | $N_A = k_y(y_{A1} - y_{A2})$ $\quad k_y = \frac{D_{AB}P^2}{RT\delta p_{BM}}$ | $p_{BM} = \frac{p_{B2} - p_{B1}}{\ln \frac{p_{B2}}{p_{B1}}}$ |
| | In terms of concentrations<br>$N_A = k'_c(C_{A1} - C_{A2})$ $\quad k'_C = \frac{D_{AB}}{\delta}$ | $N_A = k_c(C_{A1} - C_{A2})$ $\quad k_C = \frac{D_{AB}P}{\delta p_{BM}}$ | |
| in LIQUIDS | In terms of concentrations<br>$N_A = k'_L(C_{A1} - C_{A2})$ $\quad k'_L = \frac{D_{AB}}{\delta}$ | $N_A = k_L(C_{A1} - C_{A2})$ $\quad k_L = \frac{D_{AB}}{\delta x_{BM}}$ | |
| | In terms of mole fractions<br>$N_A = k'_x(x_{A1} - x_{A2})$ $\quad k'_x = \frac{CD_{AB}}{\delta}$ | $N_A = k_x(x_{A1} - x_{A2})$ $\quad k_x = \frac{CD_{AB}}{\delta x_{BM}}$ | $x_{BM} = \frac{x_{B2} - x_{B1}}{\ln \frac{x_{B2}}{x_{B1}}}$ |

# Notations

| Symbol | Explanation | Units |
|---|---|---|
| $N_A$ | molar flux of A with respect to a stationary observer | mol/(m$^2$·s) |
| $D_{AB}$ | diffusivity of A in mixture of A and B | m$^2$/s |
| $\delta$ | length of the diffusion path | m |
| $R$ | gas constant (8.31451) | (Pa·m$^3$)/(mol·K) |
| $T$ | temperature | K |
| $P$ | total pressure | Pa |
| $C$ | average molar concentration | mol/m$^3$ |
| $p_{A1}$ | partial pressure of A in bulk | Pa |
| $p_{A2}$ | partial pressure of A in the interphase | Pa |
| $p_{B0}$ | partial pressure of B in bulk | Pa |
| $p_{B2}$ | partial pressure of B in the interphase | Pa |
| $p_{BM}$ | log mean partial pressure of B | Pa |

# Notations

| Symbol | Explanation | Units |
|---|---|---|
| $C_{A1}$ | molar concentration of A in bulk | mol/m$^3$ |
| $C_{A2}$ | molar concentration of A in the interphase | mol/m$^3$ |
| $y_{A1}$ | mole fraction of A in gaseuous mixture in bulk | mol/mol |
| $y_{A2}$ | mole fraction of A in gaseuous mixture in the interphase | mol/mol |
| $x_{A1}$ | mole fraction of A in a liquid solution in bulk | mol/mol |
| $x_{A2}$ | mole fraction of A in a liquid solution in the interphase | mol/mol |
| $x_{BM}$ | log mean molar concentration of B in liquid solution | mol/mol |
| $k_C$, $k'_C$ | mass transfer coefficient in terms of concentrations in gases | m/s |
| $k_G$, $k'_G$ | mass transfer coefficient in terms of partial pressures in gases | mol/(s·m$^2$·Pa) |
| $k_L$, $k'_L$ | mass transfer coefficient in terms of concentrations in liquids | m/s |
| $k_y$, $k'_y$ | mass transfer coefficient in terms of mole fractions in gases | mol/(s·m$^2$) |
| $k_x$, $k'_x$ | mass transfer coefficient in terms of mole fractions in liquids | mol/(s·m$^2$) |

# Conversions

- If the concentration of A is expressed in the mole ratio unit:

For the gas phase

$$N_A = k_Y(Y_{A1} - Y_{A2})$$

For the liquid phase

$$N_A = k_X(X_{A1} - X_{A2})$$

Conversions between different types of mass transfer coefficients:

| | Equimolar counter diffusion | | Diffusion of A through non-diffusing B | |
|---|---|---|---|---|
| GAS | $k'_C = k'_G RT = \frac{RT}{P} k'_y$ | | $k_C = k_G RT = \frac{RT}{P} k_y$ | |
| | $k'_G = \frac{k'_y}{P} = \frac{k'_C}{RT}$ | $k'_y = Pk'_G = \frac{Pk'_C}{RT}$ | $k_G = \frac{k_y}{P} = \frac{k_C}{RT}$ | $k_y = Pk_G = \frac{Pk_C}{RT}$ |
| LIQUID | $k'_L = \frac{k'_x}{C}$ | $k'_x = Ck'_L$ | $k_L = \frac{k_x}{C}$ | $k_x = Ck_L$ |

# Approximations of mass transfer coefficients

- There are approximations for mass transfer coefficients in a typical separation equipment:
  - Gas phase: $k_c \sim 10^{-2}$ m/s (film thickness $l \sim 1$ mm)
  - Liquid phase: $k_L \sim 10^{-5}$ m/s (film thickness $l \sim 0.1$ mm)
- With these approximations it is easy to determine the **orders of magnitude** of other type of mass transfer coefficients.
- For example, we can estimate the mass transfer coefficient in gaseous phase when A is diffusing through non-diffusing B in terms of mole fractions at 300 K and 3 bar at a low concentration:

$$k_y = \frac{Pk_C}{RT} = \frac{3 \cdot 10^5 \mathrm{Pa} \cdot 10^{-2} \mathrm{m/s}}{8.31451 \, \frac{\mathrm{Pa} \cdot \mathrm{m}^3}{\mathrm{mol} \cdot \mathrm{K}} \cdot 300\mathrm{K}} = 1.2 \cdot 10^{-10} \frac{\mathrm{mol}}{\mathrm{m}^2 \cdot s}$$

# Dimensionless groups in mass transfer

- Mass transfer coefficients and other important parameters (e.g. velocity, fluid properties, characteristic lengths) can also be expressed with so called **dimensionless groups**.
- Dimensionless groups in mass transfer have many analogies to dimensional groups in heat transfer.
- These are not covered more specifically in this course.

| Mass transfer | Heat transfer |
|---|---|
| Reynolds number Re | The same |
| Schmidt number Sc | Prandtl number Pr |
| Sherwood number Sh | Nusselt number Nu |
| Stanton number $St_M$ | Stanton number $St_H$ |
| Lewis number, Le = Sc/Pr | |

Dimensionless numbers in mass transfer and heat transfer.

# Mass transfer theories

- There are several theories concerning **the physical mechanism of convective mass transfer at a phase boundary**.
- These theories aim to determine the **expressions for the mass transfer coefficients theoretically**.
- The most commonly used theories are:
  - Film theory (Film model)
  - Penetration theory
  - Surface renewal theory
  - Boundary layer theory
  - Film-penetration theory
- These theories are not covered in this module.

# Summary

- When the turbulent flow has a significant role in mass transfer, it is called **convective mass transfer**. It is much more rapid than diffusion.
- Convective mass transfer is a combination of **diffusion and advection** (the transport of a substance by bulk motion).
- Mass transfer by convection involves the **transport of material between a boundary surface and a moving fluid**.
- **Mass transfer coefficients** are used to simplify the calculations.
- They are determined separetarly for gas and liquid phases.
- They can be expressed in terms of concentrations, mole fractions or partial pressures (for gases).
- There are several theories which aim to determine the mass transfer coefficients theoretically.

# References


Benitez, J. 2016. Principles and Modern Applications of Mass Transfer Operations. Wiley, pp. 91-96.

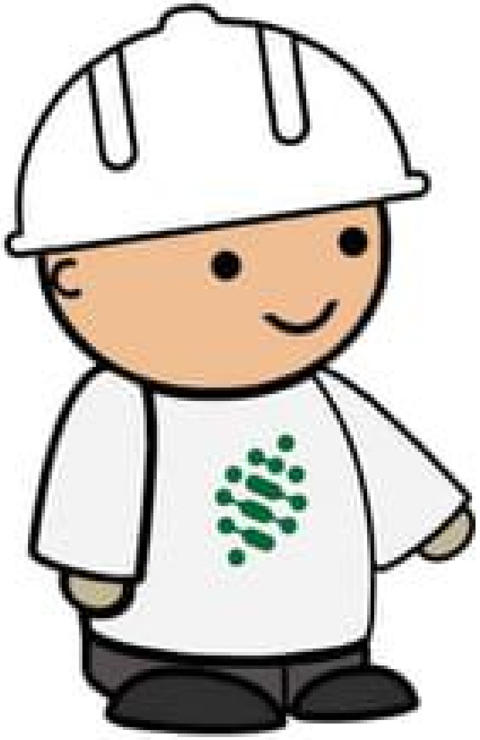
Dutta, B. K. 2007. Principles of mass transfer and separation processes. New Delhi: Prentice-Hall, pp. 74-117.

Treybal, R. E. 1980. Mass-transfer operations. 3rd ed. Auckland: McGraw-Hill, pp. 45-71.


**Videos:**

- Mass transfer coefficients: https://youtu.be/cYNqJU65oNo
- Mass transfer coefficients in equimolar counter diffusion: https://youtu.be/cPUCKrdWGtE

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869993.



# Mass transfer equipment

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869993.

# Introduction

- There are numerous types equipment used in mass transfer industry. Some of them are briefly introduced here.
- Most of the equipment in industry operates in **continuous mode**. **Batch operations** can be used in **small production units**.
- The main objective is to achieve the high rate of mass transfer to ensure an effective process.
- Turbulent **mixing** is often needed. **Heating** and **cooling** can also be provided to maintain the desired process conditions.

Typical industrial distillation columns.
Picture: Luigi Chiesa CC BY-SA 3.0

# Classification

- Equipment for **interphase mass transfer** can be classified in four categories.

| **Phases contacting** | **Operations** |
|---|---|
| Gas-liquid | Distillation, gas absorption, stripping, humidification |
| Liquid-liquid | Solvent extraction |
| Gas-solid | Drying, adsorption |
| Liquid-solid | Leaching, crystallization, ion exchange |

- In this module, we will **focus on gas-liquid contacting** equipment.
- The others will be studied in specific modules of different mass transfer operations.

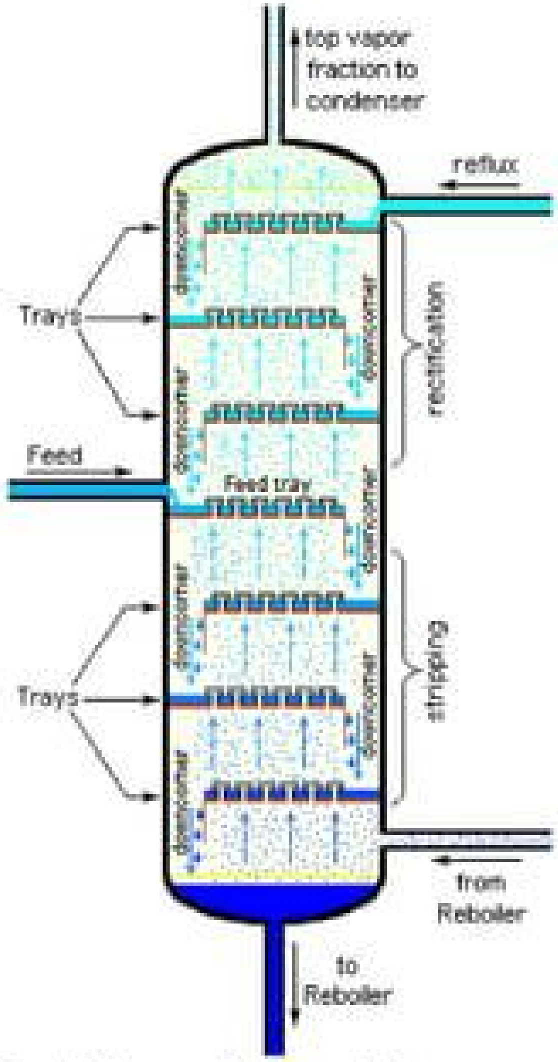
# Gas-liquid contacting equipment

- There are several types of gas-liquid contacting equipment. The following are introduced here:
  - Tray/plate columns
  - Packed columns
  - Bubble columns
  - Spray columns
  - Agitated vessels
- In tray colums, bubble columns and agitated vessels, **gas is dispersed in the liquid** in the form of bubbles.
- In packed columns and spray columns **liquid is dispersed in a continuous gas phase** in the form of droplets or discontinuous films.

Multi-purpose pilot plant for the separation of mixtures by distillation. (Sulzer ©)

# Plate column (tray column)

- In plate column, **liquid** flows **downward** via gravity and **gas** flows **upward** (countercurrent flow).
- In the simplest case, there is only one feed stream and two product streams (top and bottom).
- **Trays** (or plates) divide the column into **stages**.
- Liquid flows through **downcomers** from one tray to the lower one. The downcomer is the region near the wall.
- Gas-liquid contact occurs in the trays.
- The most common types of trays are **bubble-cap, sieve and valve trays**.




Distillation column with trays.
Picture: CC BY-SA 2.5

# Examples of trays

Pictures © from Sulzer

| Bubble-cap trays | Sieve trays | Valve trays |
|---|---|---|
|  |  |  |
| - The oldiest type of tray<br>- Bubble cap consists of the cap and the riser. The riser acts as a vapour passage.<br>- Bubble-caps are arranged on a plate. | - The simplest type of trays<br>- Bubble-caps are replaced by holes. Diameters may vary from 1/8 inch to ½ inch.<br>- Holes are usually made by punching. | - Relatively new class of tray<br>- Valves can slide vertically on the tray floor.<br>- This provides variable area for the gas flow depending upon the flow rate. |

- There are many modifications of these on the market and also other types.

# Packed column

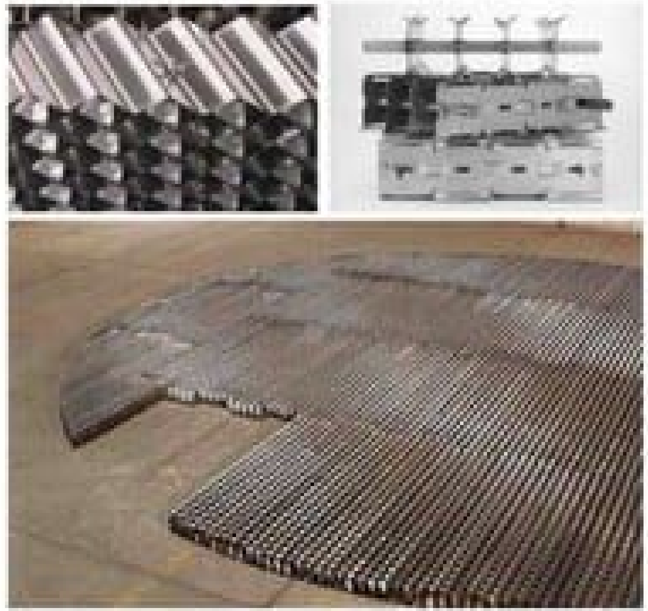
- Packed column (or tower) is a **continuous contact** equipment.
- They are widely used for distillation, gas absorption and liquid-liquid extraction.
- A packed column is filled with suitable **packing materials** to provide a large **contacting area** between the phases.
- **Packing materials** can be divided into three categories:
  - random packings (just dumped into the shell)
  - structured packings (arranged or stacked packings)
  - grid packings
- In addition to actual packing materials, **tower internals** consist of gas and liquid distributors and redistributors, packing supports, liquid collectors, etc.

Packed column. (Sulzer)

# Examples of packing materials

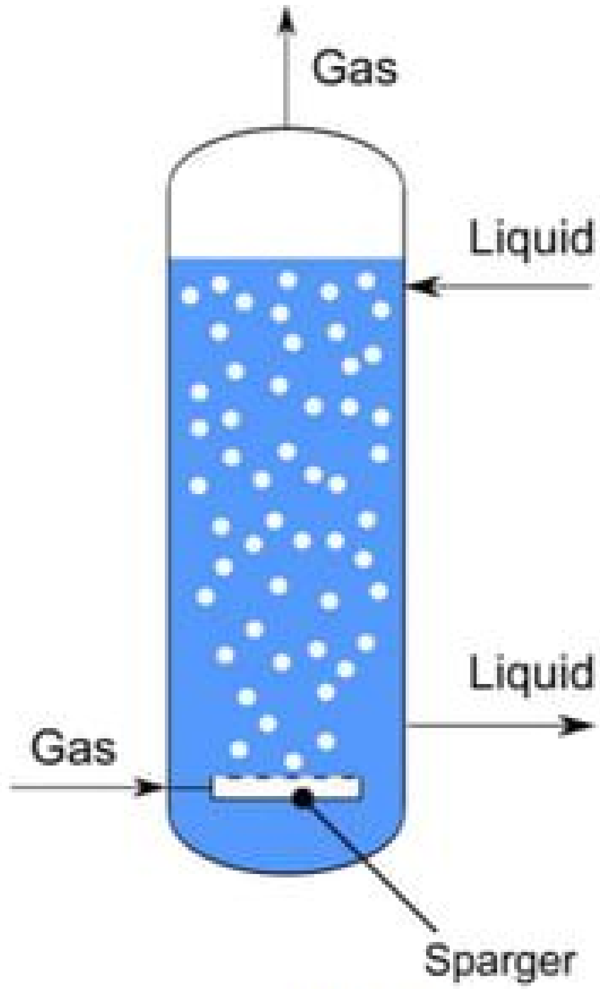
Pictures © from Sulzer

- Packing materials can be made of plastics, ceramic, metals or carbon. Different materials are suitable for different process conditions.

| Random packings | Structured packings | Grid packings |
|---|---|---|
|  |  |  |

# Bubble column

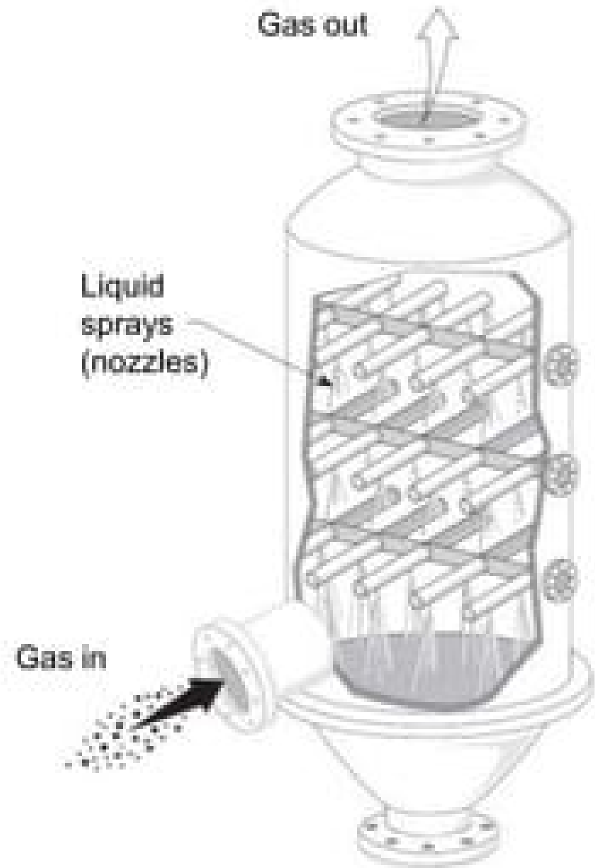
- A bubble column is quite a **simple** construction.
- It does not usually have any internals or moving components.
- Gas is fed from the bottom through the **sparger**.
- In continuous bubble columns, liquid can be fed from the bottom or from the top (**cocurrent or countercurrent** flow).
- Liquid may also be fed batchwise.
- Bubble coulmns are used e.g. for aerobic waste treatment, organic oxidation reactions and $CO_2$ capture.




Bubble column. Picture: Daniele Pugliesi CC BY-SA 3.0

# Spray column

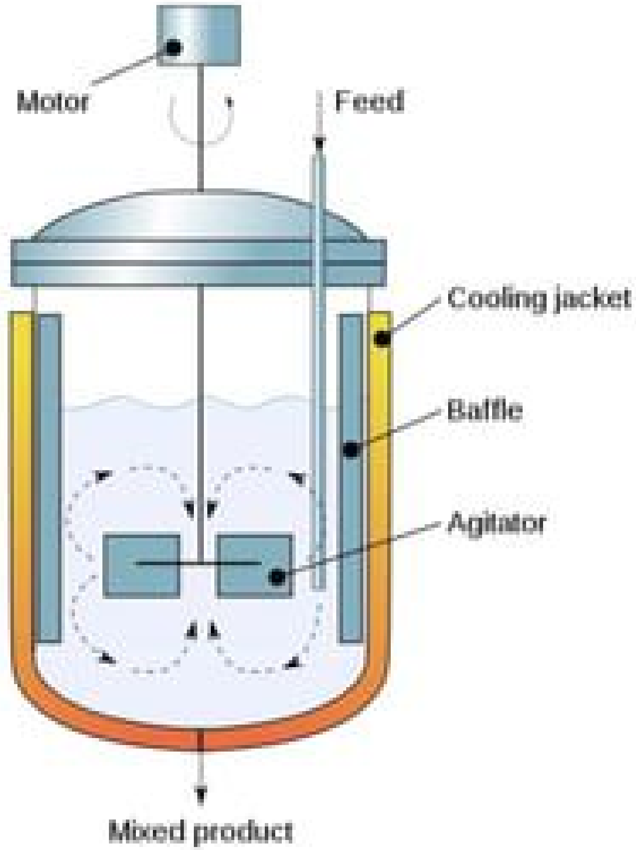
- The spray tower (or column) is another **simple gas-liquid contactor**.
- The gas flows upwards against the downflowing spray of liquid.
- **Gas** is the **continuous** phase and **liquid** is the **dispersed** phase.
- To achieve the best gas-liquid contact, spraying should be uniform over the cross-section of the vessel.
- Spray columns have **applications** in liquid-liquid extraction and in purification of various waste gas streams.




Spray tower.
Picture: Public domain

# Agitated vessels

- An agitated vessel for gas absorption contains a few internals: **agitator shaft with impellers**, baffles and a gas spargler.
- Gas is fed to the bottom of the vessel, below the impeller. There are several types of impellers, e.g. disk-, turbine- and paddle-type.
- The baffles help to increase the turbulence.
- Agitated vessels are used when there is a **chemical reaction** between the gas and liquid.
- This vessel type is not used for physical absorption.




Agitated vessel. Picture: Daniele Pugliesi CC BY-SA 3.0

# Selection decision

- Mass transfer equipment are usually **custom-built** to meet the client's needs. Choices are often partly limited by the **process and its conditions**.
- **Economics and environmental aspects** play a significant role. Sometimes the **simpler alternative** might be the choice because it would more likely be trouble-free and that would save **costs in the long term**.
- Comparisons of the equipment within a specific operation (distillation, crystallization, extraction, etc.) are covered in their own modules.

Distillation tower with different types of internals (Sulzer ©)

# Summary

- Packed columns and tray colums are the two most widely used equipment in distillation, gas absorption and stripping.
- **Plate column** is another name for tray column.
- In this column type, the column is divided into **stages** by trays.
- The three main types of trays are sieve tray, bubble-cap tray and valve tray. There are also several other types of trays and manufacturers have their own modifications.
- **Packed columns** can have three types of packings: **random, structured or grid packings**.
- Tray columns work always in countercurrent flow.
- Packed columns can be designed to work countercurrently or cocurrently.

# References

Dutta, B. K. 2007. Principles of mass transfer and separation processes. New Delhi: Prentice-Hall, pp. 172-182, 212-215, 216-230, 241-253.

Theodore, L. & Ricci, F. 2010. Mass Transfer Operations for the Practicing Engineer. John Wiley & Sons, Inc, pp. 102-107.

**Videos:**

- Distillation columns: https://youtu.be/UIOR-Oo7U-U (10:43)
- Distillation column animation: https://youtu.be/deP6FNDhryw (5:23)
- Sieve tray: https://youtu.be/gqLtFT5q_2s (4:08)
- Random packing demonstration: https://youtu.be/yoWNau1Fqak (1:50)
- Structured packing demonstration: https://youtu.be/p5S6Ri5aemA (1:43)

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