AquaSPICE

Advancing Sustainability of Process Industries through Digital and Circular Water Use Innovations

Technologies Mentioned in BREFs

AquaSPICE course 2024

Laurence Palmowski & Team

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Recap: Wastewater and Water Pollutants

Wastewater sources:

Domestic

Stormwater runoff

Industrial

Pollutants (depending on source):

- Organic pollutants
- Inorganic pollutants
- Suspended solids (e.g. sand, clay, colloids)
- Nutrients (e.g. phosphorus, ammonia)
- Pathogens (e.g. viruses, bacteria)
- etc.

Water quality parameters:

- Physical parameters (e.g. electrical conductivity, turbidity, temperature, color, odor,…)
- Chemical parameters (e.g. pH, water hardness, dissolved oxygen, …)
- Biological parameters

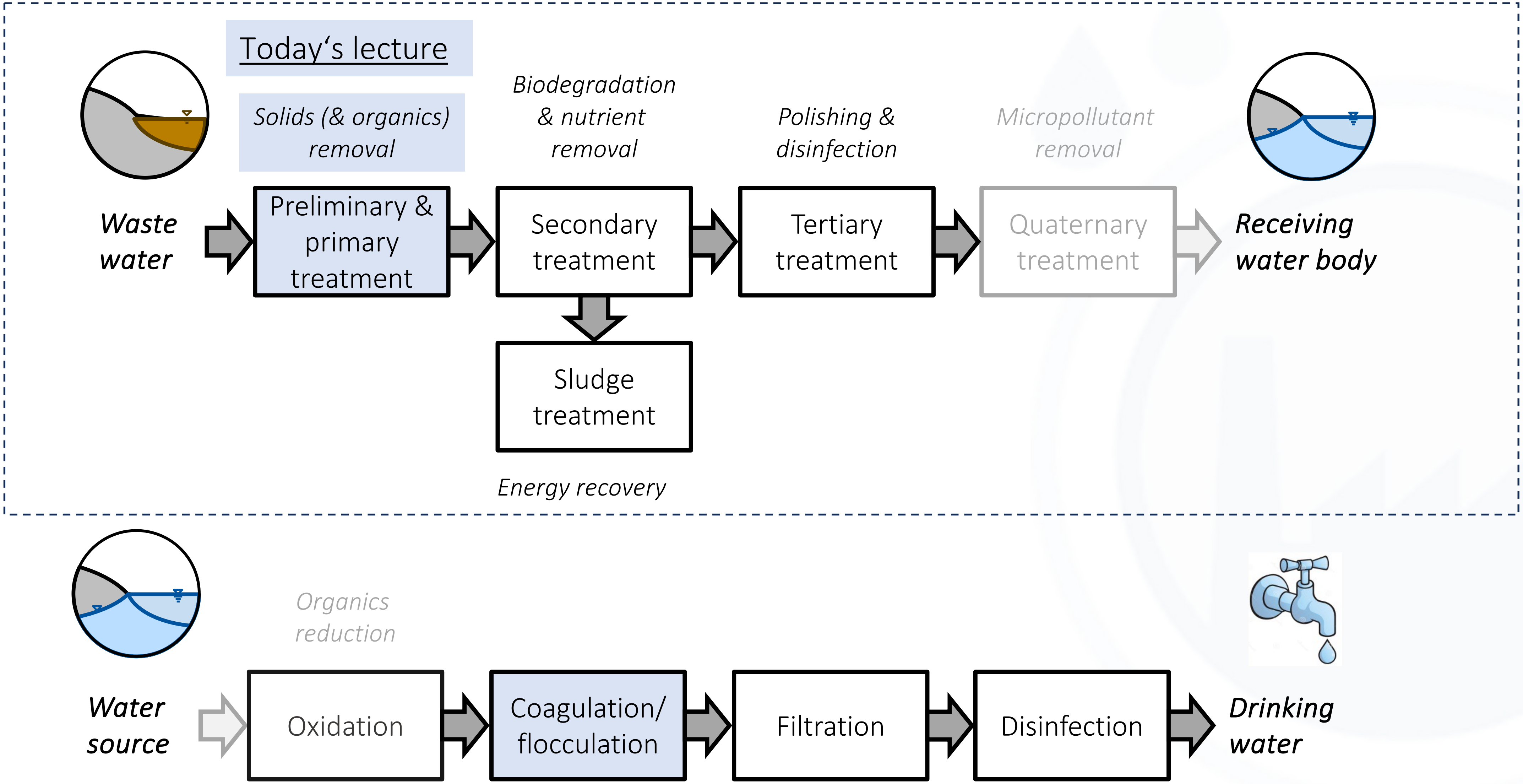
Illustration sources:
1 - https://i2.wp.com/www.asg-haustechnik.at/wp-content/uploads/2019/04/asg_haustechnik_abfluss_wien.jpg?fit=1920%2C1281&ssl=1
2 - https://www.wetteronline.de/wetterlexikon/regen
3 - https://pumps-systems.netzsch.com/de/anwendungen-und-loesungen/umwelt-energie/industrieabwasser

Goals of (Waste)Water Treatment

- Removal of pollutants
- Protection of public health and environment
  - Prevent spread of waterborne diseases and pathogens
  - Reducing risk of illness caused by contaminated water
- Resource recovery
  - Reclaimation of
    - Water
    - Energy
    - Nutrients
    - Etc.
- Compliance with regulations

How Does Wastewater Treatment Work?

Typical Treatment Schemes



Technologies mentioned in BREFs

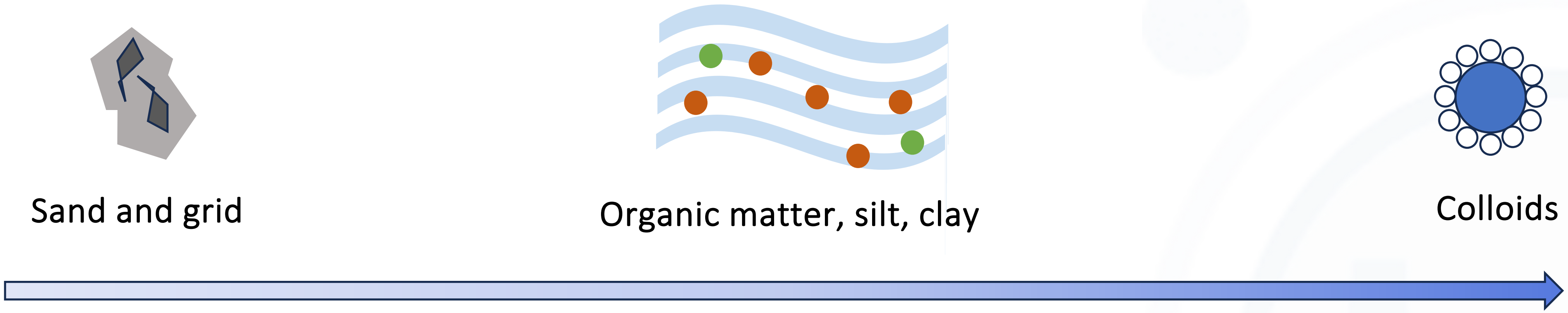
Structure

1. Suspended solids removal
    1. Coagulation/Flocculation
    2. Sedimentation
    3. Flotation
    4. Filtration
2. Physico-chemical treatment processes
    1. Precipitation
    2. Thermal treatment processes (Distillation/Rectification, Extraction)
    3. Oxidation
3. Biological treatment processes
4. Membranes

Suspended solids removal

Suspended Solids in Wastewater

Pollutant particle sizes



mm

decreasing particle size/
increasing difficulty to remove particle

nm

The smaller a particle the harder it is to remove from water!

→Idea: Clumping of small particles (colloids) to create bigger agglomerates that are easier to remove

→ Done in preliminary treatment step: Coagulation/Flocculation

Coagulation and Flocculation

Definitions

- Coagulation:

  Addition of a chemical (**coagulant** / **coagulation aid**, often multivalent metal ions) to water with the objective of destabilizing particles by neutralization of charge, so they aggregate or form a precipitate that will sweep particles from solution or adsorb dissolved consituents.

  → Chemical Process

- Flocculation:

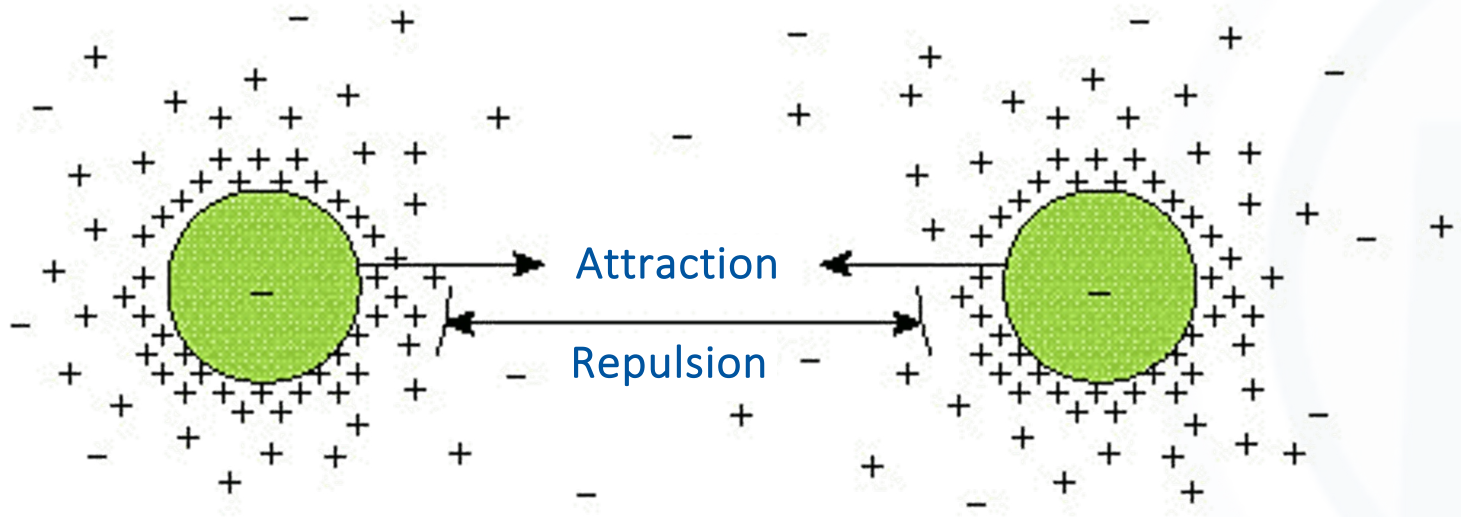
  Aggregation of destabilized particles into larger masses that are easier to remove from water than the original particles. This is often enhanced by addition of a **flocculant** / **flocculation aid** (often polyelectrolytes or organic polymers).

  → Physical Process

What even are stabilized/destabilized particles?

Stabilized Colloids

- Small, dispersed particles (= colloids) are usually (negatively) charged
- Repulsion by negative surface loading is stronger than van der Waals attraction forces



→Dispersed particles are „*stabilized*“ (=evenly distributed)

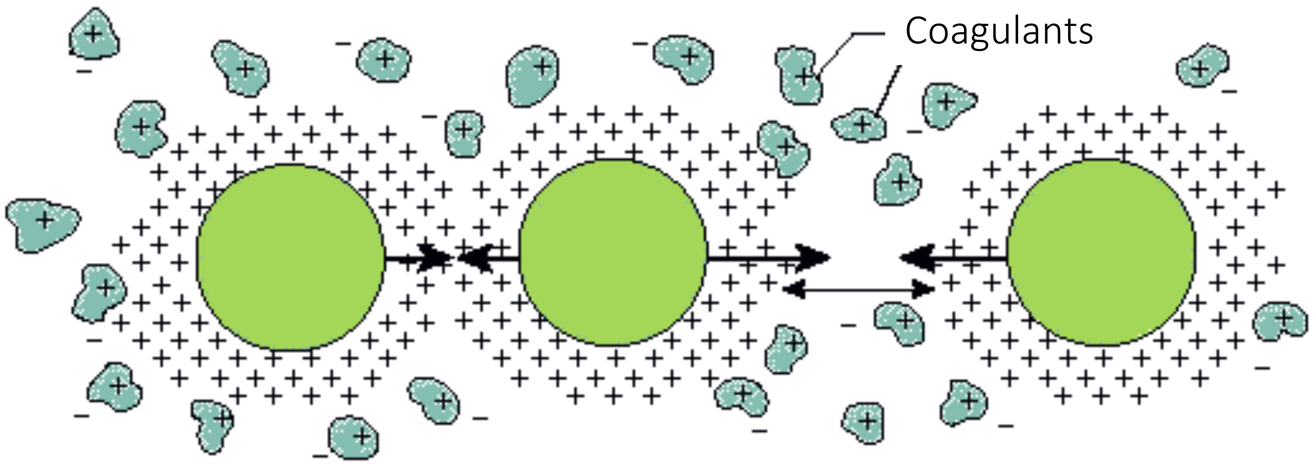
→No agglomeration

Destabilized Colloids

- Double layer is compressed by addition of electrolytes (preferably multivalent ions, like water soluble calcium-, aluminium- or iron salts)

  → Radius of repulsive forces decreases → Particles agglomerate
- Compensation of negative surface loading
- Colloidal destabilizing by adding coagulants (Coagulation)

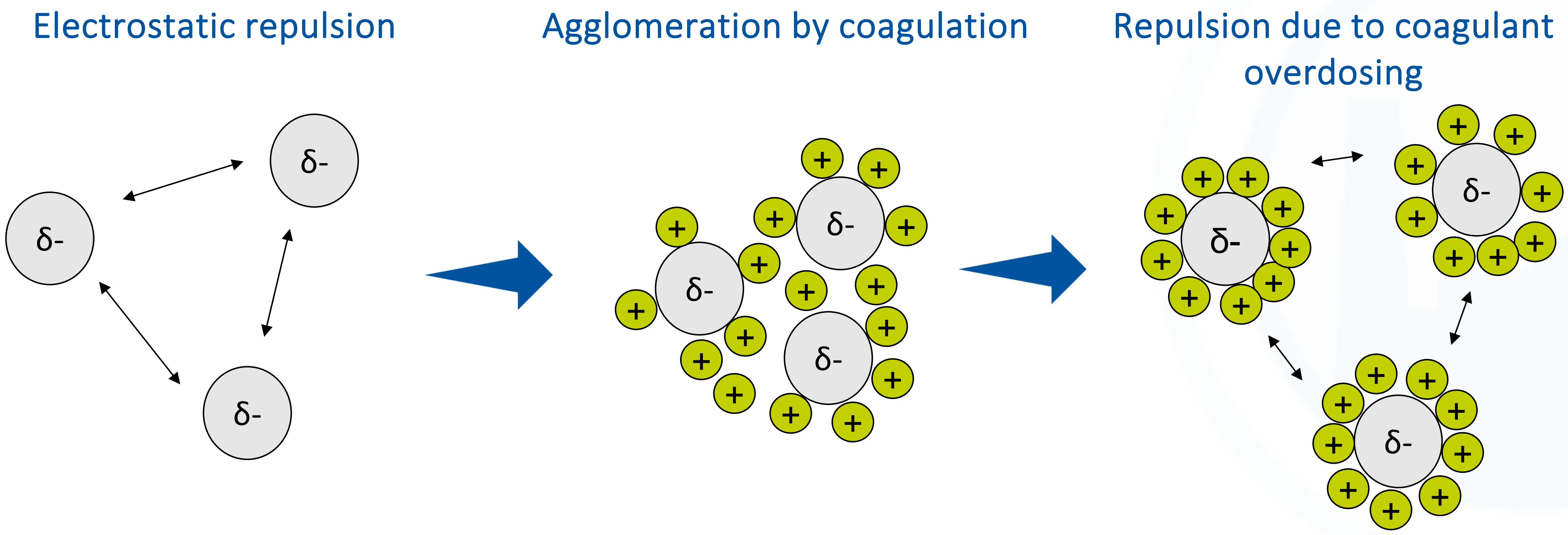
  → Agglomeration of colloids (enhanced by rapid mixing)



Overdosing of Coagulant: Restabilized Colloids

- Overdosing of coagulant can cause restabilization of colloids

  → no agglomeration

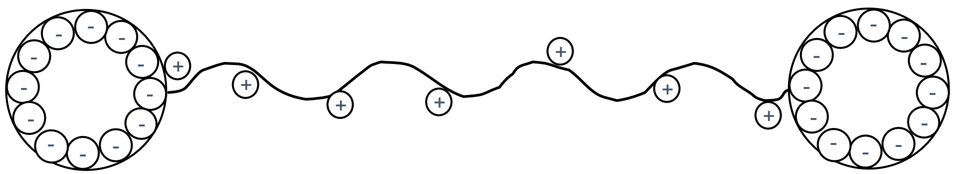


Flocculation

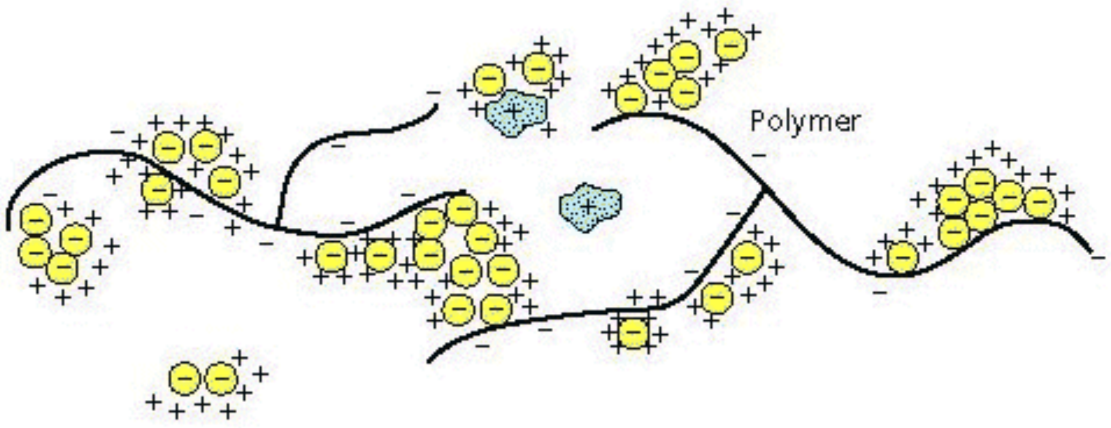
Flocculation = Growth of Agglomerates

- Flocculation with polymeric flocculants
  - Typical polyelectrolytes: Polyacrylate (polyanion), Polyamine (polycation), etc.
  - Adsorption of polymer chains at the particle surface

- Relatively small amount of flocculants needed (1-10 g/kg Total Solids (TS))



→ **Growth of agglomerates from microflocs to macroflocs**



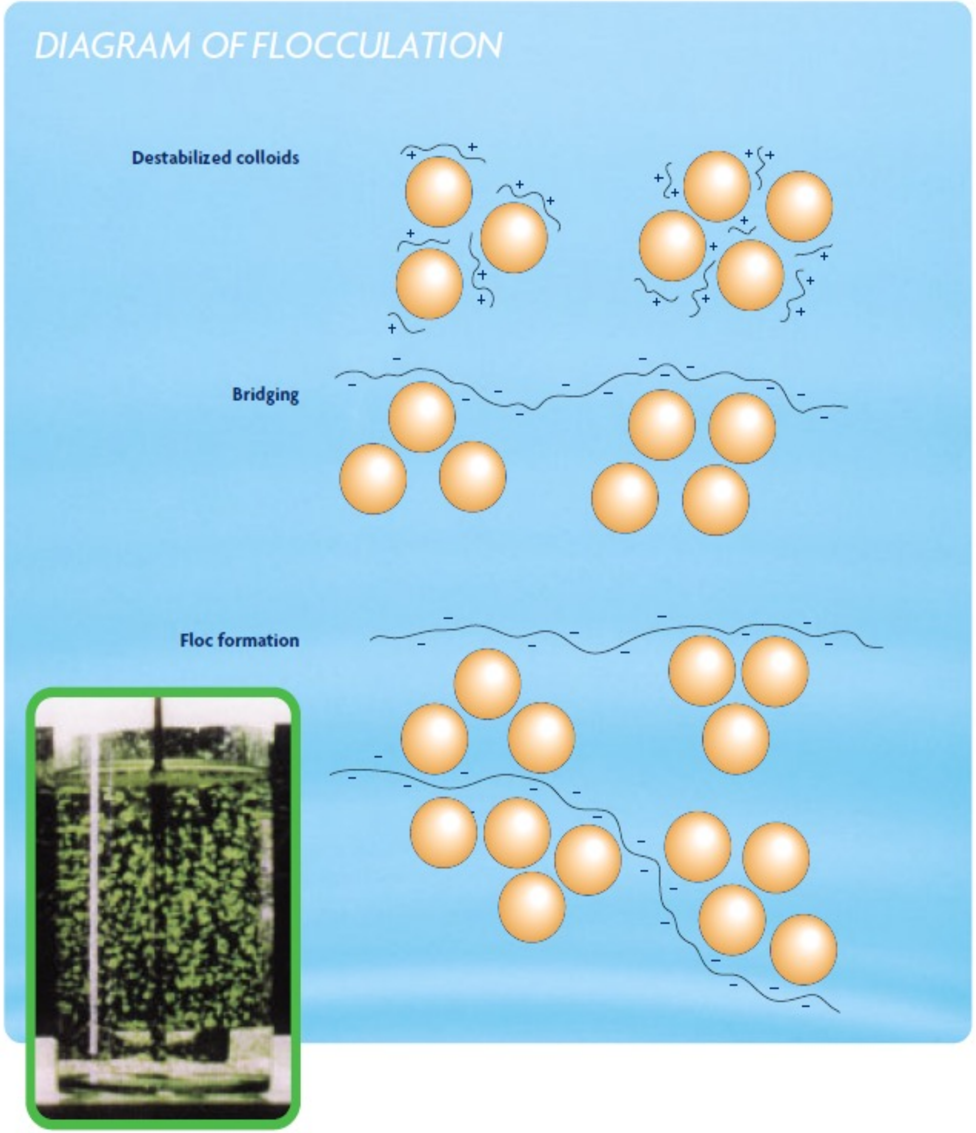
From Microflocs to Macroflocs

- Assemble **microflocs** to **macroflocs**
  - Long-chained charged polymers
  - Bridging and binding microflocs
  - Strength flocs and increase weight

- Gentle mixing

- Flocculant
  - Anionic flocculant (-) for mineral particles
  - Cationic flocculant (+) for organic particles

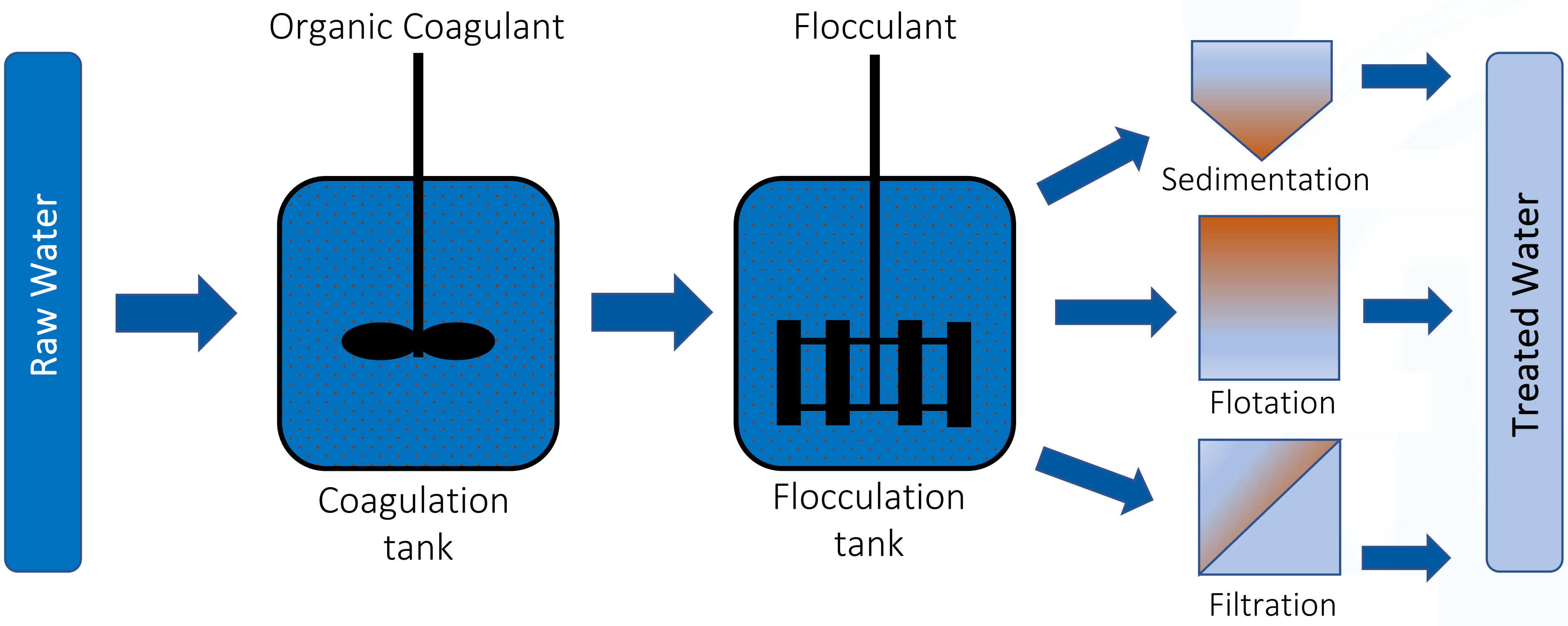
[5]



[5] https://pure-h2o-learning.eu/randd-managers/chapter-4

Coagulation/Flocculation within General Treatment Scheme

- Basic steps: **Coagulation → Flocculation → Solid-liquid-separation**



- Several parameters must be taken into consideration when selecting coagulants and flocculants
  - pH, dry matter content, ionic strength, contact time, mixing, etc.

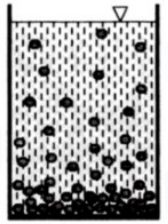
Solid-liquid separation: Mechanical Processes

Sedimentation, Flotation, Filtration

Mechanical Separation Principles

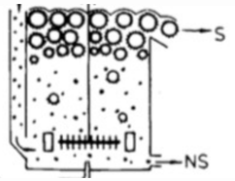
For Solid-Liquid Separation

- **Density difference** between particles and surrounding medium
  - Sedimentation of particles with higher density, e.g. mineral substances
  - Floating of particles with lower density, e.g. oils and fats

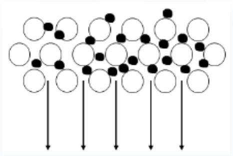


Sedimentation

- **Adhesion** of solids or gases on surfaces
  - Adhesion on rising gas bubbles → separation due to density difference = Flotation
  - Adhesion on a porous surface = Deep Bed Filtration

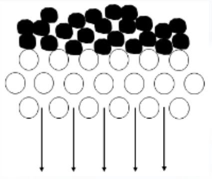


Flotation



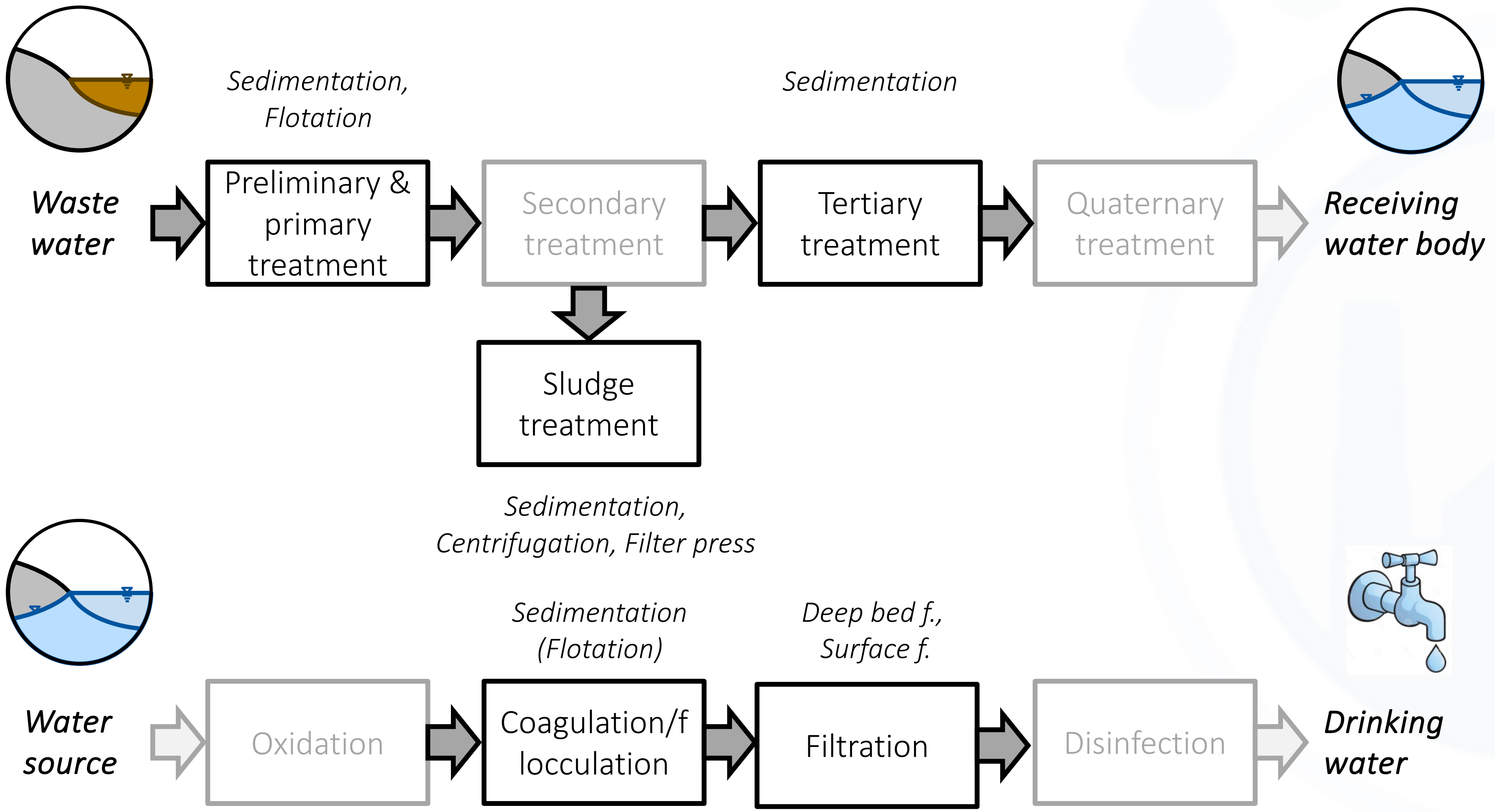
Deep Bed Filtration

- Separation based on **particle size** and resulting steric hindrance
  - Surface filtration: additional retention by the filter cake



Surface Filtration

Mechanical processes in Water Treatment Chain



Definitions

- **Total suspended solids (TSS), mg/l:**
  - Concentration of insoluble material in water or waste water
  - Possible measurement method:
    - Filtering a carefully measured volume of water through a filter with specific pore size (e.g. 0.45 µm)
    - 1 L for waste water, 3 L for very clean water
    - Glass fiber should be dried over night at 110°C under light vacuum before and after use
- **Total dissolved solids (TDS), mg/l:**
  - Concentration of all materials present in solution (survive filtration through a filter with 0.45 µm pores)
  - Possible measurement method:
    - Evaporation of the liquid solvent
    - Measuring the mass of the left residues
    - Method is time-consuming

Definitions

- Mixed liquor suspended solids (MLSS), mg/l:
  - Suspended solids concentration in the mixed liquor in an activated sludge plant
  - Mixed liquor: combination of raw or unsettled waste water and activated sludge in an aeration tank
  - Consists mostly of microorganisms and non-biodegradable suspended matter

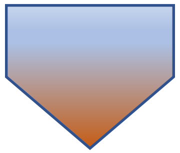
- Surface loading (e.g. of a clarifier):
  - $$Surface\ loading = \frac{volume\ flow\ [\frac{m^3}{h}]}{surface\ area\ [m^2]} = [\frac{m}{h}]$$

Definitions

- **Total organic carbon (TOC), mg/l as C:**
  - Measure of the concentration of carbon derived from organic matter in water or waste water
  - Possible measurement method:
    1. Acidification (removing total inorganic carbon, gas release to the air)
    2. Oxidation (remaining organic carbon, gas for measurement)
    3. Detection and Quantification

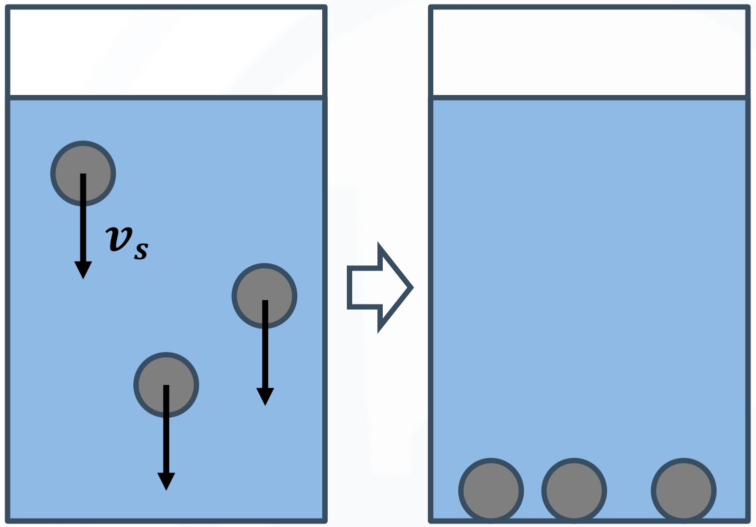
- **Dissolved organic carbon (DOC), mg/l:**
  - Filtrate the sample through syringe filter (0.45 µm) into the TOC-vial (~ 40 ml)
  - Place the vial into the TOC analyzer and start the measurement

Sedimentation



Sedimentation Fundamentals

- Aim:
  - Clarification of the feed from suspended particles
  - Concentration of the separated particles in the sludge
- Separation principle: **Density difference**
  - …between suspended solids and liquid phase
- Driving force: **Gravitation**
  - Separation occurs when: $t_{residence} > t_{sedimentation}$
  - Crucial parameter: **terminal sedimentation velocity v_s**
- Minimal particle size: 100 µm
  - Economically feasible separation of smaller particles by flotation or deep bed filtration
- Used for pre- and post clarification basins



Suspension

Clarified water
+ sludge

Sedimentation Principles

Force balance

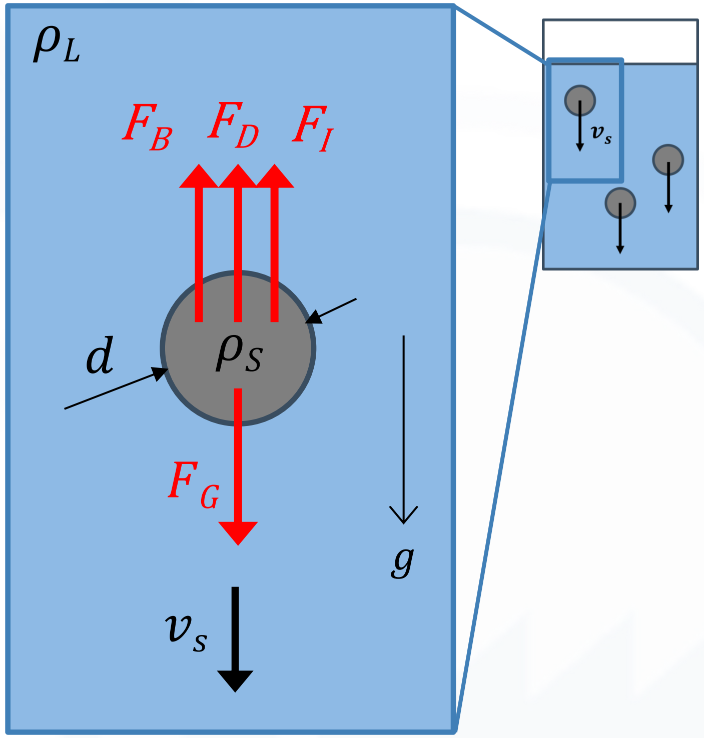
Assumptions: Ideal system
- Diluted suspension → no interaction between particles
- Infinitely wide container → no wall influence on partivle behaviour
- Rigid, spherical particles

Force balance on particle:

- Gravitational force: $F_G = \boldsymbol{\rho_S} \cdot V \cdot g$
- Buoyancy: $F_B = \boldsymbol{\rho_L} \cdot V \cdot g$
- Drag (or resistance): $F_D = \xi \cdot \rho_L \cdot \frac{\pi}{4} \cdot d^2 \cdot \frac{{v_S}^2}{2}$
- Inertial force: $F_I = (\rho_S + \alpha \cdot \rho_L) \cdot V \cdot \frac{dv_S}{dt} = \mathbf{0}$

$= 0$, stationary

$$\boldsymbol{F_G - F_B - F_D - F_I = 0}$$



g = Gravitational acceleration
V = Particle volume
d_p = Particle diameter
ρ_s = Particle density
ρ_l = Fluid density
η = Fluid viscosity
v_s = Particle sedimentation velocity
ξ = Drag coefficient

Separation by Density Difference

$$(\rho_S - \rho_L) \cdot V \cdot g - \xi \cdot \rho_L \cdot \frac{\pi}{4} \cdot d^2 \cdot \frac{{v_S}^2}{2} = 0$$

if $Re << 1$ (*Stokes flow* (=creeping flow)):
Drag coefficient $\xi = \frac{24}{Re}$
with Reynolds number $Re = \frac{d \cdot v_s \cdot \rho_L}{\eta}$

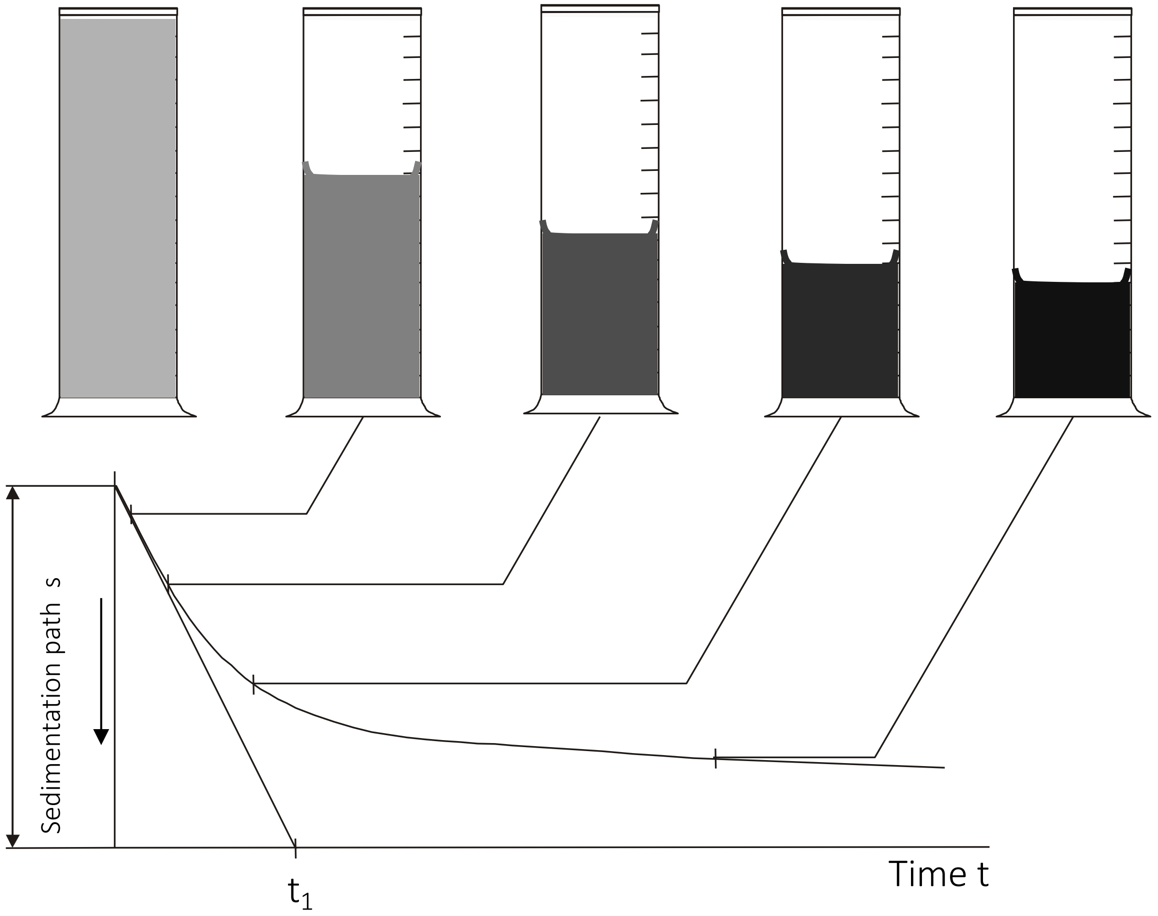
- Velocity of sedimentation v_S (Stokes-velocity) of an ideal spherical particle:

$$v_S = \frac{g}{18} \cdot \frac{(\rho_S - \rho_L)}{\eta} \cdot d^2$$

- Sedimentation velocity of particles decreases if particle concentration increases (Swarm effect)
- Sedimentation velocity decreases with decreasing particle size
  → small particles might not sediment within a resonable residence time and thus remain suspended in the treated water

Experimental Determination of the Settling Velocity

Laboratory Scale Experiments



Free settling velocity: $v_s = s/t_1$

Sludge Index, ISV [ml/g]:

Volume [ml] of 1 g dry substance (MLSS) of activated sludge after sedimentation for 30 min

Design of Continuous Sedimenters

Clarifying Area A as Design Parameter

- Average fluid velocity $\bar{v}$ through sedimenter:

$$\bar{v} = \frac{\dot{V}_2}{A} = \frac{4\dot{V}_2}{\pi D^2}$$

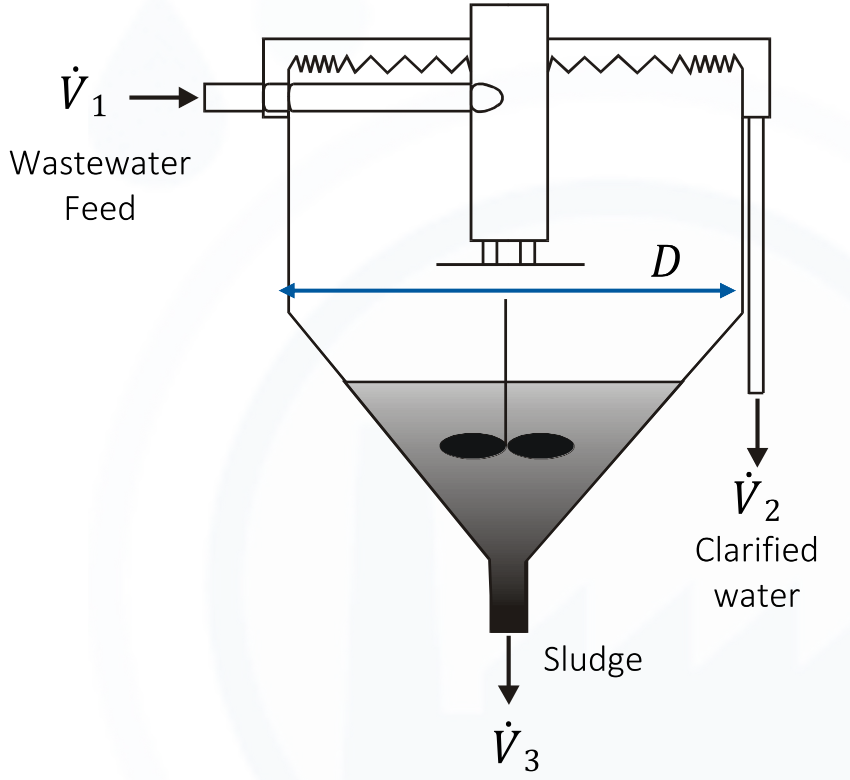
- Condition for separation by sedimentation:

$$\bar{v} \leq vs \text{ , or also } \bar{v} = k \cdot v_s$$

  - The fluid has to move slower through the apparatus than the particles are sinking, so that the particles have enough time to sediment.

- Dimensioning: clarification area A as design parameter:

$$\frac{\dot{V}_2}{A} = k \cdot v_s$$

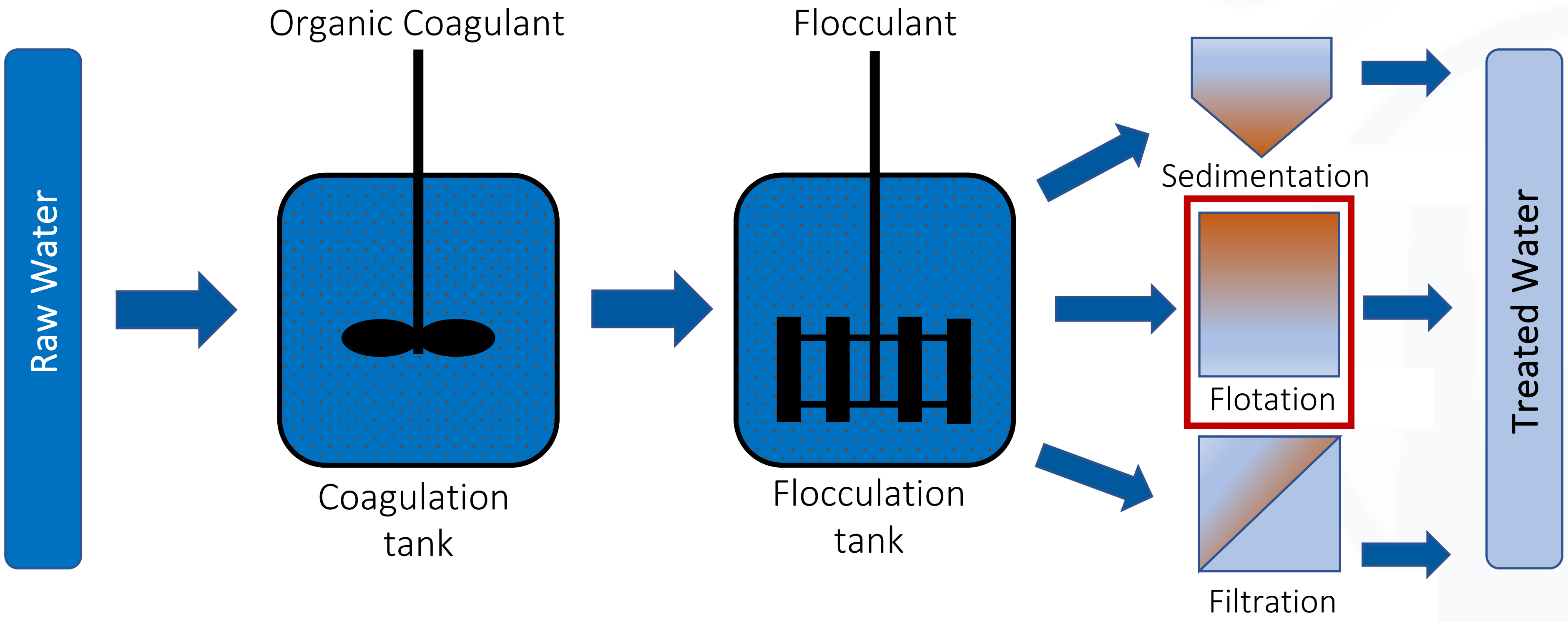


- With k<1 for real systems (k=1 for ideal system)
- k includes nonideal, real phenomena, such as non sperical particles, particle swarm behaviour, wall influence
- typically 0.3 < k < 0.5

Flotation

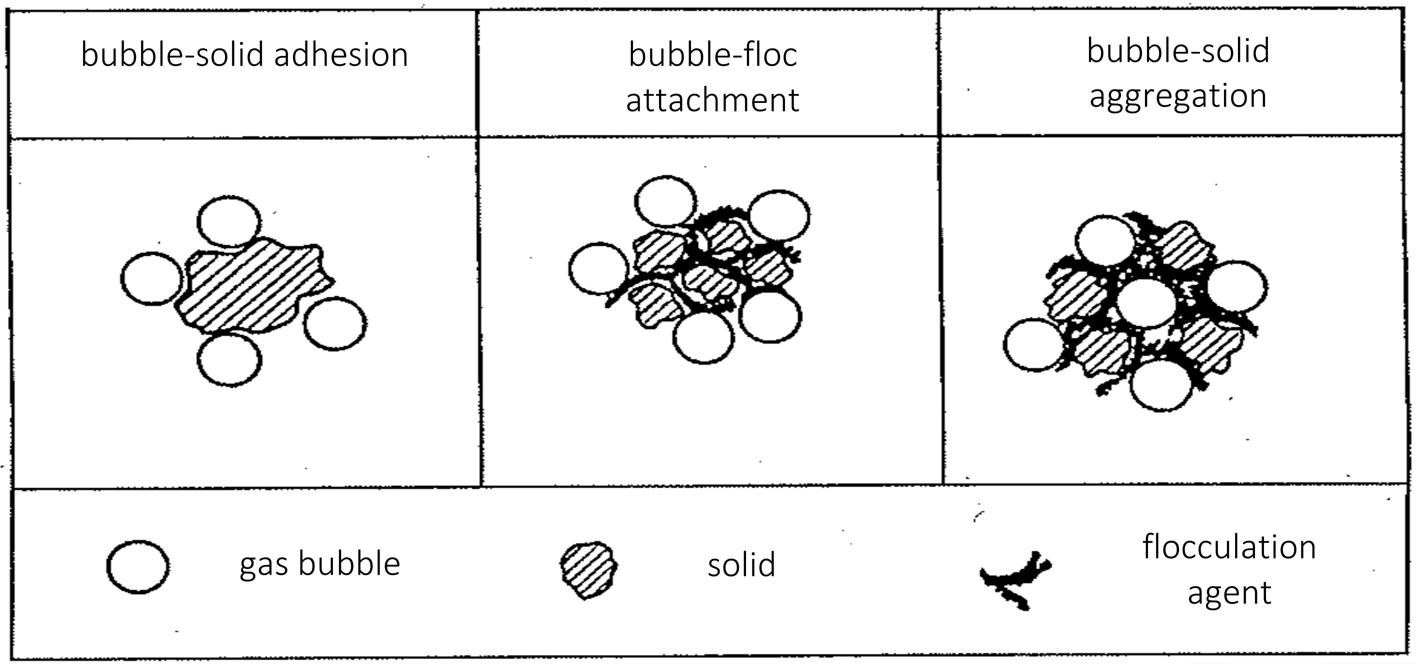
Flotation for Solid-Liquid-Separation

- Basic steps: Coagulation → Flocculation → Solid-liquid-separation



- Flotation involves the **adhesion** of solid particles to **air bubbles** in water to make them **rise to the surface**, facilitating their removal.

Flotation Fundamentals I



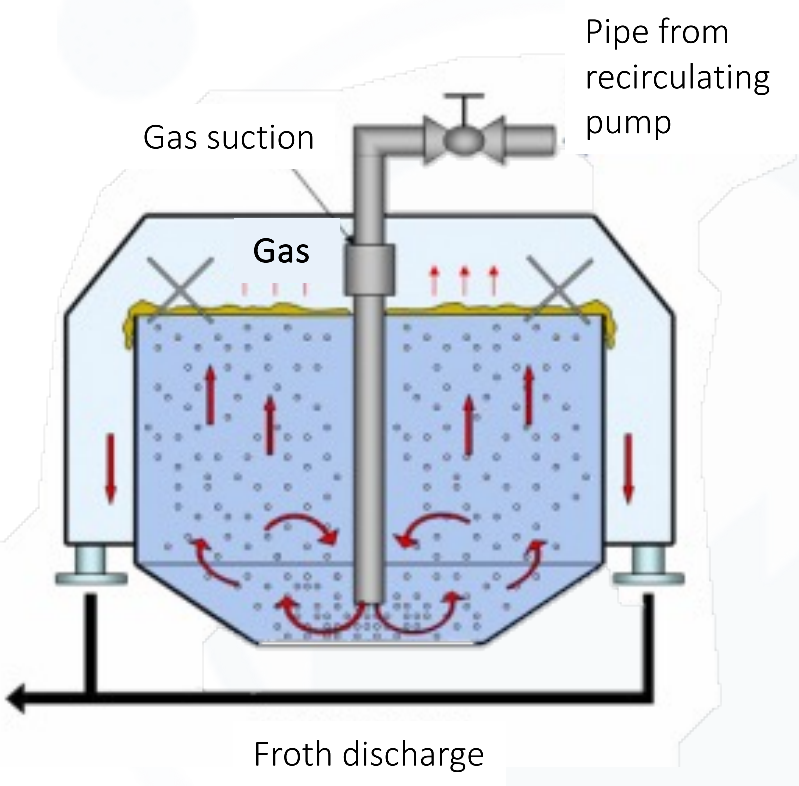
- Requirements for increased flotation possibilities of flocs
  - Hydrophobic solids
    - Alternatively: Flocculation and hydrophobization by polymeric flocculation agents
  - Good coagulation
  - Stability for shearing effects

Flotation Fundamentals II

Typical separation step during ore processing:

- Solids of different **surface charge** or **hydrophobicity** get in contact with air bubbles:
  - Type A adheres on bubble, type B does not
  - Result: A floats, B settles
  - → Solid particles with different surface characteristics can be **sorted** via flotation!

- Particle surface can be conditioned by flotation additives:
  - „Collectors“ cause hydrophobization (adhesion on bubbles)
  - „Suppressants“ cause hydrophilization (no adhesion)

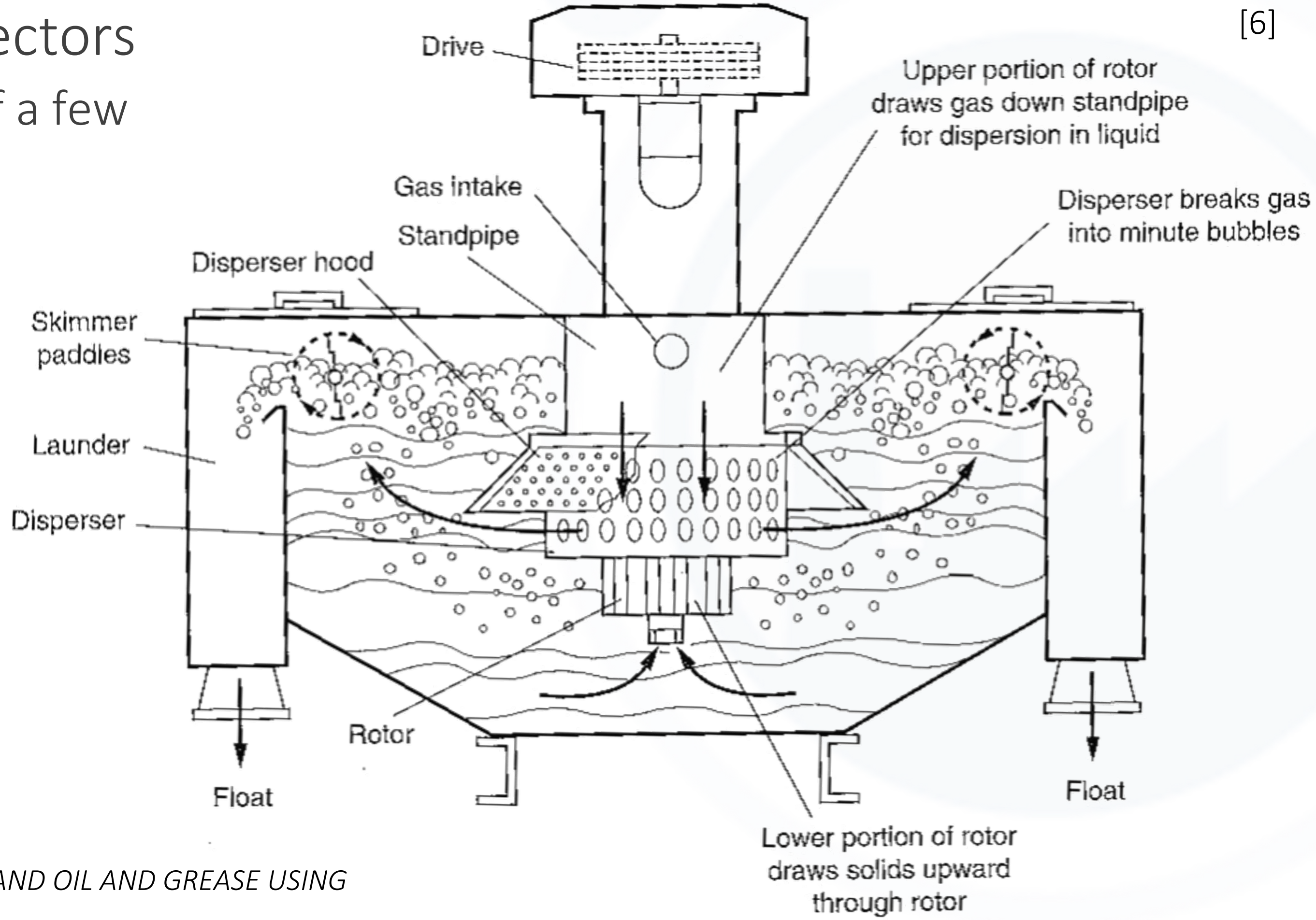


Flotation Fundamentals III

- Dispersion of air by mixer or injectors
  - Typical bubble size in the range of a few millimeters

- Apparatus: „Flotation cell“

- Technology: „Froth flotation“



[6] Rahman, Tunku Abdul et al. *“REMOVAL OF TOTAL SUSPENDED SOLIDS AND OIL AND GREASE USING FLOTATION UNIT LAU ONN SEIN.” (2011).*

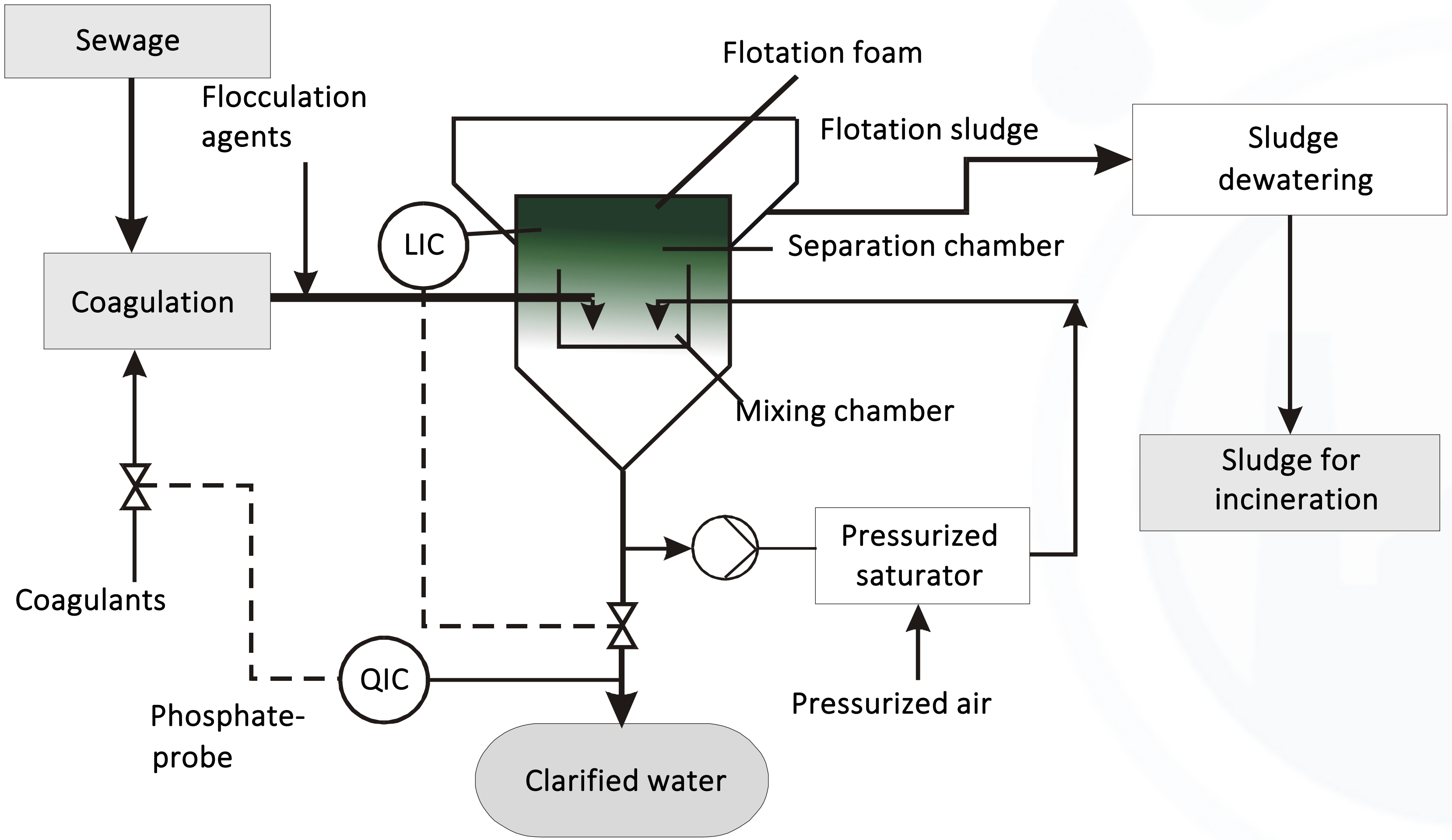
Flotation for Complete Suspended Solids Removal

Dissolved air flotation

- Typical technology: Dissolved air flotation (DAF)
  I. Fresh water or part of clarified outflow is saturated by air at excess pressure (3-8 bar), decompressed and mixed with feed suspension
  II. Bubbles are formed due to lower gas solubility at lower pressures (typically size around 50 µm)
  III. Bubbles rise with adhered sludge to the surface and form a solid-enriched sludge („Flotation tailings“)
  IV. Floating sludge is removed mechanically at the top, the clarified waste water is drained at the bottom of the plant
  V. Applications: Fat and oil precipitation, separation of precipitated solids and separation of fine turbidities (alternative to sand filters)

Process Example

Coagulation, Flocculation, Flotation, Sludge dewatering



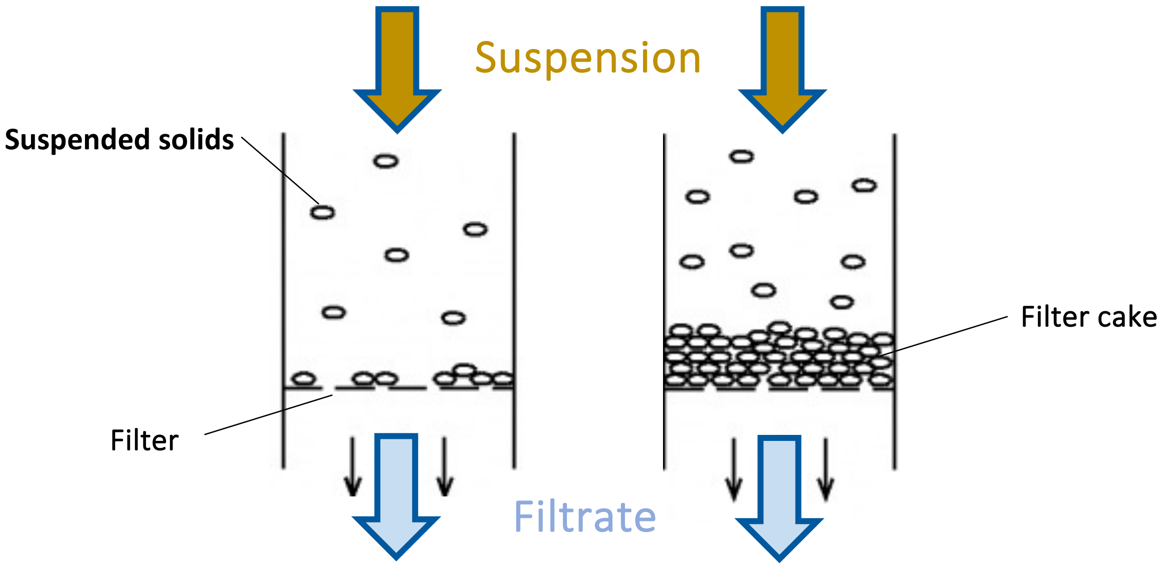
Filtration

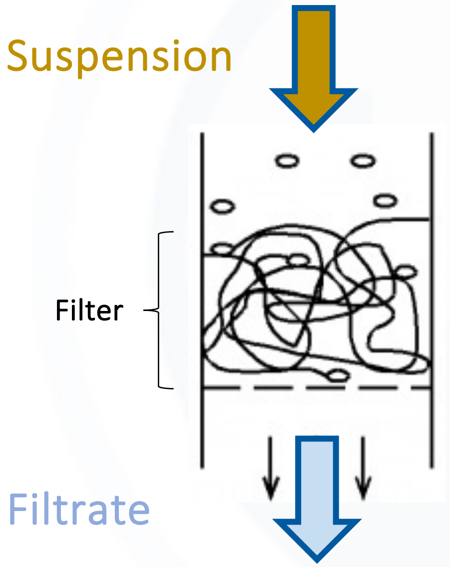
Deep Bed Filtration | Surface Filtration

Forms of Filtration

Surface Filtration and Deep Bed Filtration

- During filtration, the separation takes place through the effect of separating forces using a liquid-permeable filter medium
- 2 Types of Filtration:



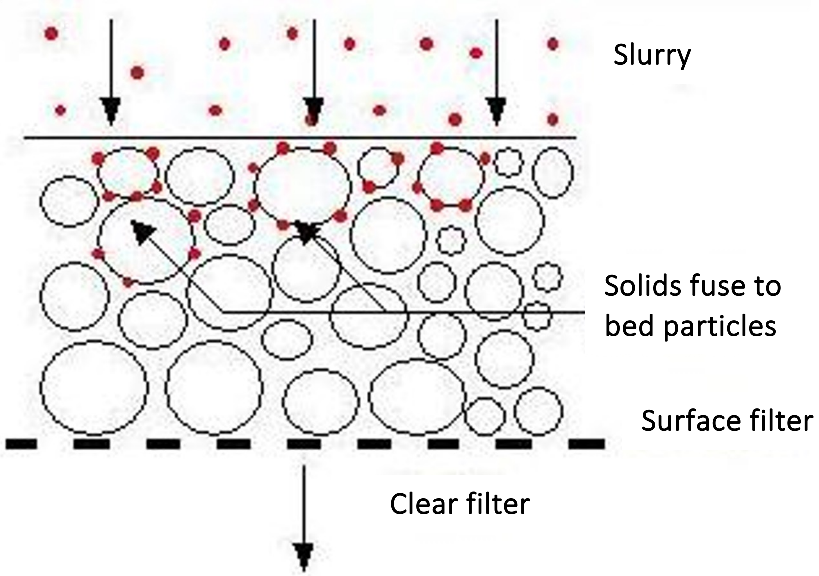


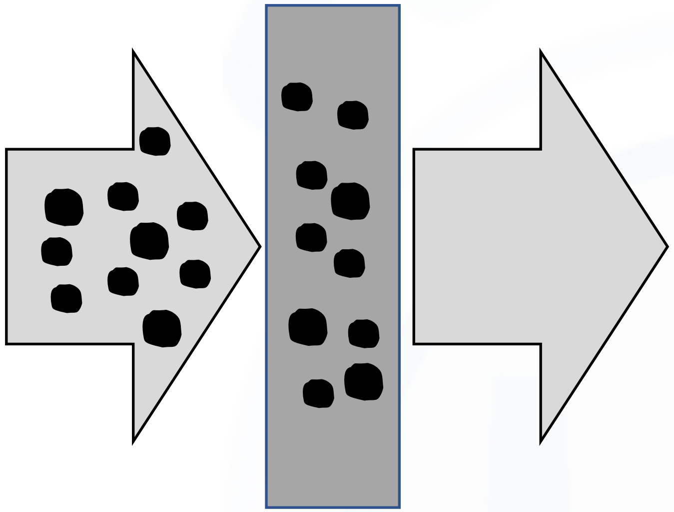
Surface Filtration: solids that remain on the filter surface form a **filter cake**, which is where the actual separation happens

Deep Bed Filtration: The separation takes place in the depth of the filter medium . The formation of a filter cake is not desired!

Deep Bed Filtration

Fundamentals I/II





- Forming capillary-like structures where particles are retained **throughout** the filter medium
- Particles of different sizes can be separated
- Able to attain high quantity of particles without loosing efficiency
- Backwashing necessary for cleaning the filter medium

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Deep Bed Filtration

Fundamentals II/II

- Useful for the separation of low amounts of particles from waste water
  - Concentration of solid particles should be below 50 mg SS/l

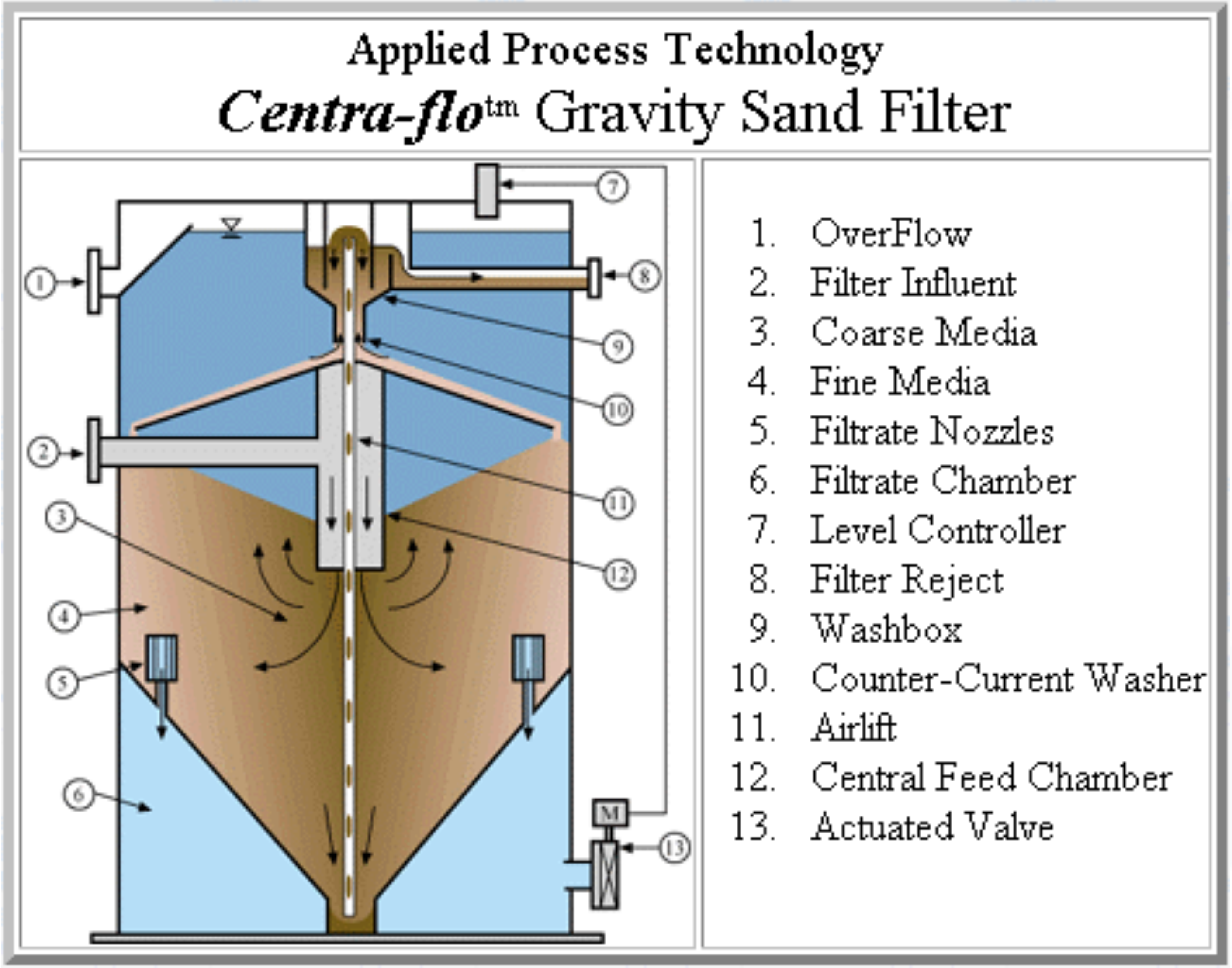
- Most common deep bed filter: Sand filter   e.g. used at BASF Antwerp in AquaSPICE
  - Smallest particles settle in the turbulence-free zones on the surface of a sand grain
  - Backwashing of the filter necessary after some time
  - Produced suspension from can be further processed, e.g. by membrane filtration
  - Filter depth ranges between 0.5 - 2 m

Multi Media Filtration (MMF)

- At MMF, wastewater passes through layers of different filter materials with varying sizes and densities

- Goal: removal of wide range of contaminants
- Typical filter materials:
  - Anthracite
  - Sand
  - Gravel

Sand Filter



[7]

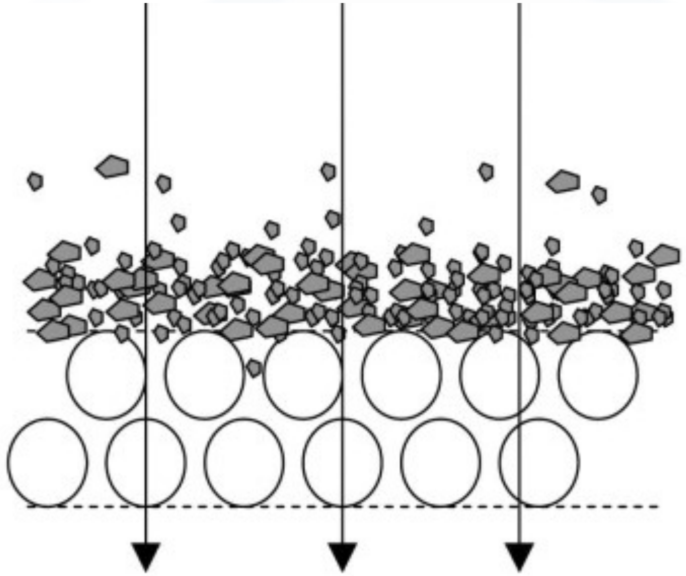
[7] https://web.deu.edu.tr/atiksu/ana52/ani4111.html

Surface Filtration

Fundamentals

- Filtration medium with pores of diameter d_{pores} (e.g. cloth, sieve mesh) builds the basis of the filter cake

- Principle:
  - Particles with $d > dpores$ stay on filter surface
  - smaller particles brake through at the beginning
  - Accumulation of retained particles → filter cake growth
  - → retention of particles with $d < d_{pores}$ possible in filter cake



- Filter cleaning necessary once the filter cake is too thick thus the pressure loss across filter is too high

- Mainly suitable for wastewater with low solid concentration

Surface Filtration

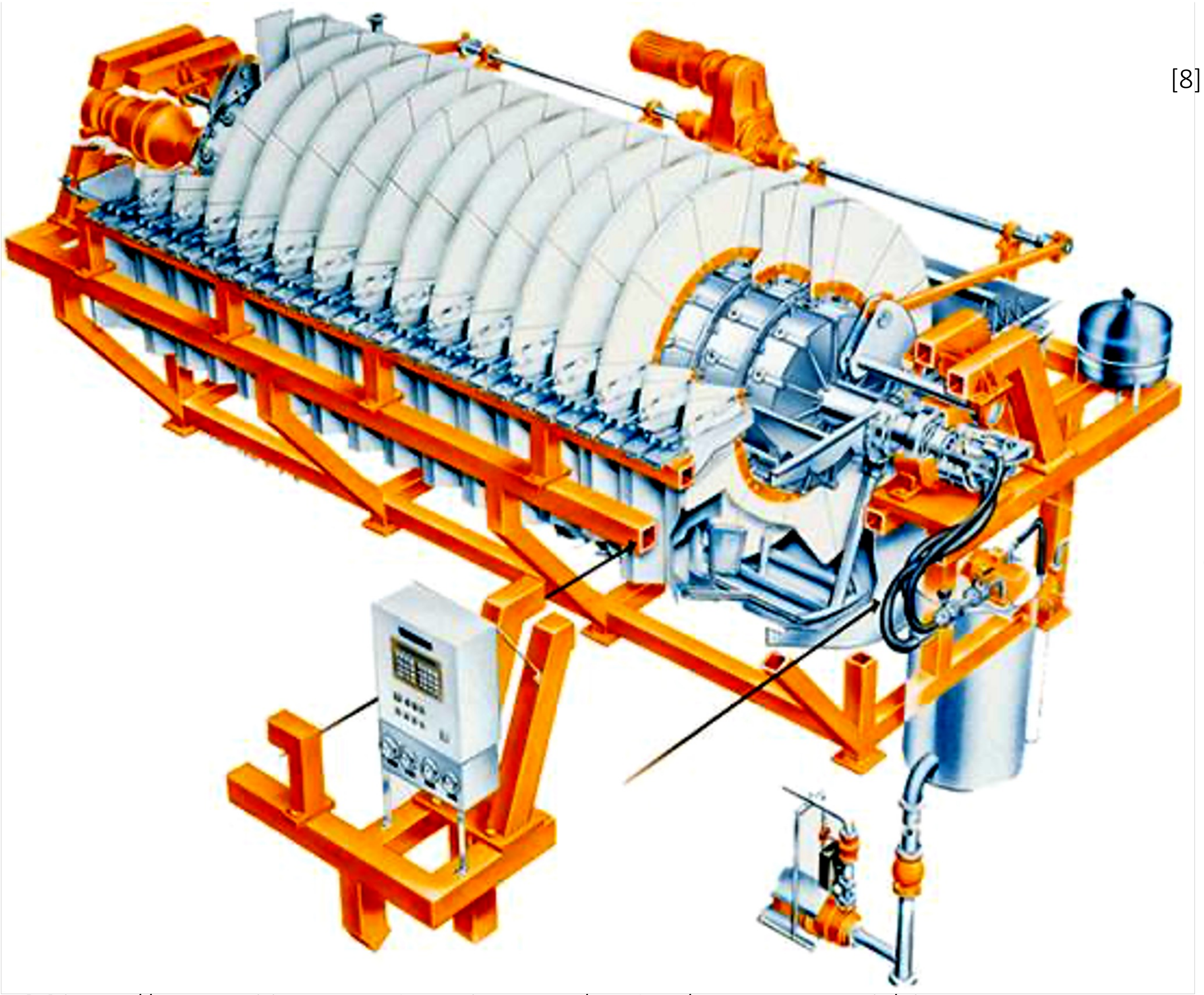
Filter Resistance

- High pressure → Compaction of the filter cake → R_{Cake} ↑

- Determination of the volume flow rate $\dot{V}$ through the filter:
  - A Filter surface area [m²]
  - η Fluid viscosity [N·s/m²]
  - R Filter and cake resistance [1/m]
  - Δp Pressure difference [Pa]

$$\dot{V} = \frac{A \cdot \Delta p}{\eta \cdot R}$$

Filter Unit Examples – Disc Filter



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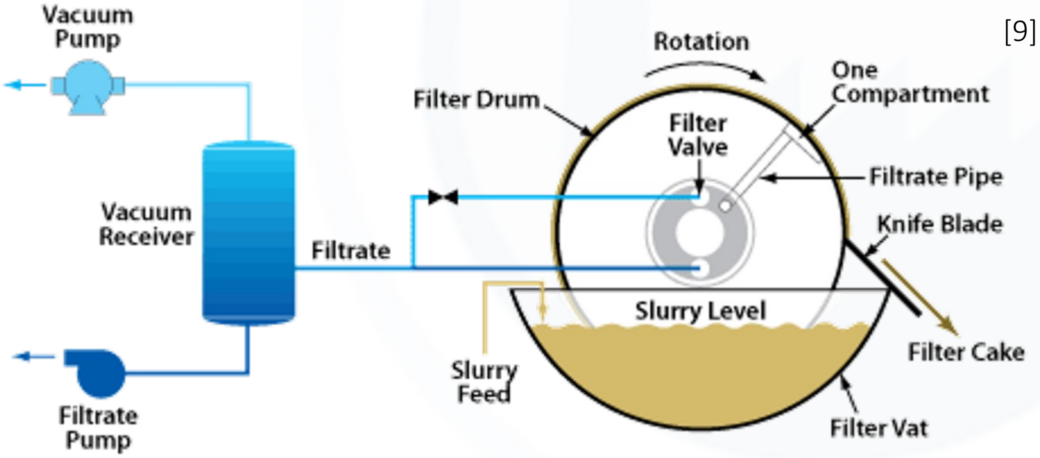
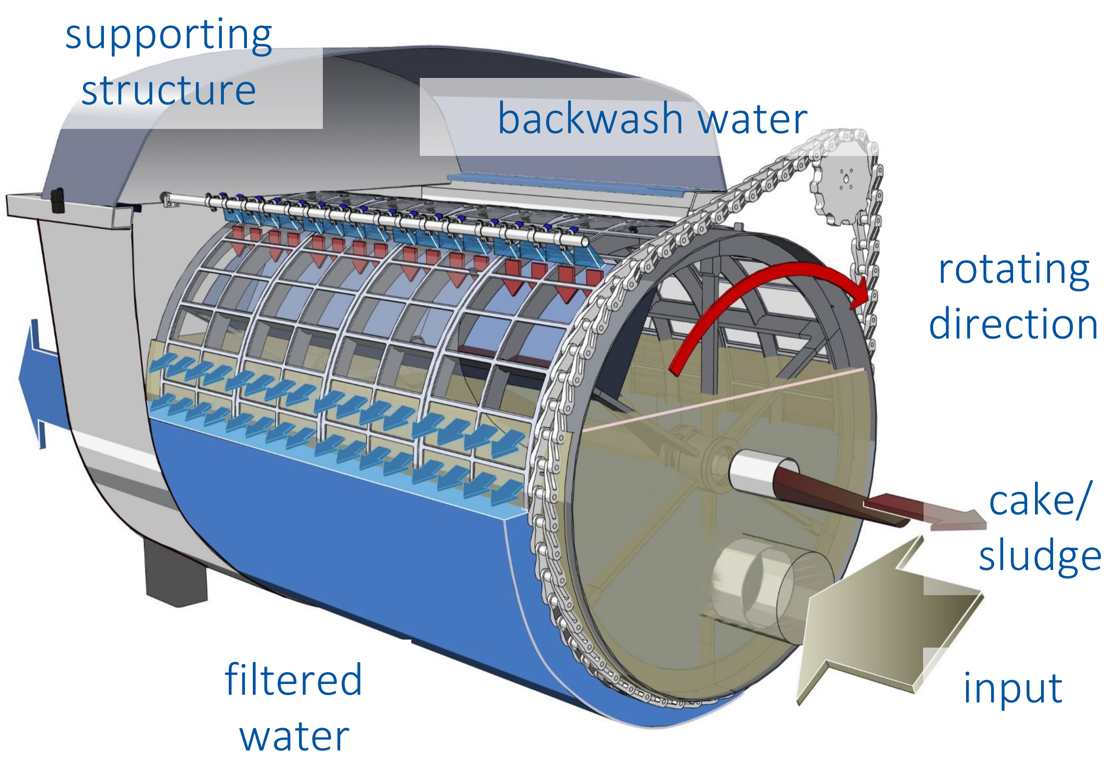


[9]

[8] https://sunny-rubber.en.made-in-china.com/product/SKMQOcYjMeUb/China-Ceramic-Disc-Vacuum-Filter-with-Ceramic-Micropore-Filtering-Plate.html
[9] Komline Sanderson

Filter Unit Examples – Drum Filter

[10]



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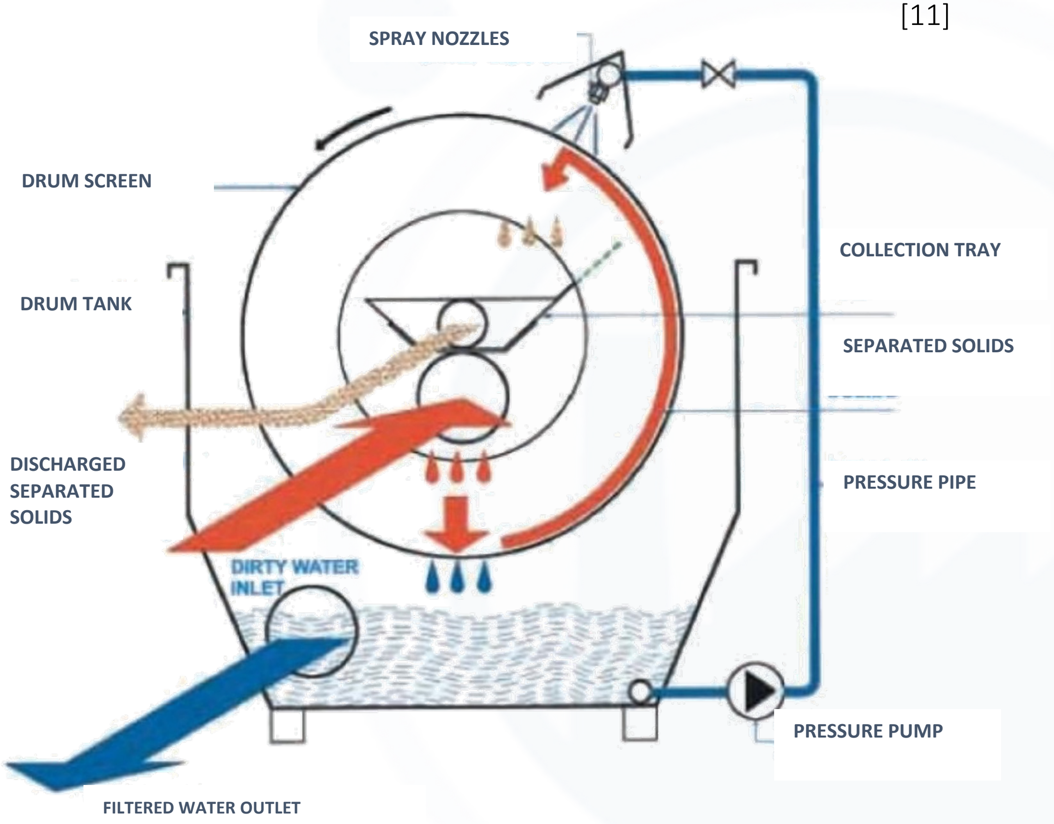


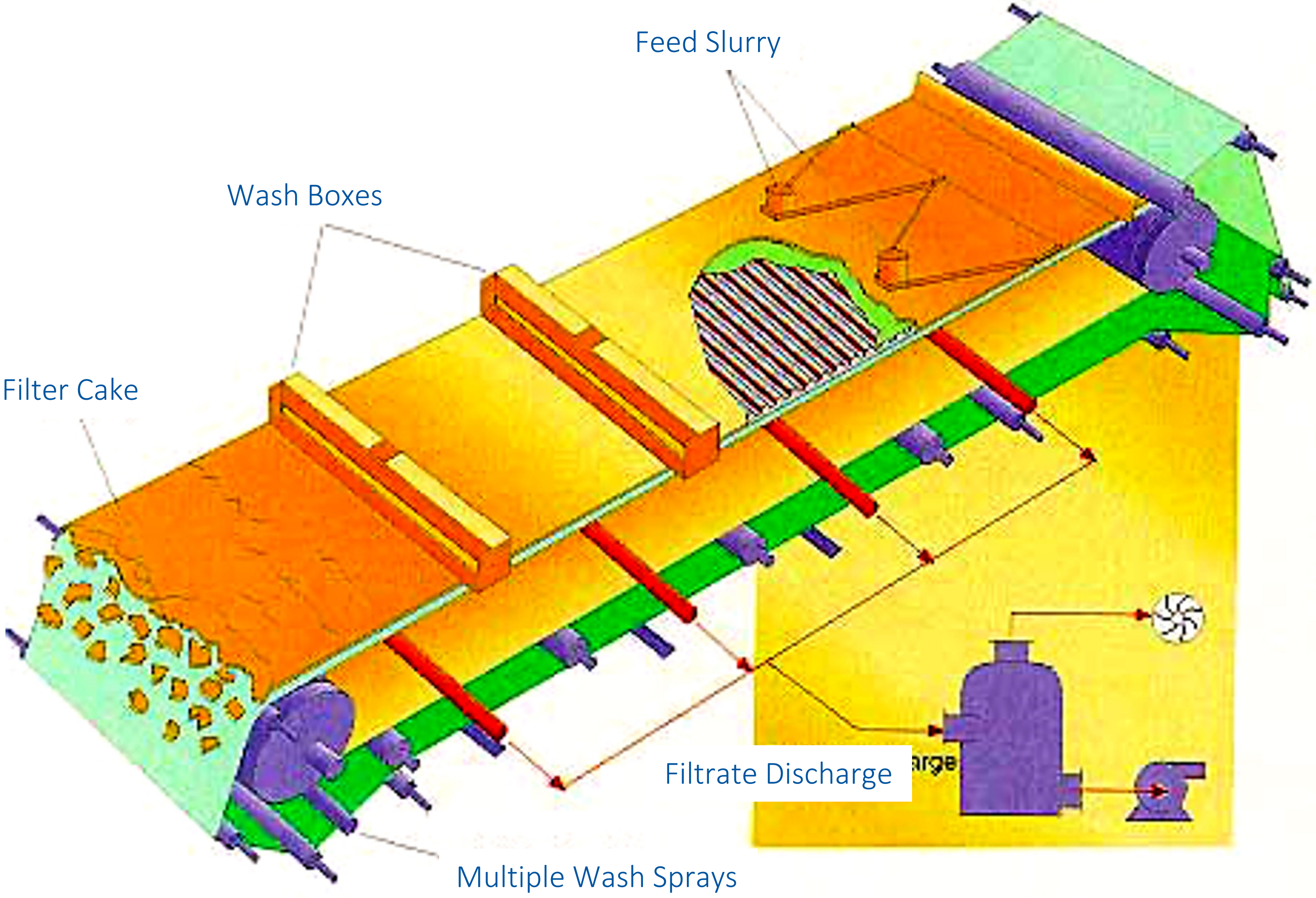
[10] https://www.sulzer.com/brazil/-/media/files/products/screening_sedimentation_and_filtration_solutions/brochures/dynadrum_self-cleaning_drum_filter_e10787.pdf?sc_lang=de-ch

[11] https://vista.gov.vn/news/ket-qua-nghien-cuu-trien-khai/hoan-thien-he-thong-thiet-bi-va-cong-nghe-nuoi-tham-canh-ca-chinh-hoa-anguilla-marmorata-bang-thuc-an-cong-nghiep-6019.html

Filter Unit Examples - Sieve Belt Press

by Baker Hughes

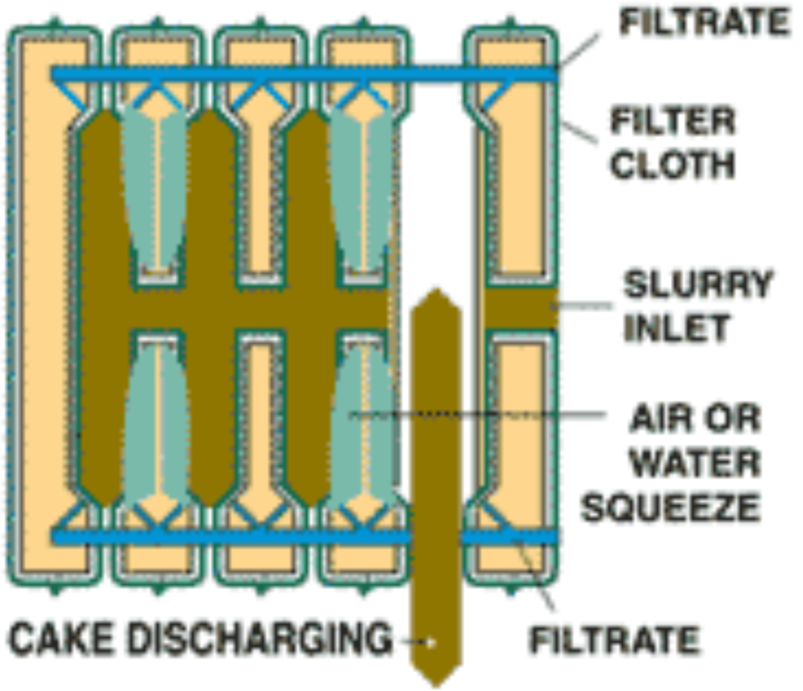
[12]



[12] https://omim-bg.com/product/filter-systems-belt-vacuum-filter/

Filter Unit Examples – Chamber Filter Press

[13]



[14]

[13] Ader Abwasserreinigung GmbH

[14] micronicsinc.com

Control Questions – Coagulation/Flocculation

1) What is the main motivation of coagulation/flocculation?
2) What is the occuring mechanism happening, when coagulants are overdosed? Use the actual technical terminology.
3) Which mechanical separation principles are used in waste water treatment?
4) What is the Sludge Index and what is it used for?
5) Describe the working principle of flotation.
6) Explain the different forms of filtration by using corresponding graphs and illustrations.
7) What is the most common deep bed filter in waste water treatment?

Advancing Sustainability of Process Industries through Digital and Circular Water Use Innovations

Thank you!

Laurence Palmowski & Team

info@aquaspice.eu www.aquaspice.eu aquaspice aquaspice