CT4471 Drinking Water 1

Coagulation & flocculation

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Room 2.98

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Contents

Introduction

Why coagulation and flocculation?

Removal of turbidity (clay) and colour (humic acids)

→ public health and aesthetics

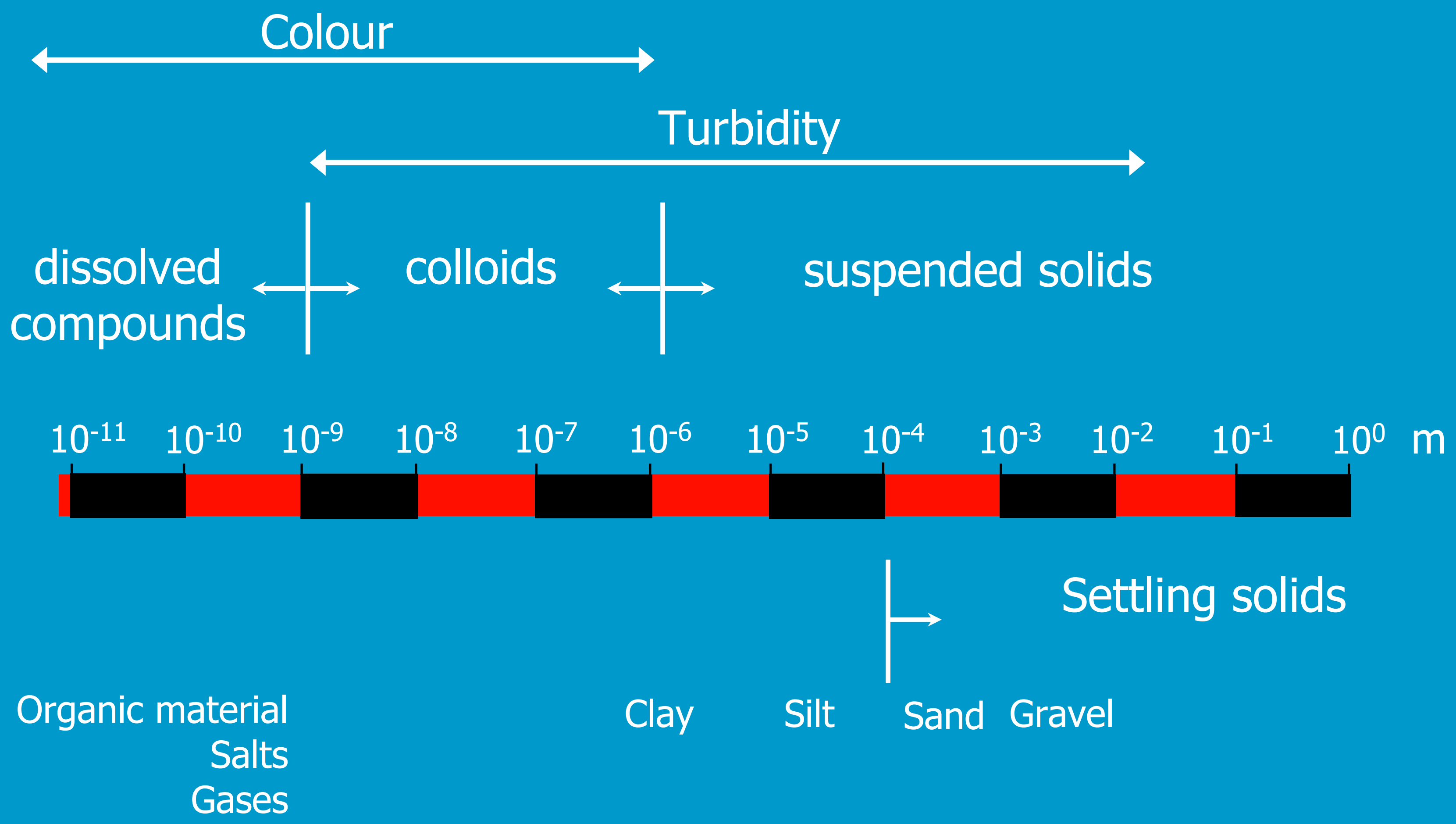
Public health:

Removal of heavy metals and organic compounds

Aesthethics:

Attractiveness of water

Classification



Settling velocity of particles

particle diameter (mm)	particle ρ = 2,650 kg/m^3	Sedimentation time (over 30 cm)
10	gravel	0.3 seconds
1	coarse sand	3 seconds
0.1	fine sand	38 seconds
0.01	silt	33 minutes
0.001	bacteria	35 hours
0.0001	clay	230 days
0.00001	colloids	63 years

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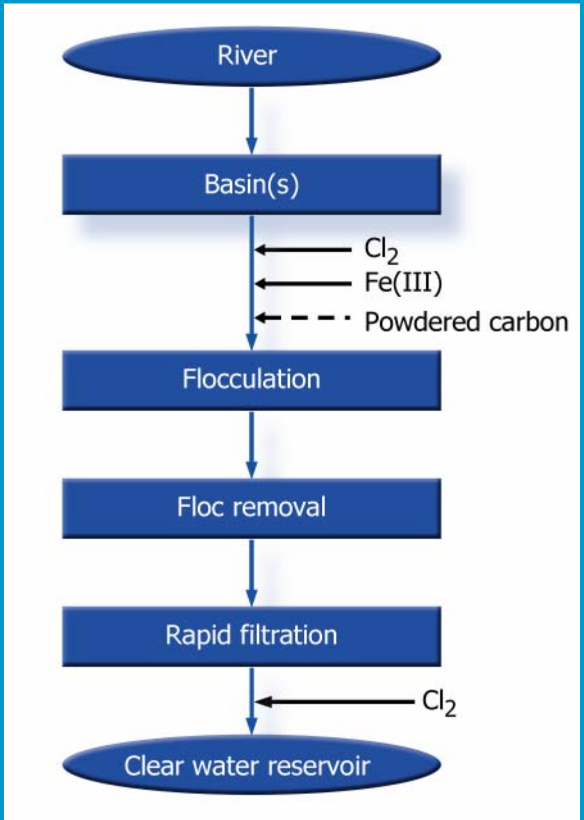
Principle of coagulation & flocculation

Colloids and humic acids are negatively charged
→ stability

Adding coagulant (coagulation) → destabilisation

Flocculation → Growth of aggregates

After coagulation and flocculation removal of floc aggregates by sedimentation and/or filtration



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Quality of surface water

	Suspended matter [mg/l]	Turbidity [FTU]	Colour [mg Pt/l]	DOC [mg/l]
Rhine	9.0 - 53	5.5 – 22.5	9 - 17	3.1 - 6
Meuse	4.0 - 31	2.2 - 17	10 - 22	3.4 – 5.4
Biesbosch reservoirs	1.4 – 9.0	0.9 – 5.6	6 - 12	3.2 – 4.0
Lake IJssel	4.0 - 115	2.5 - 40	10 - 30	5 – 13.3
Drentse Aa	2.2 - 20	3.4 - 39	20 - 100	4.8 – 14.9
Tropical river	10,000	5,000	1,000	500
Standards for drinking water	< 0.05	< 0.1	< 20 (<10)	- (3)

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Quality of surface water, worldwide

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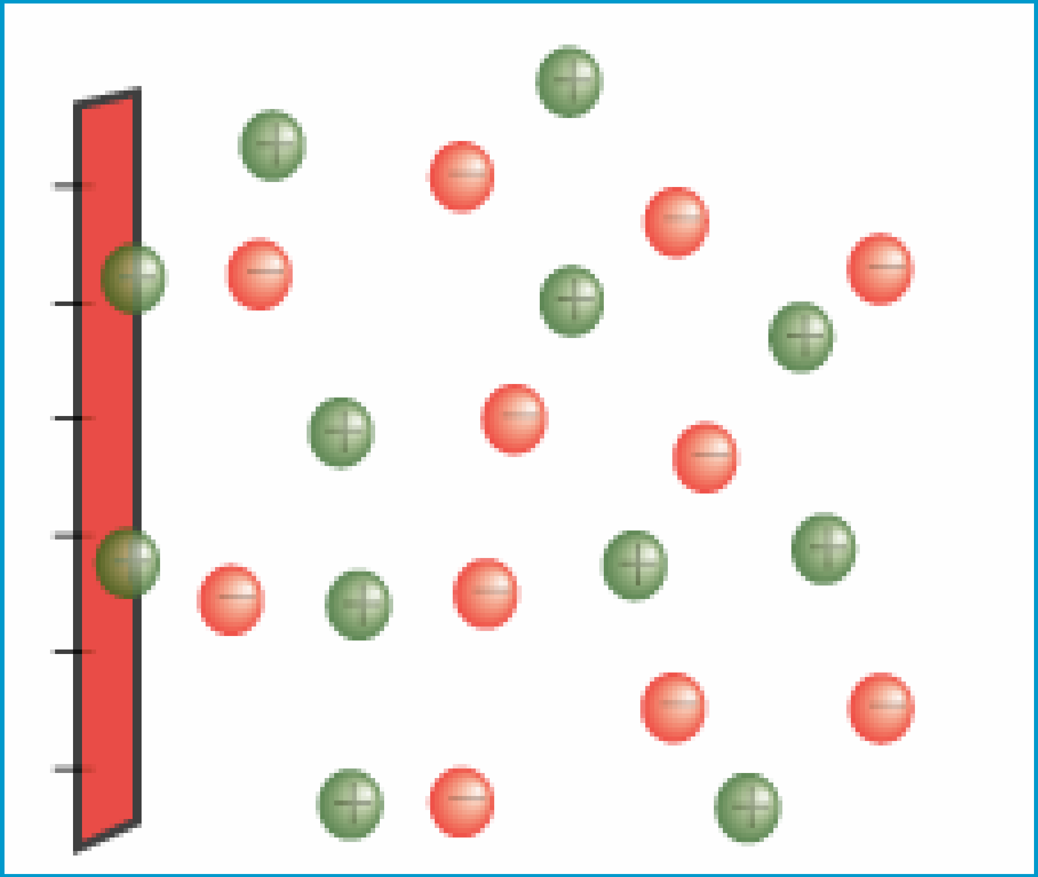
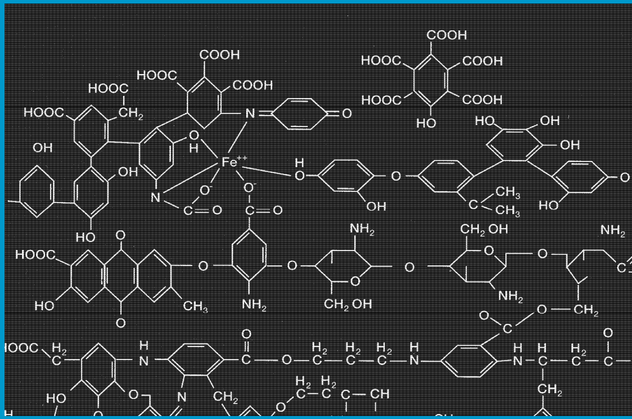
Coagulation: theory



Turbidity and humic acids

Turbidity
→ clay particles/colloids
→ size 0.1 - 10 μm
→ charge = negative



Color
→ Humic compounds
→ size 0.01μm
→ charge of humic acids depends on the pH

$$C_nH_{2n}OH + H_2O \leftrightarrow C_nH_{2n}O^- + H_3O^+$$

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Coagulants

The appearance of iron salts in water depends on pH.

Calculation of Fe^{3+} concentration

$Fe(OH)_3$	$\rightarrow$	$Fe^{3+} + 3 \cdot OH^-$	$K = 1 \cdot 10^{-38}$
$2 \cdot H_2O$	$\rightarrow$	$H_3O^+ + OH^-$	$K = 1 \cdot 10^{-14}$

$$K_w = [H_3O^+] \cdot [OH^-] \Rightarrow [OH^-] = \frac{1 \cdot 10^{-14}}{[H_3O^+]}$$

$$[Fe^{3+}] \cdot [OH^-]^3 = 10^{-38} \Rightarrow [Fe^{3+}] = \frac{10^{-38}}{(10^{-14})^3} \cdot [H_3O^+]^3 = 1 \cdot 10^4 \cdot [H_3O^+]^3$$

$$\log[Fe^{3+}] = \log(1 \cdot 10^4) + 3 \cdot \log(H_3O^+) = 4 - 3 \cdot pH$$

Coagulants

A concentration of Fe^{3+} ions of 0.05 mg/l is desired
Only at pH of the water is 3.3

$[Fe^{3+}]$ = 0.05 mg/l = $9.0 \cdot 10^{-4}$ mmol/l
$\log[Fe^{3+}] = \log[9.0 \cdot 10^{-7}] = 4 - 3 \cdot pH$ → pH = 3.3
pH < 3.3 then more Fe^{3+}
pH > 3.3 then less Fe^{3+}

Surface water has a pH of approximately 7. The consequence is that $1 \cdot 10^{-17}$ mol/l Fe^{3+} can maximally be dissolved.
If there are more Fe^{3+} ions in the water, they will precipitate with OH- ions and form $Fe(OH)_3$.

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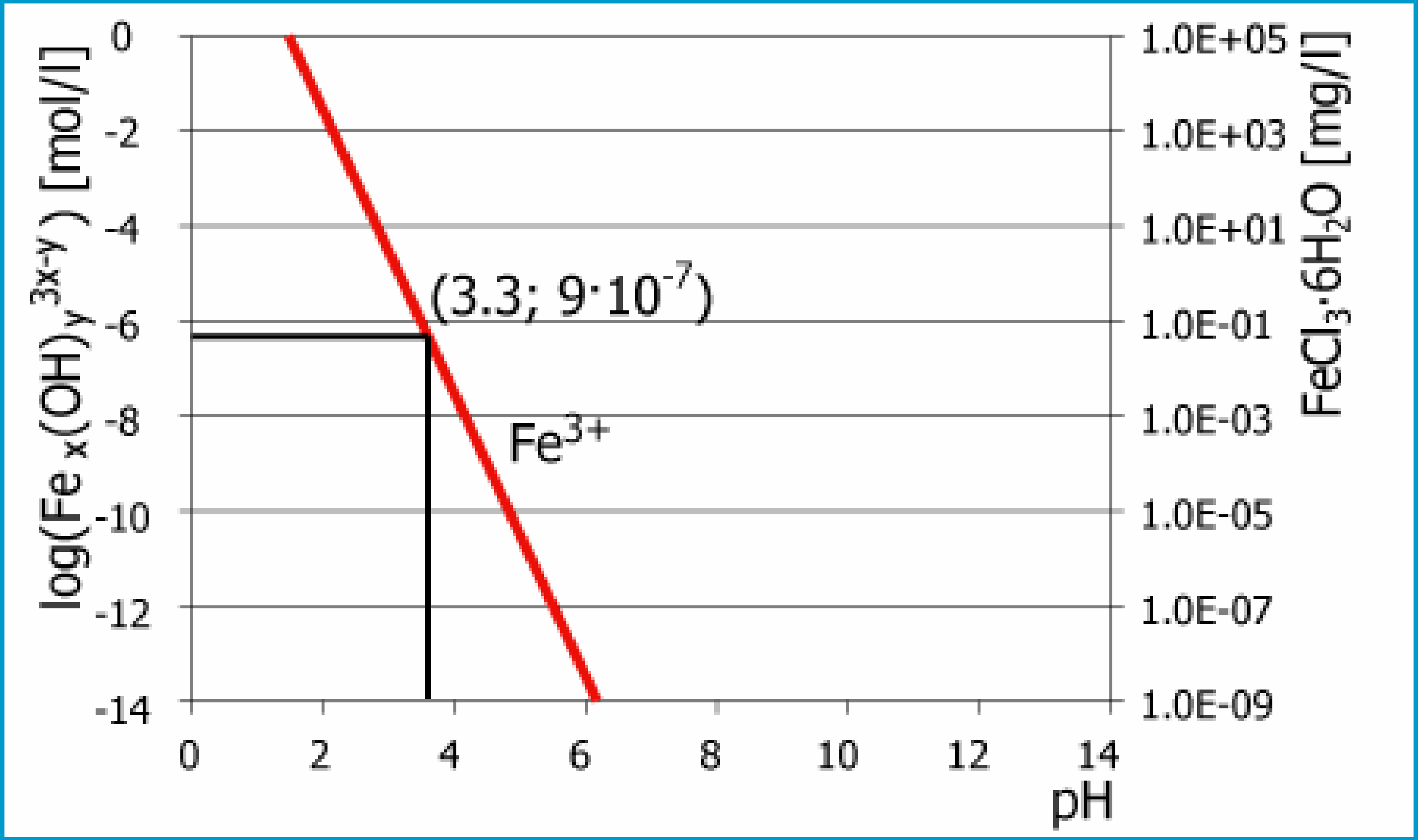
Coagulants



log(Fe x(OH)y 3x-y) [mol/l]
0
-2
-4
-6
-8
-10
-12
-14
0
2
4
6
8
10
12
14
pH
(3.3; 9·10-7)
Fe3+
1.0E+05
1.0E+03
1.0E+01
1.0E-01
1.0E-03
1.0E-05
1.0E-07
1.0E-09
FeCl3·6H2O [mg/l]

Coagulants

dosing in practice

10^{-4} mol/l Fe = 5.6 mg/l Fe

= 27 mg/l $FeCl_3 \cdot 6H_2O$

dosing of iron is done with $FeCl_3$

$FeCl_3 \cdot 6H_2O \rightarrow Fe^{3+} + 3\ Cl^- + 6\ H_2O$

$Fe^{3+} + 3\ OH^- \rightarrow Fe(OH)_3 \downarrow$

Result of dosing coagulants = pH decrease,
thus conditioning

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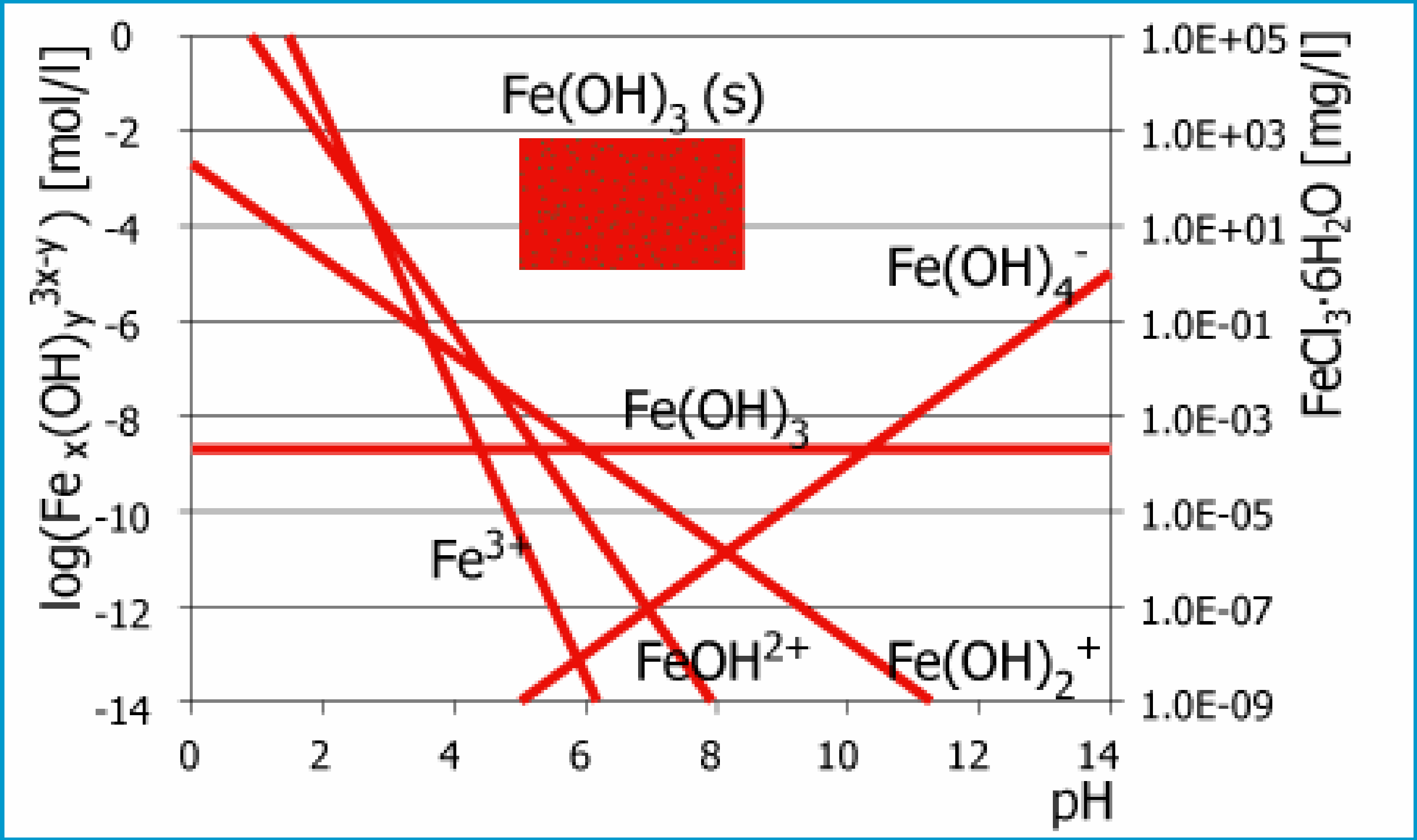
Coagulants

Reaction coefficients

Solubility products of iron salts

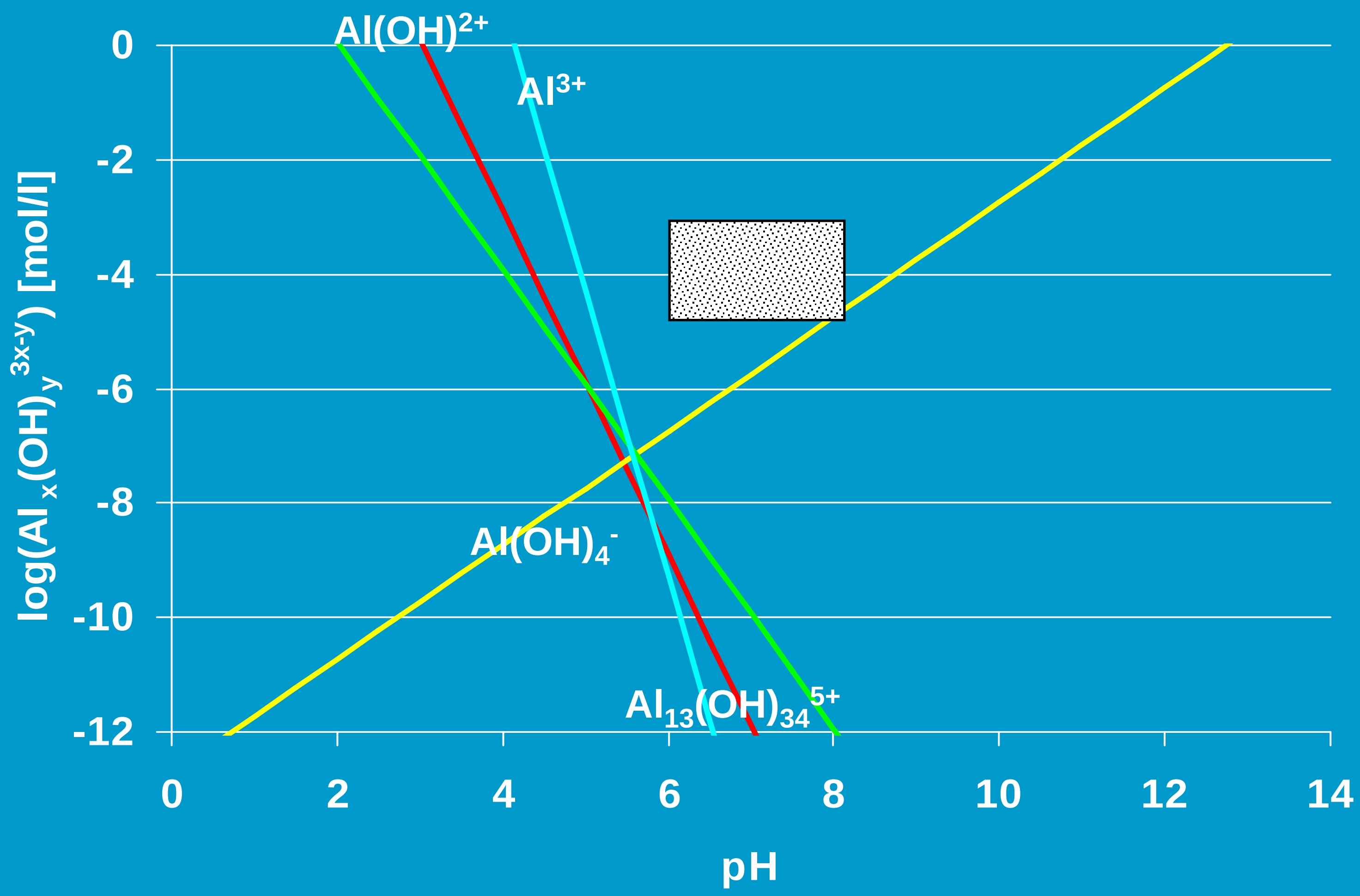
$Fe^{3+} + 2H_2O$	$\rightarrow$	$Fe(OH)^{2+} + H_3O^+$	$K = 6.8 \cdot 10^{-3}$
$Fe(OH)^{2+} + 2H_2O$	$\rightarrow$	$Fe(OH)_2^+ + H_3O^+$	$K = 2.6 \cdot 10^{-5}$
$Fe(OH)_2^+ + 2H_2O$	$\rightarrow$	$Fe(OH)_3 \downarrow + H_3O^+$	$K = 1 \cdot 10^{-6}$
$Fe(OH)_3 + 2H_2O$	$\rightarrow$	$Fe(OH)_4^- + H_3O^+$	$K = 1 \cdot 10^{-10}$

Coagulants



Fe(OH)3 (s)
Fe(OH)4-
Fe(OH)3
Fe3+
FeOH2+
Fe(OH)2+
log(Fe x(OH)y 3x-y) [mol/l]
0
-2
-4
-6
-8
-10
-12
-14
1.0E+05
1.0E+03
1.0E+01
1.0E-01
1.0E-03
1.0E-05
1.0E-07
1.0E-09
FeCl3·6H2O [mg/l]
0
2
4
6
8
10
12
14
pH

Coagulants


Al(OH)2+
Al3+
Al(OH)4-
Al13(OH)34 5+
0
-2
-4
-6
-8
-10
-12
log(Alx(OH)y 3x-y) [mol/l]
0
2
4
6
8
10
12
14
pH

Coagulants:
Pre-polymerized Aluminium Chloride (PAC)

- Part of the coagulation reaction already finished
- Very good results at low temperatures

```
      OH      Cl-    OH  OH     Cl-
      |        +      |   |      +
Cl- +Al-OH-Al-OH-Al-O-Al-O-Al-OH
      |        |      |   +      |
      OH      OH     OH  Cl-    OH
```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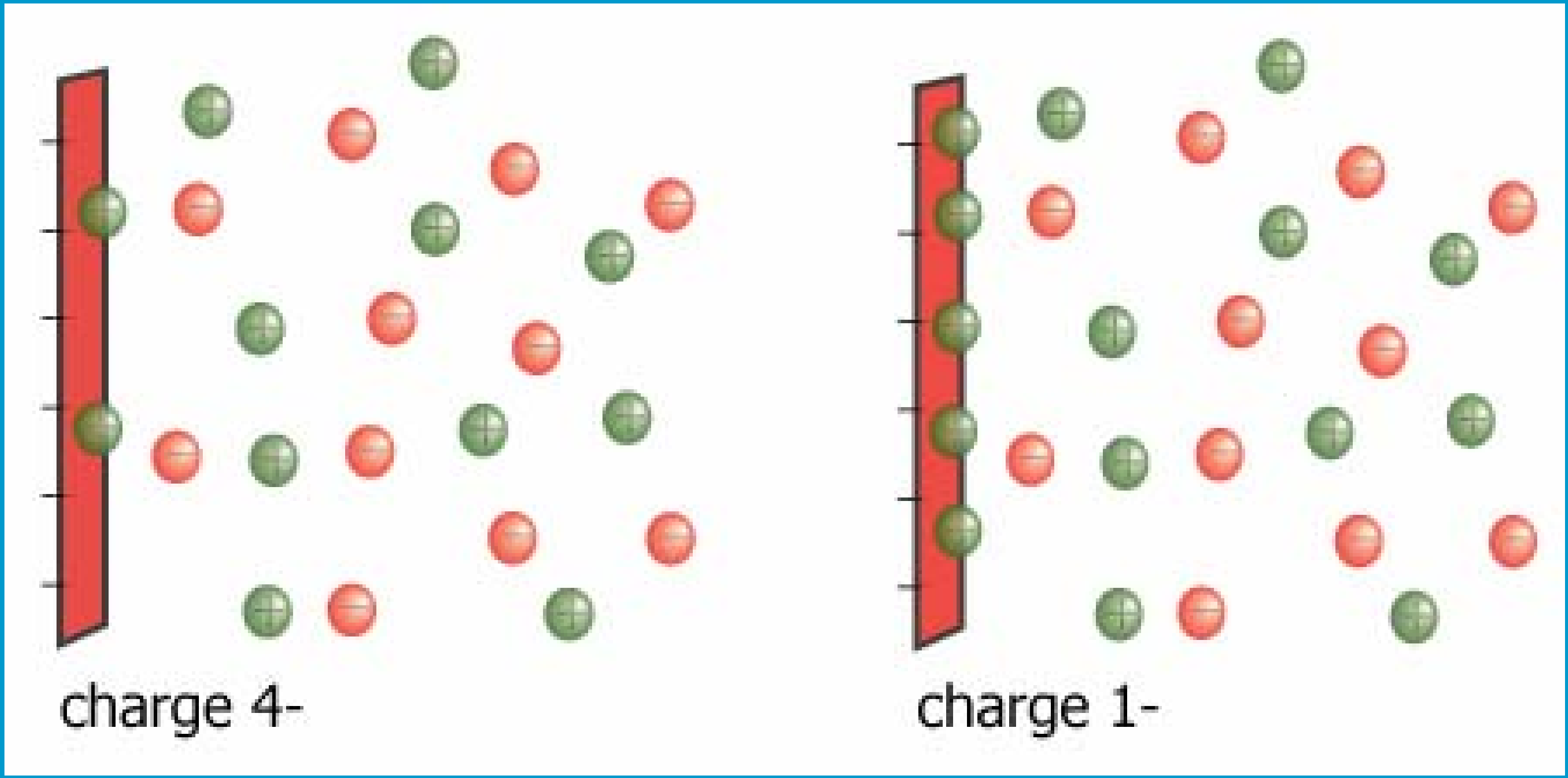
Destabilisation

Three mechanisms

- electrostatic coagulation
- adsorptive coagulation
- precipitation coagulation

Electrostatic coagulation

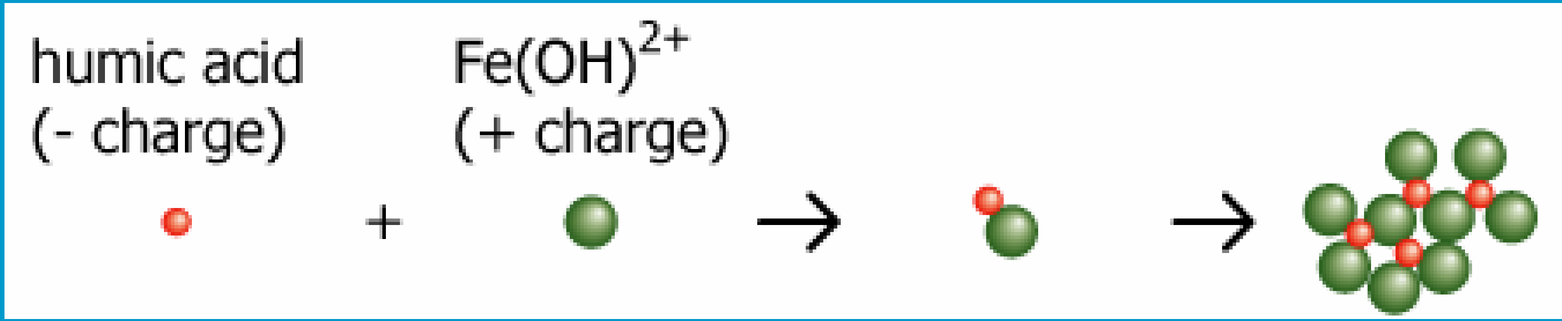


Dosage 0.025 mmol/l Fe^{3+} → pH ≈ 3

Adsorptive coagulation

< 1 sec

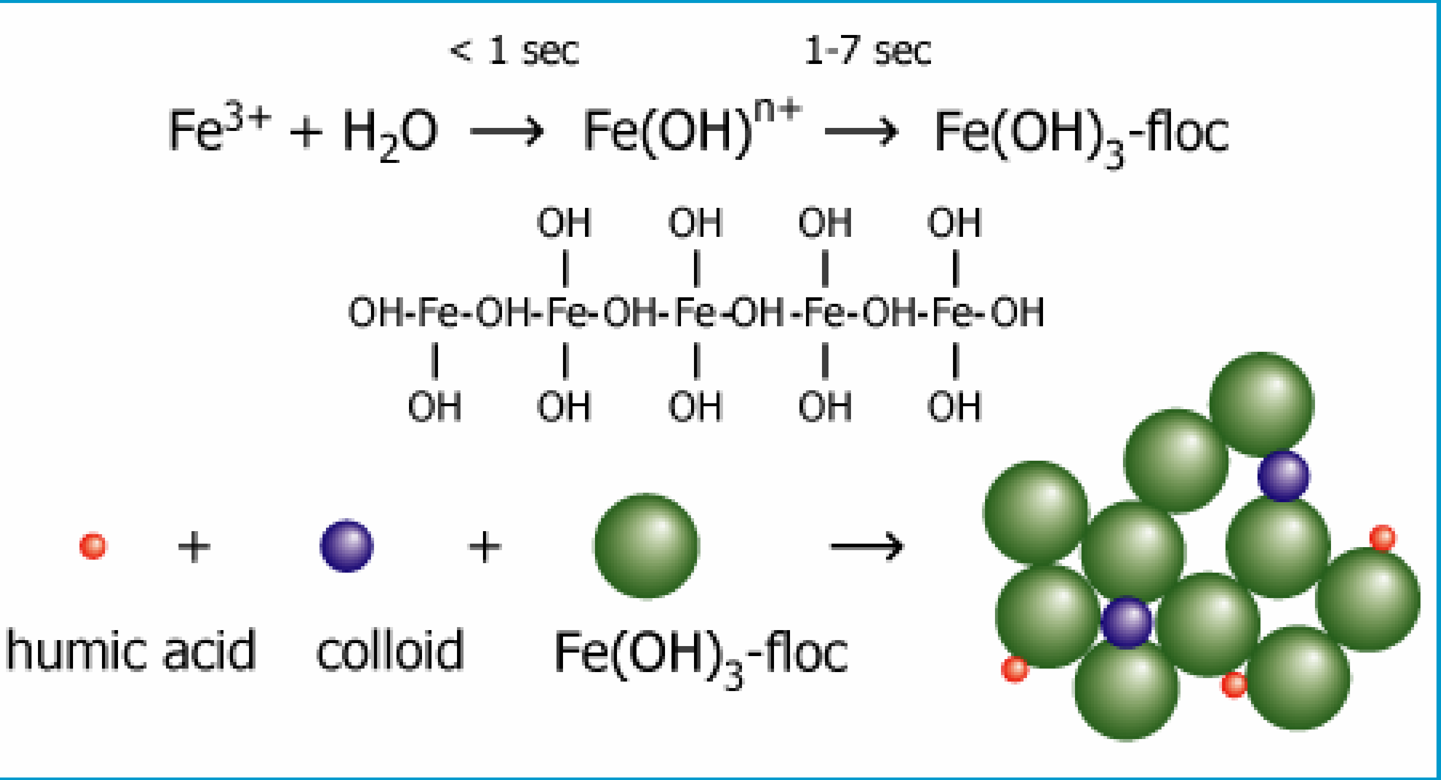
$Fe^{3+} + H_2O \rightarrow Fe(OH)^{2+}$



Adsorptive coagulation occurs at a low pH, because positive hydrolysis products are needed.

restabilisation:
- under-dosage of coagulants
- over-dosage of coagulants

Precipitation (sweep) coagulation



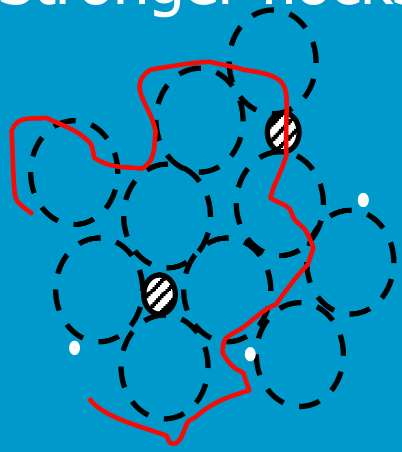
At low turbidites

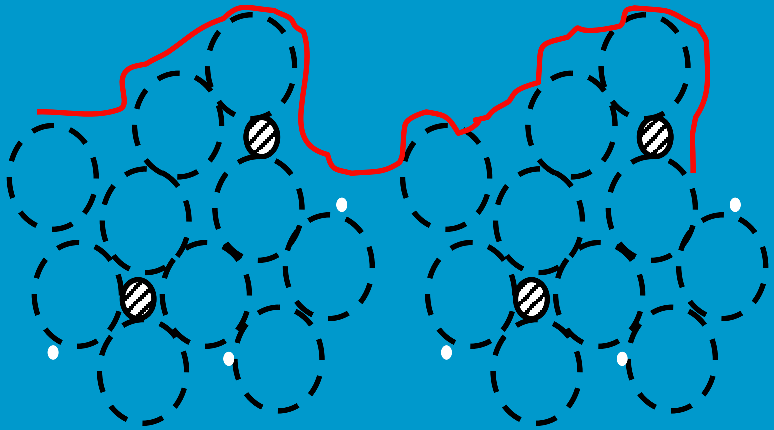
$Fe(OH)_3$ floc is neutral, flocs can collide

Polyelectrolytes (flocculant aid): long organic polymers

- Stronger flocks

larger flocks





Used at low temperatures

Conclusions coagulation

electrostatic coagulation:

→ not of importance in drinking water treatment

adsorptive coagulation

→ colour at low pH, dosing proportional with removal of organic compounds

→ low dosing

→ high dosing results in re-stabilisation

→ optimum with low pH

→ mostly for colour (organic compounds)

precipitation coagulation

→ no re-stabilisation

→ high dosing

→ for turbidity removal

→ evident optimum pH 8 with iron
pH 6 with aluminum

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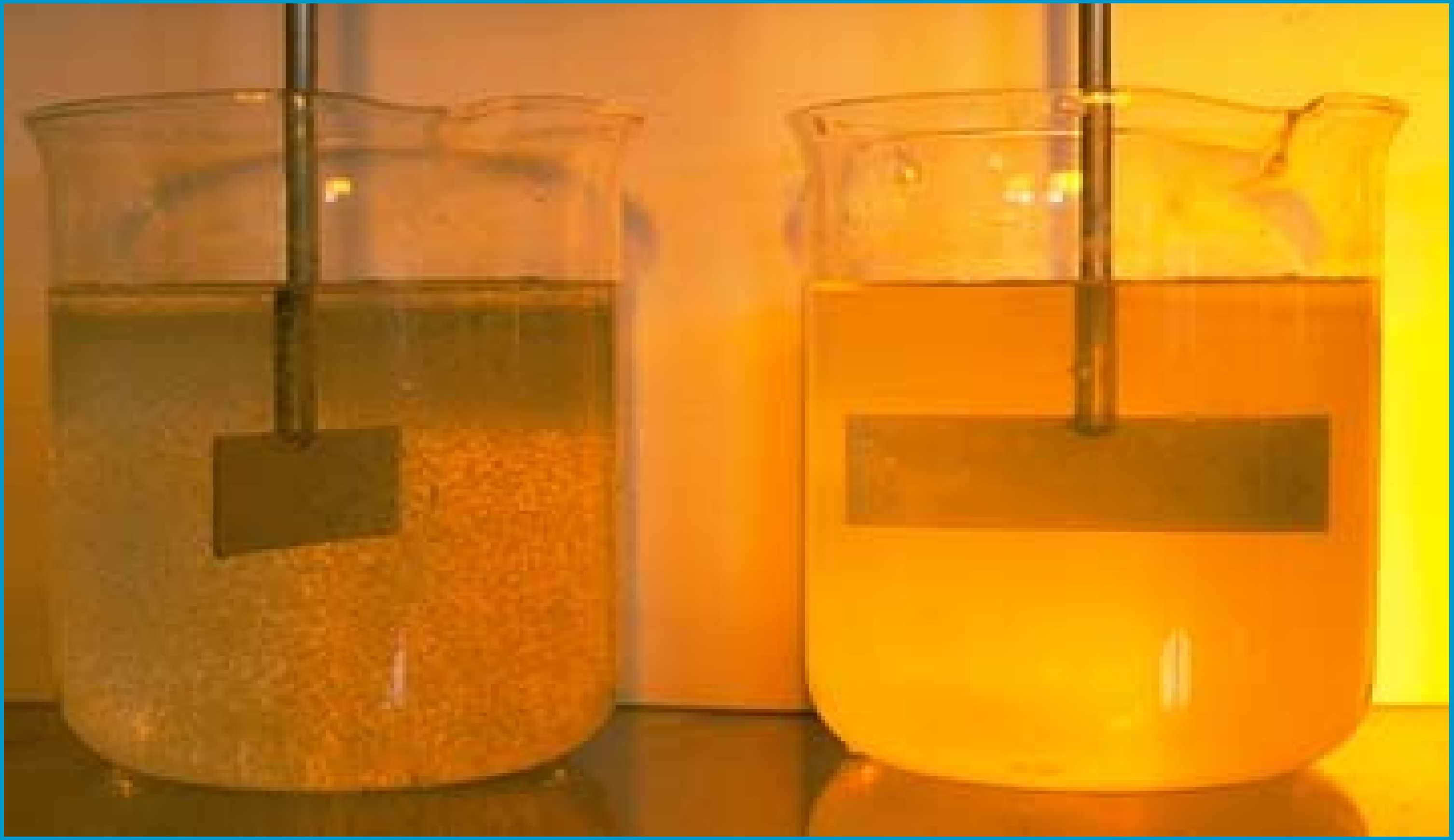
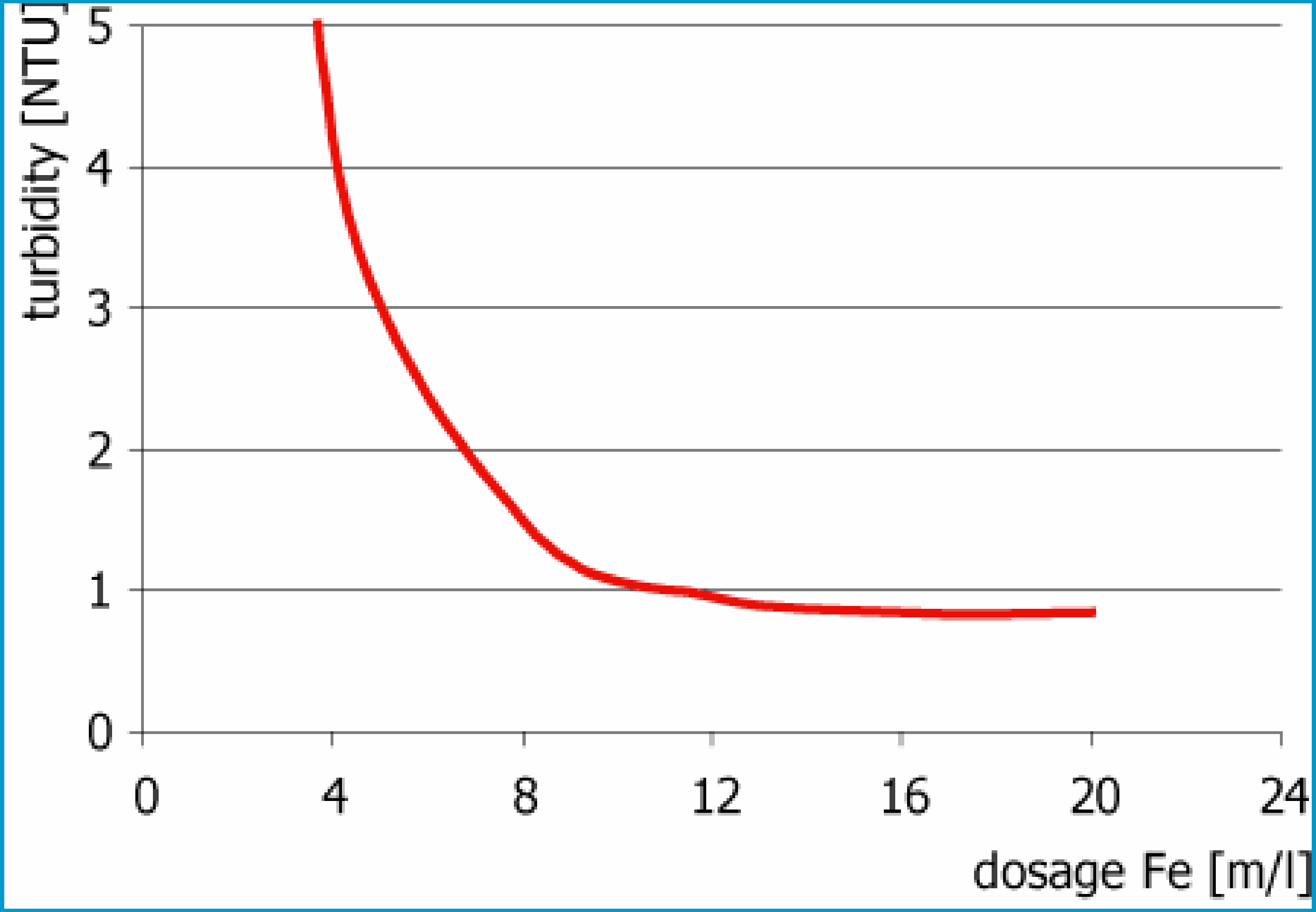
Coagulation: practice



Jar test apparatus

Variation in: pH, dosage, flocculation time, sedimentation time, stirring energy

Optmising dosage



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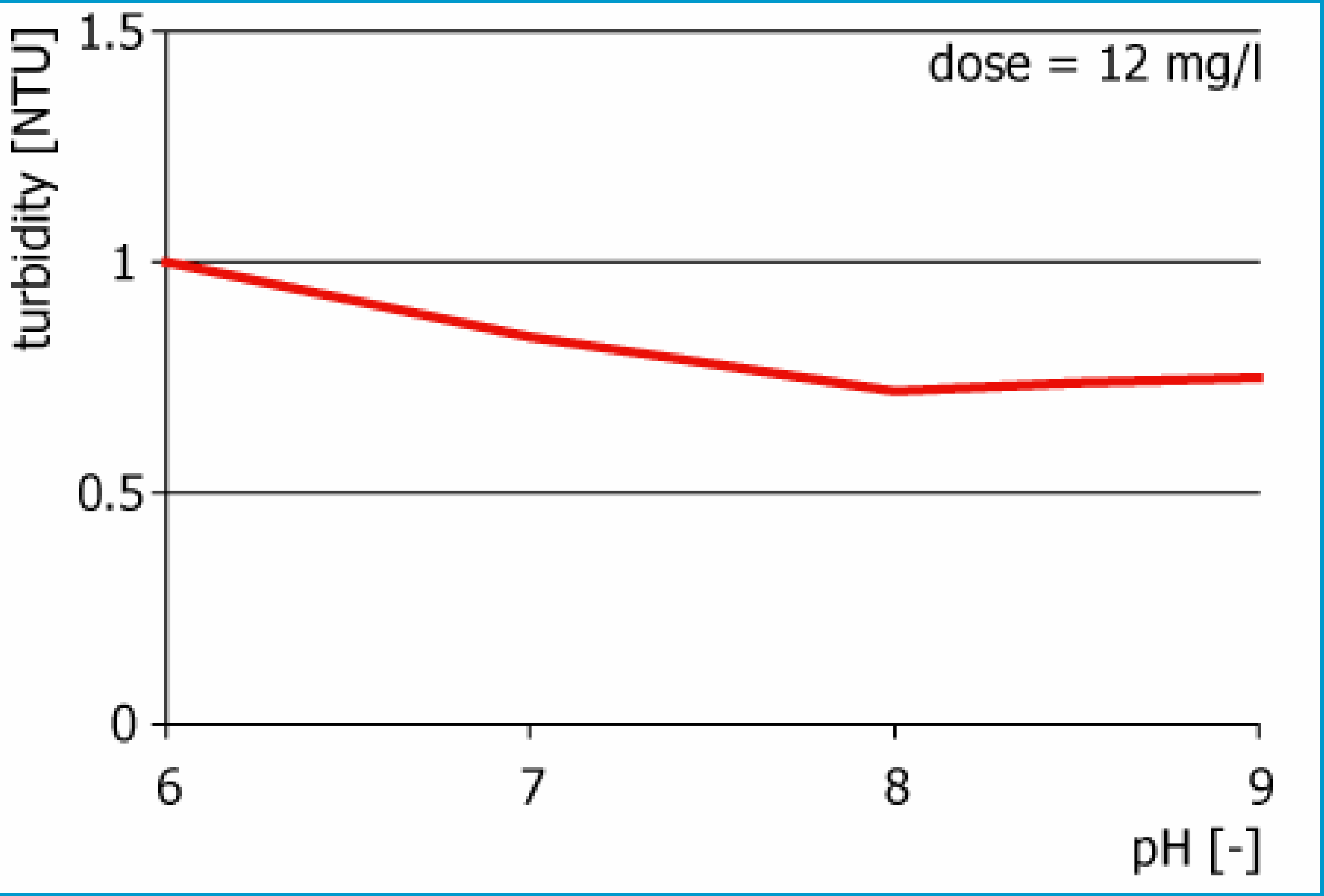
Optimising pH



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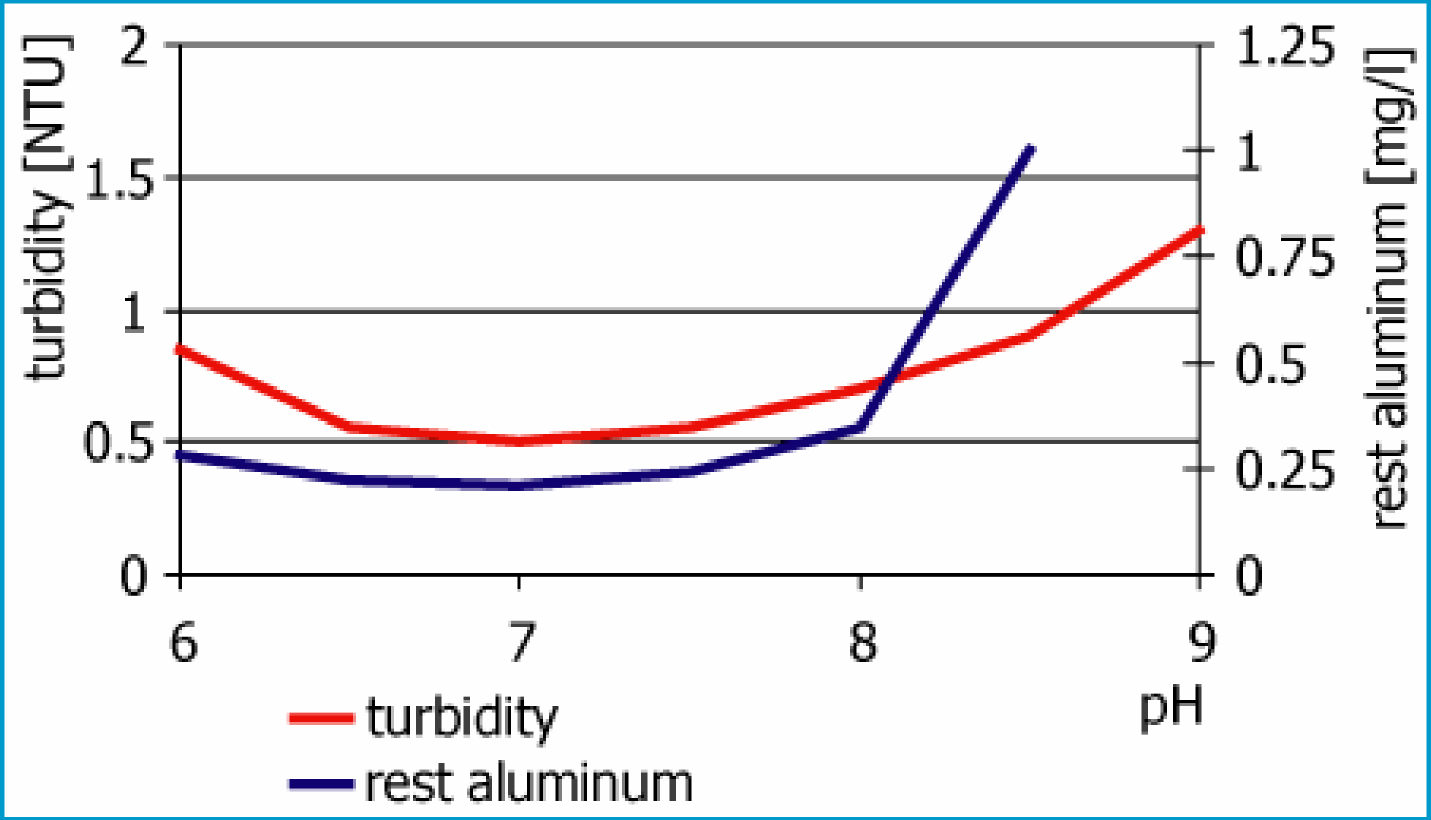
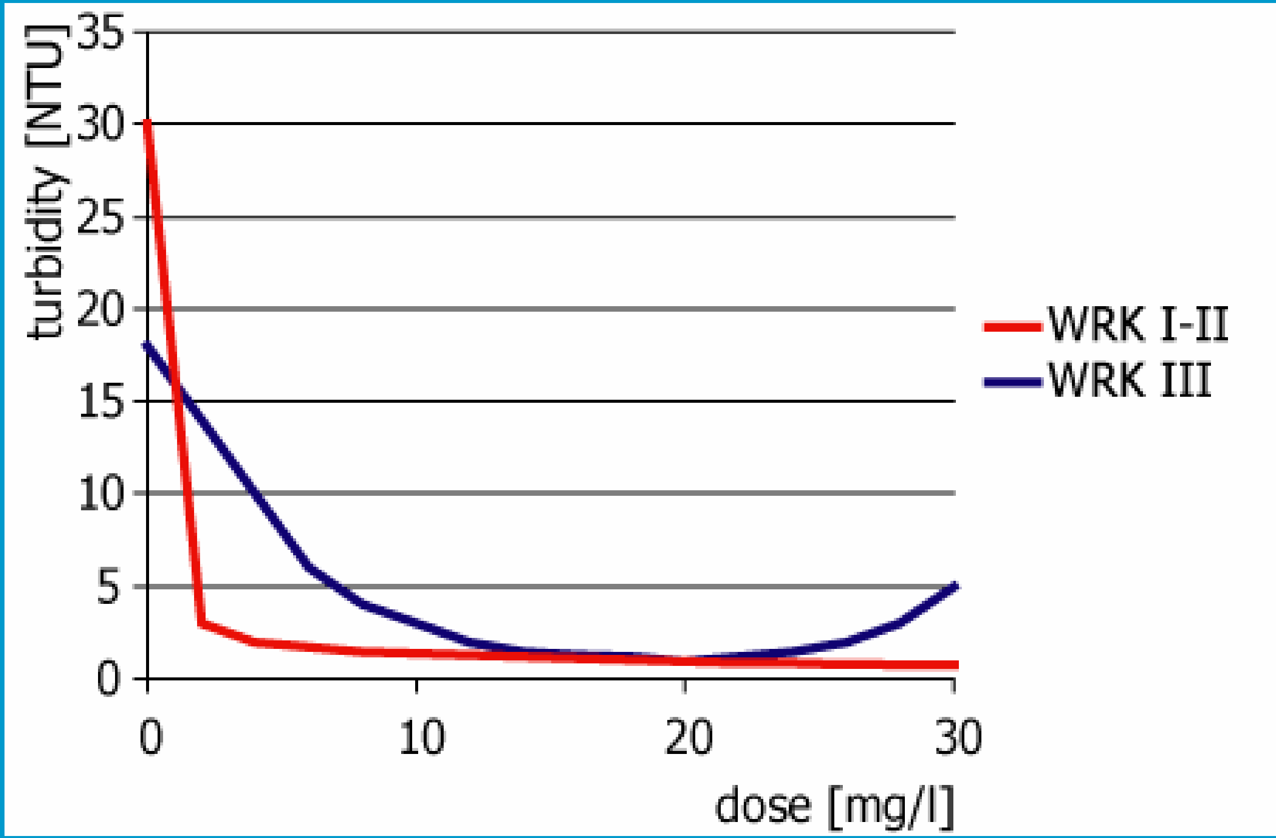
Coagulation Braakman

polder water = humic acids



WRK I-II ↔ WRK III

Rhine water <-> Lake IJssel water



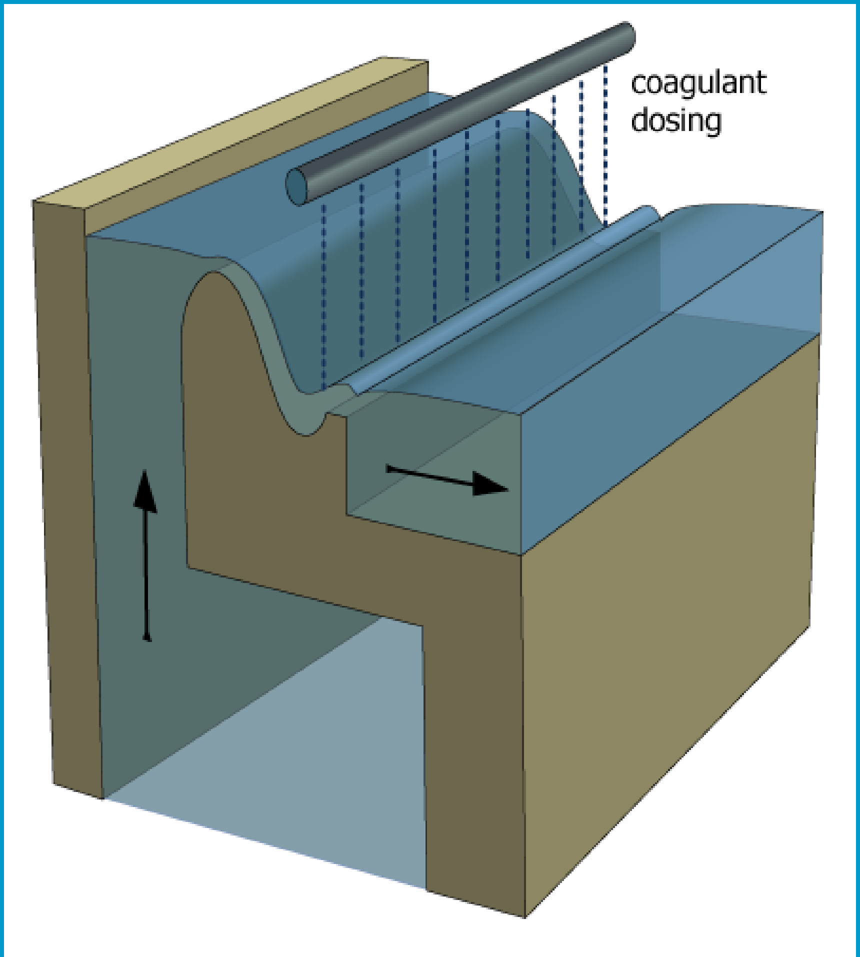
Rapid mixing

- mechanical mixers

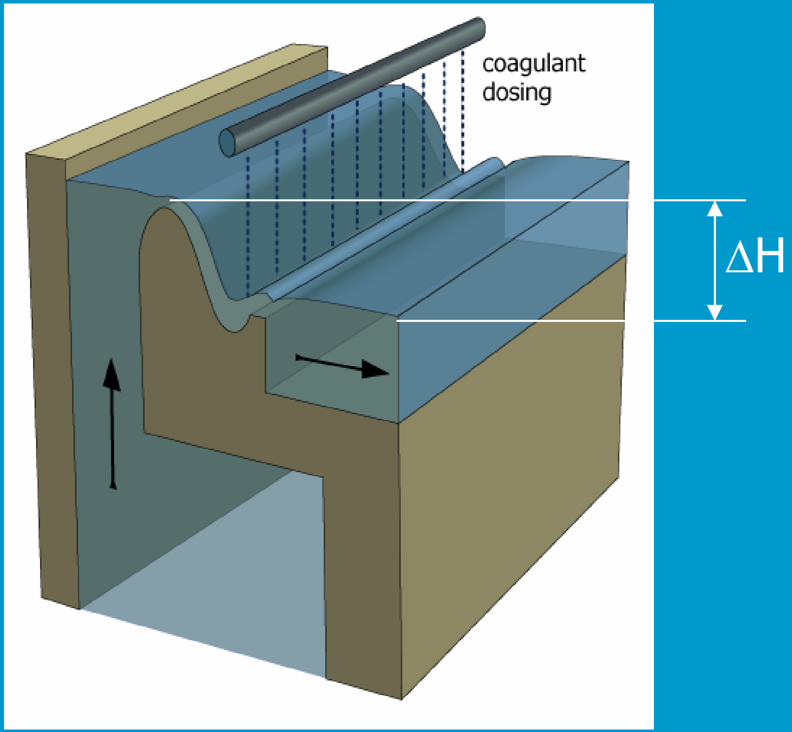
- static mixers

parameters:
- residence time (T)
- velocity gradient (G_c)

Weir mixer



Example weir mixing



static mixer $$G_c = \sqrt{\frac{\rho_w \cdot g \cdot \Delta H}{\tau_c \cdot \mu}}$$

Example:

$\Delta H = 0.75$ m; $Q = 4500$ m^3/h; $V = 2$ m^3

$T = 20°C \rightarrow \mu = 1.01 \cdot 10^{-3}$ $N \cdot s/m^2$

$Q = 4500$ $m^3/h = 1.25$ m^3/s

$\tau_c = 2/1.25 = 1.60$ sec

$$G_c = \sqrt{\frac{1000 \cdot 9.81 \cdot 0.75}{1.01 \cdot 10^{-3} \cdot 1.6}} = 2134 s^{-1}$$

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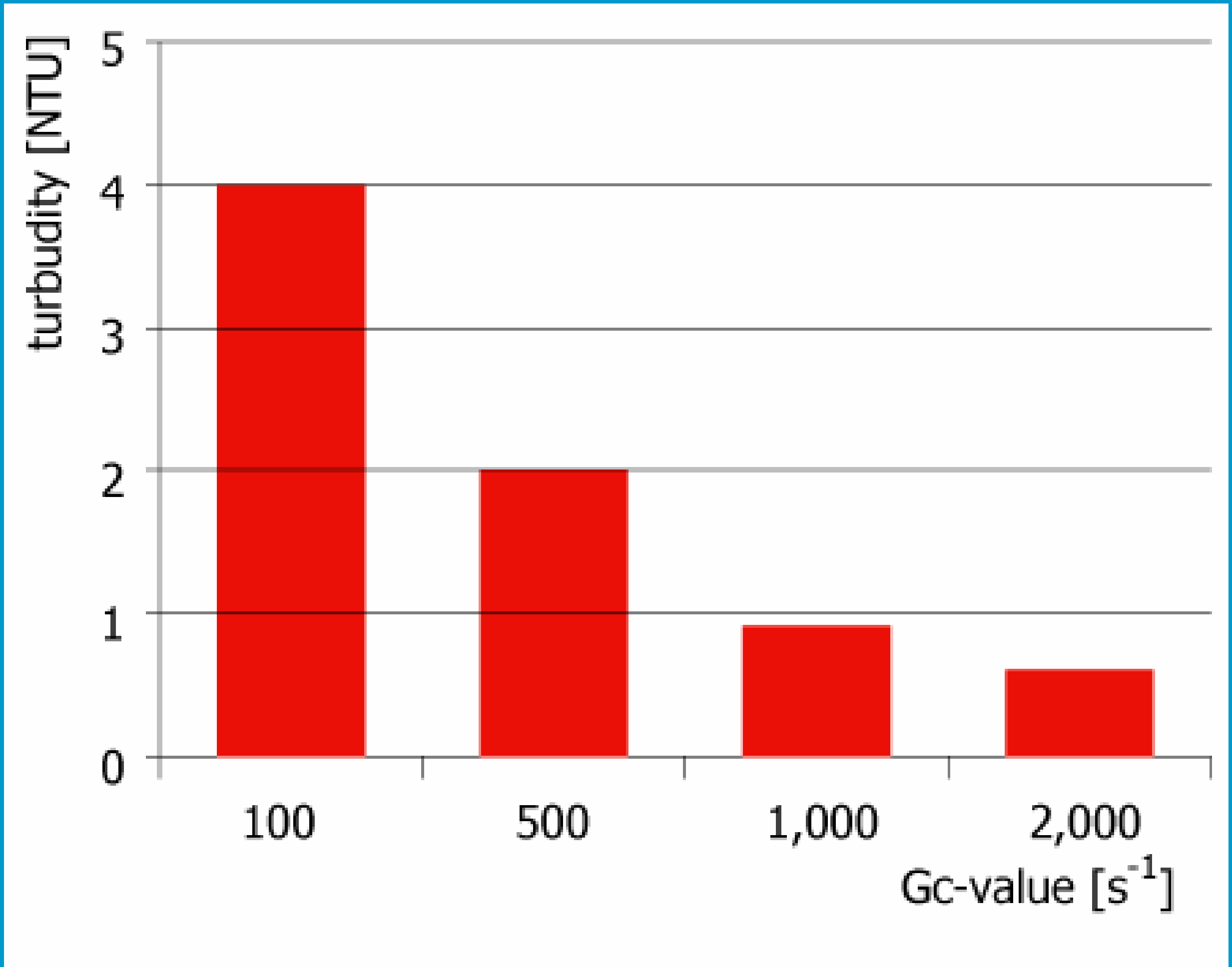
Variation in velocity gradient G_c



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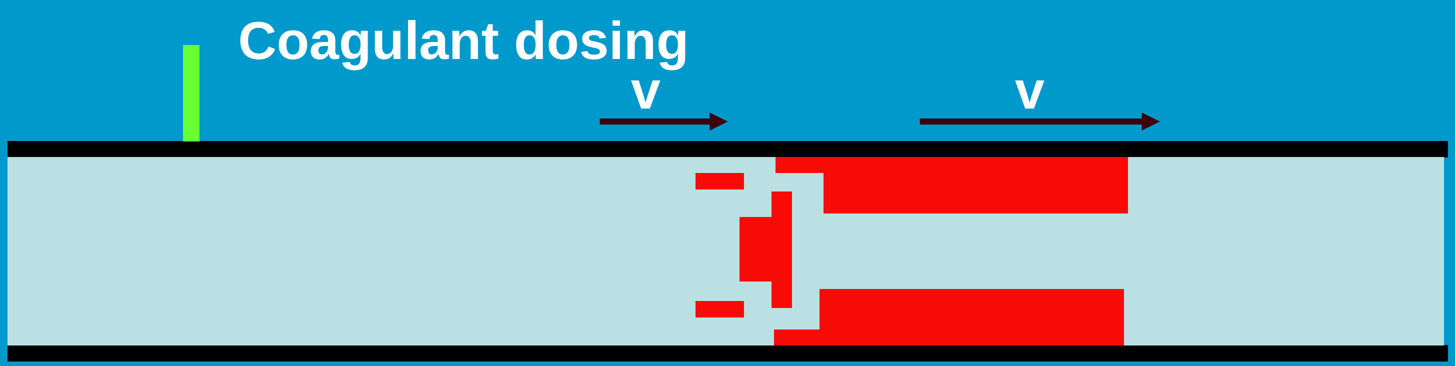
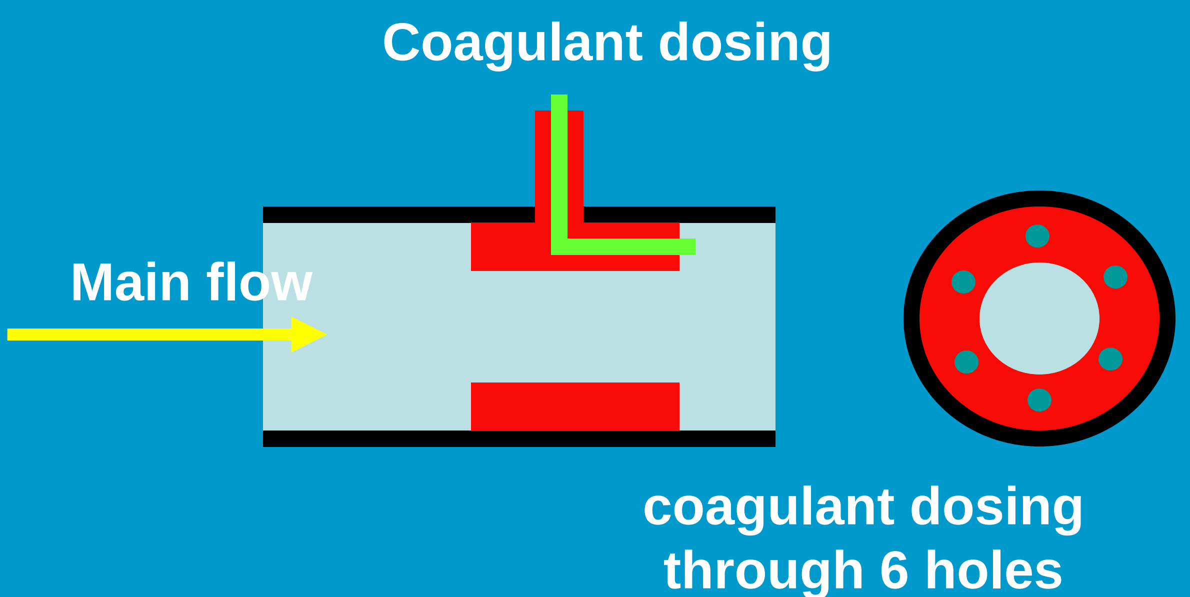
Construction forms of static mixers





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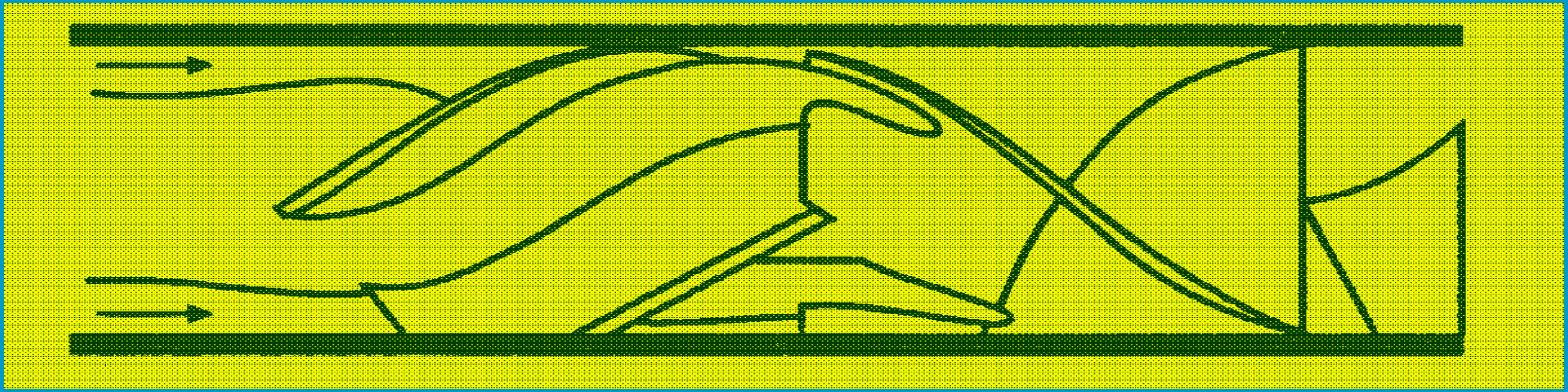
Construction forms of static mixers



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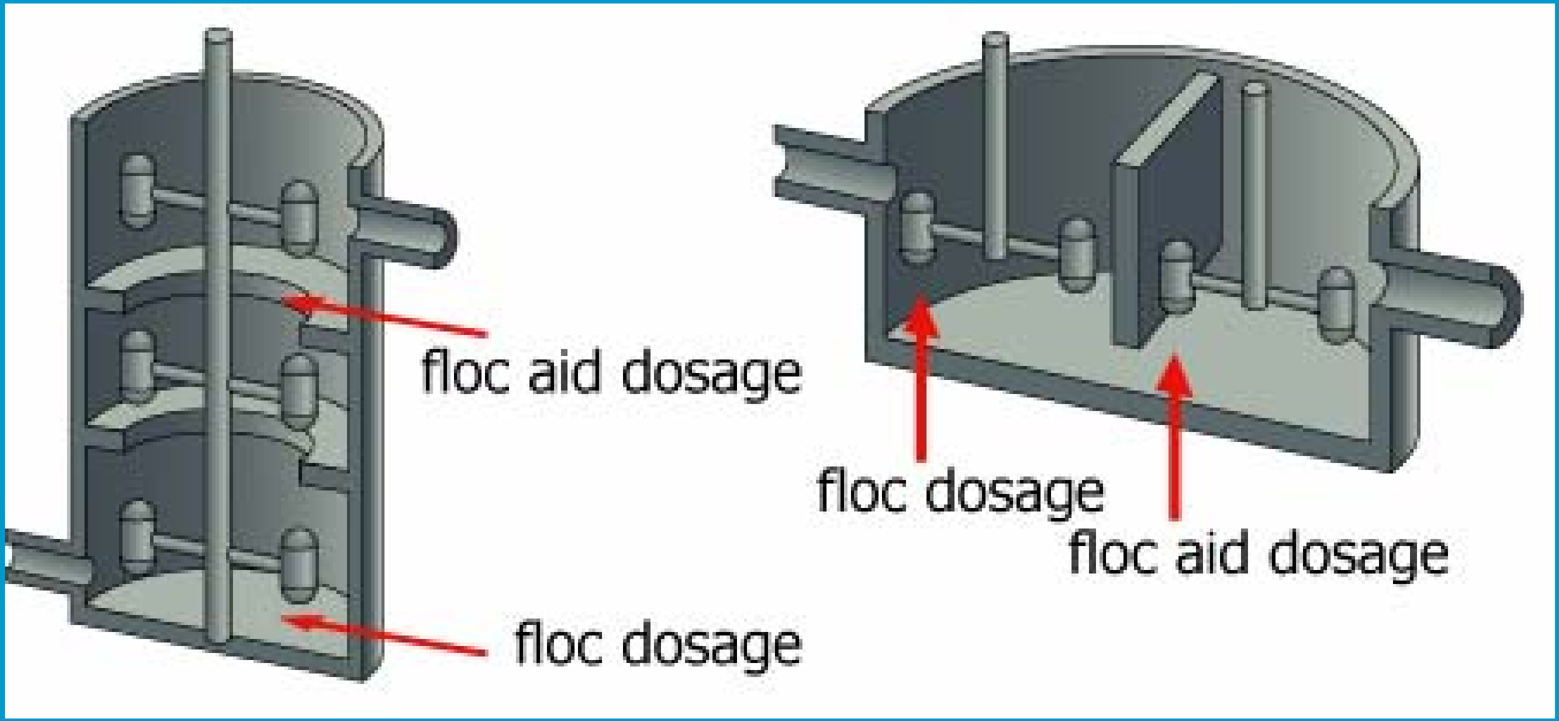
Coagulation: practice

mechanical mixer $G_c = \sqrt{\dfrac{P}{\mu \cdot V}}$



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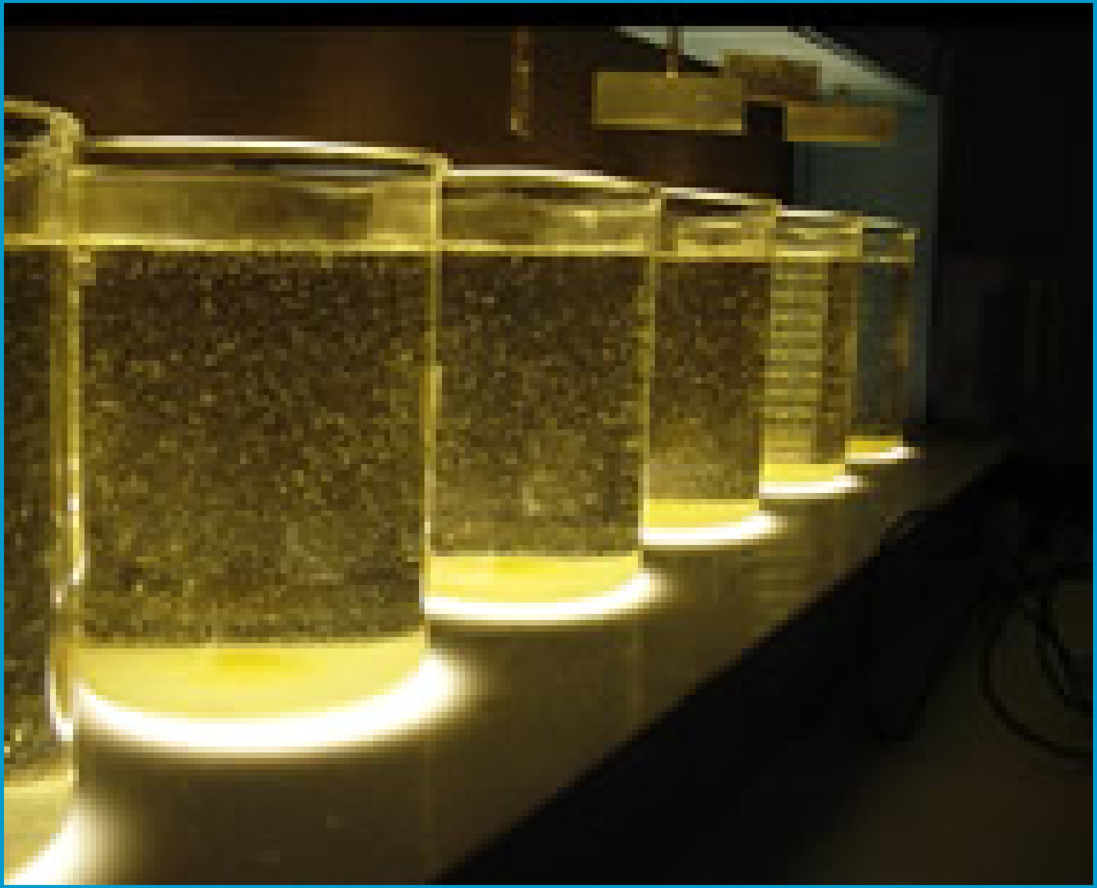
Mixing: Dutch practice

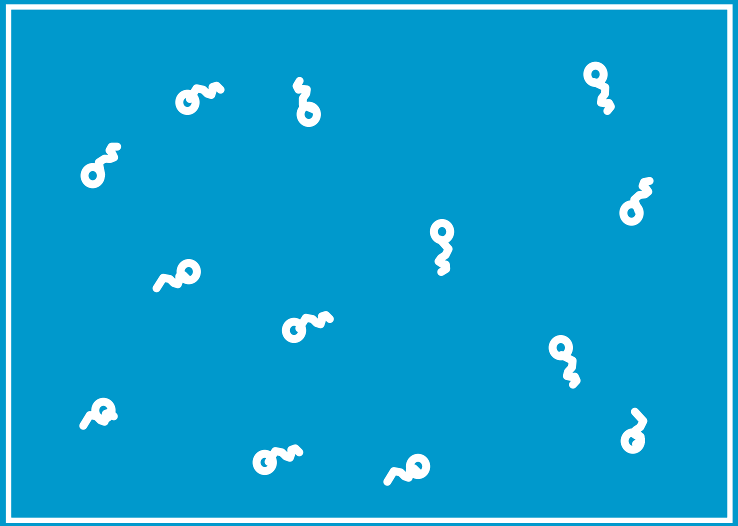
	WRK I-II	WRK III	Braakman
Type mixer	constriction	hydraulic jump	cascade
Energy loss over mixer [m]	0.02	0.30	0.50
Mixing time [s]	4.50	1.25	1.15
G_c value at 20°C [s^{-1}]	300	1530	2050
Type of coagulant	$FeCl_3$	Fe SO_4	$Al_2(SO_4)_2$
Dosing [mg/l]	2 – 10	20	5-6

Flocculation: theory



Perikinetic flocculation

driving force = Brownian movement



Von Smoluchowski: $$-\frac{dn}{dt} = \alpha \cdot \frac{4 \cdot k \cdot T}{3 \cdot \mu} \cdot n^2$$

solution: $$\frac{n}{n_0} = \frac{1}{1 + \frac{4 \cdot \alpha \cdot k \cdot T}{3 \cdot \mu}}$$

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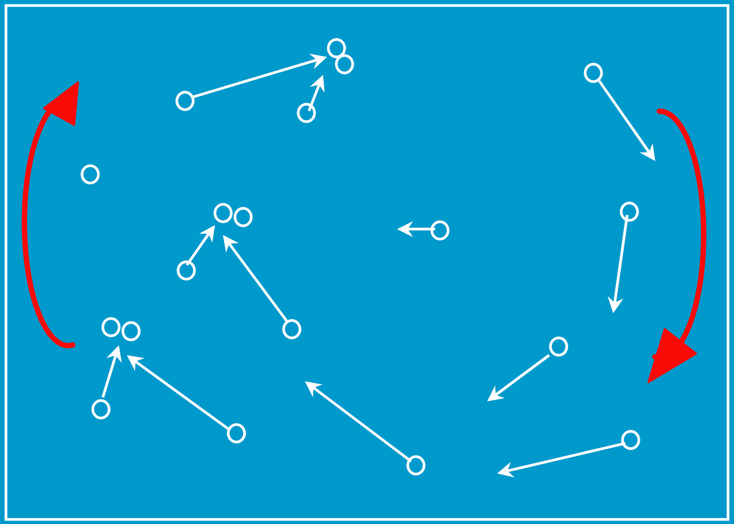
Orthokinetic flocculation

driving force = turbulence



$$-\frac{dn}{dt} = \frac{4}{3} \cdot n_1 \cdot n_2 \cdot R^3 \cdot G_v$$

Plug flow $$\frac{n}{n_o} = e^{-k_a \cdot c_v \cdot G_v \cdot t}$$

Complete mixing
$$\frac{n}{n_o} = \frac{1}{1 + k_a \cdot c_v \cdot G_v \cdot t}$$

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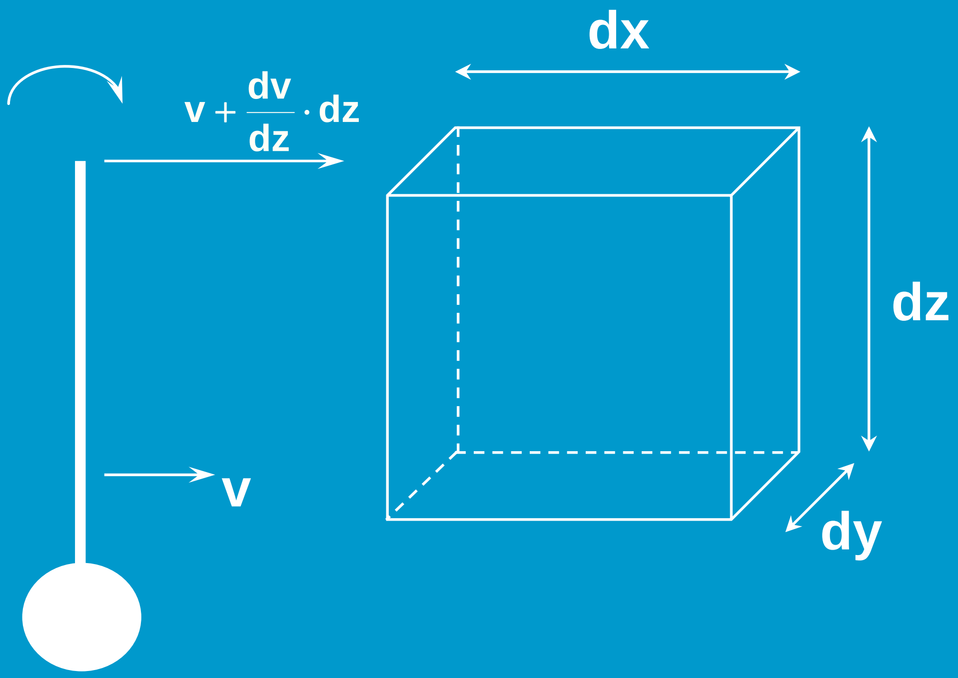
Velocity gradient



$$F = \mu \cdot \frac{dv}{dz} \cdot dx \cdot dy$$

$$P = F \cdot dv = \mu \cdot \frac{dv}{dz} \cdot dx \cdot dy \cdot dv = \mu \cdot \left(\frac{dv}{dz}\right)^2 \cdot dx \cdot dy \cdot dz = \mu \cdot G^2 \cdot V$$

$$G = \sqrt{\frac{P}{\mu \cdot V}}$$

Flocculation: practice

Construction forms of flocculation tanks

parameters:	
- residence time	T
- residence time distribution	n
- velocity gradient	G_v
- floc volume concentration	c_v

residence time: 500 - 3600 seconds

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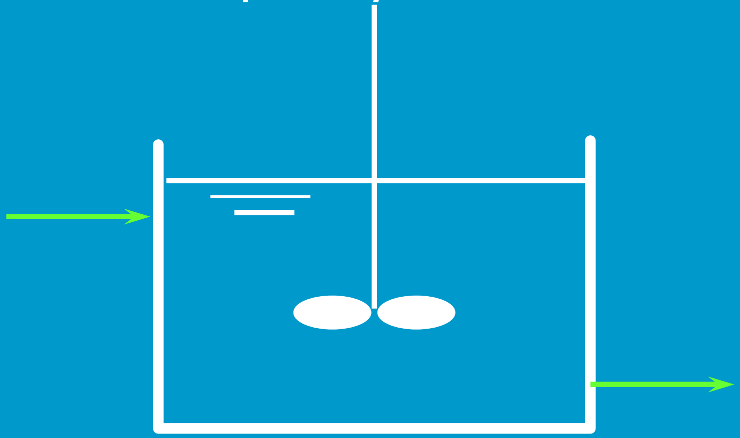
Residence time (distribution)

Plug flow

Completely mixed



no mixing, thus particle concentration differences

no residence time distribution particles

perfectly mixed, thus no particle concentration differences

residence time distribution particles

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Residence time distribution

complete mixing: $J(\Theta) = 1 - \exp\left(-\Theta\right)$

plug flow:

$t < T \quad J(\Theta) = 0;$

$t \geq T \quad J(\Theta) = 1$

mixers in series: $J(\Theta) = 1 - \exp(-n \cdot \Theta) \cdot \sum_{i=1}^{n} \frac{(n \cdot \Theta)^{i-1}}{(i-1)!}$

$\Theta = t/T$

t = time

T = calculated residence time

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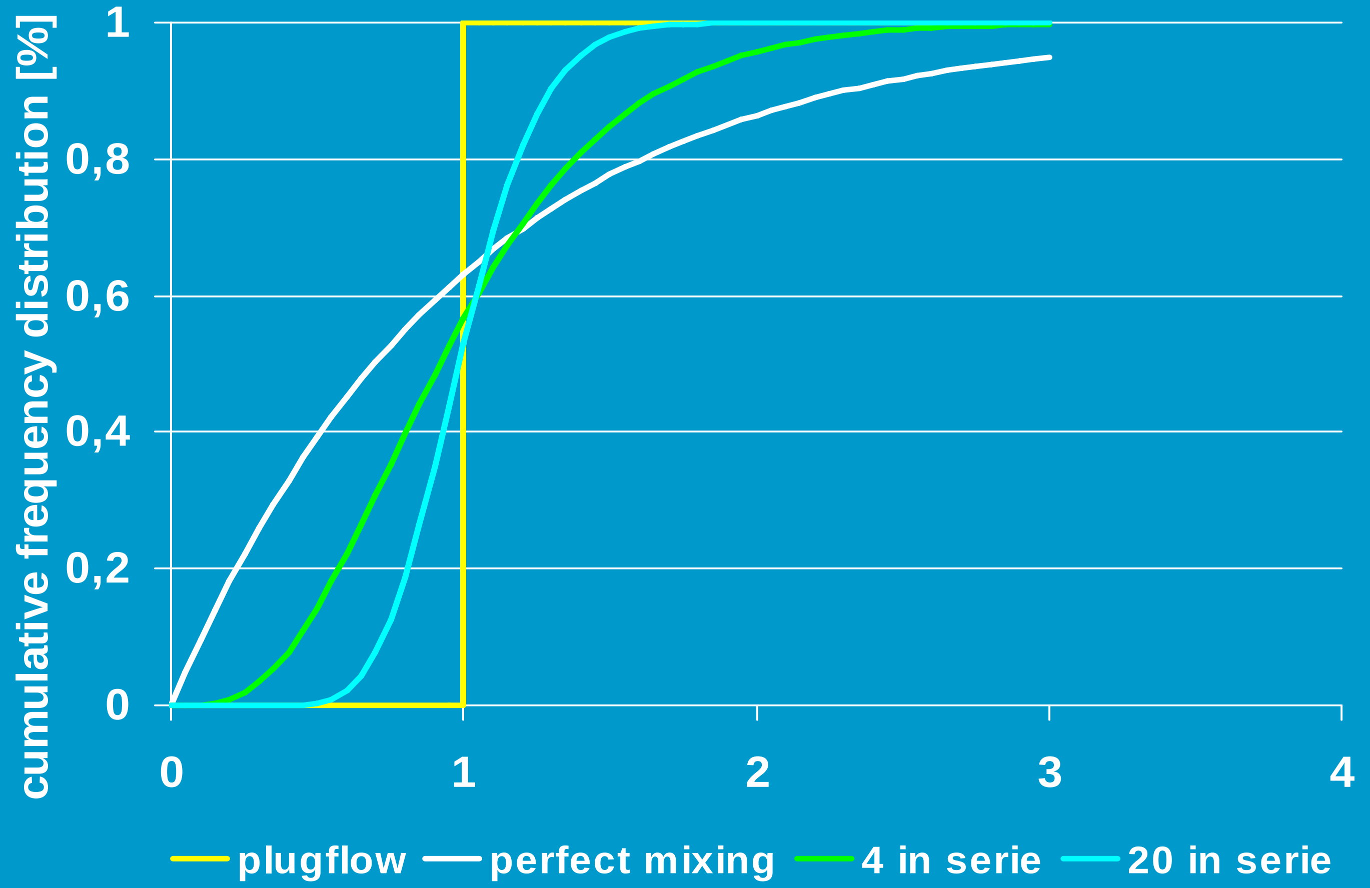
Residence time distribution



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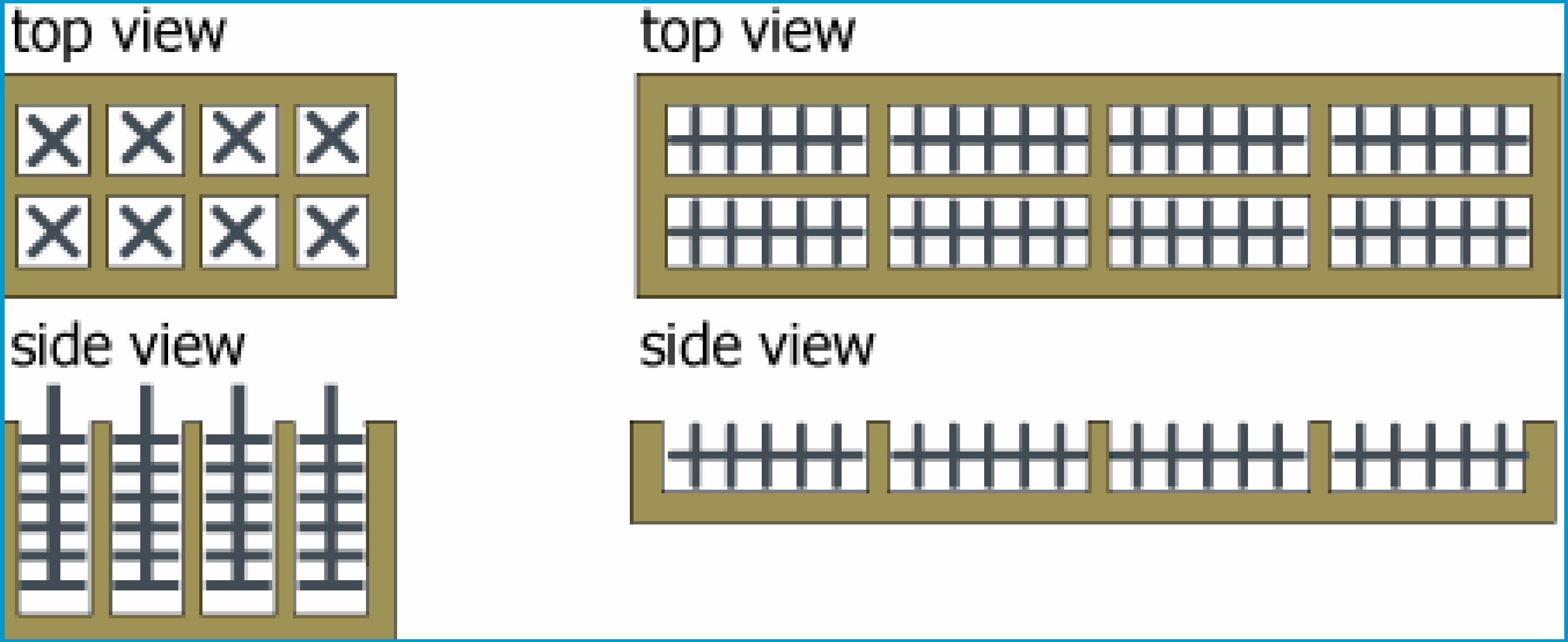
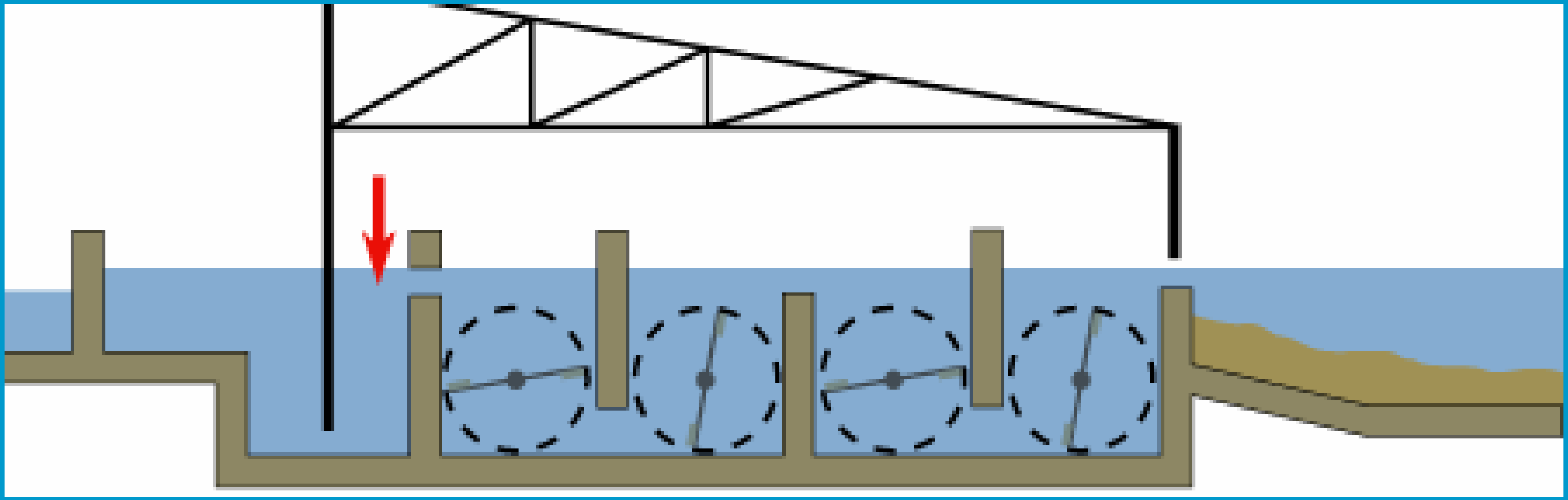
Optimal design flocculators



L/B ratio (L/B >= 3)
Vertical, deep and narrow or horizontal, long and narrow

Non optimal design



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Velocity gradient

Energy input →
turbulence →
collision of particles → flocs

Degree of energy supply = velocity gradient

$$G_v = \sqrt{\frac{P}{V \bullet \eta}}$$

Velocity gradient in practice: 10-500s^{-1}
Considering floc break up: tapered flocculation

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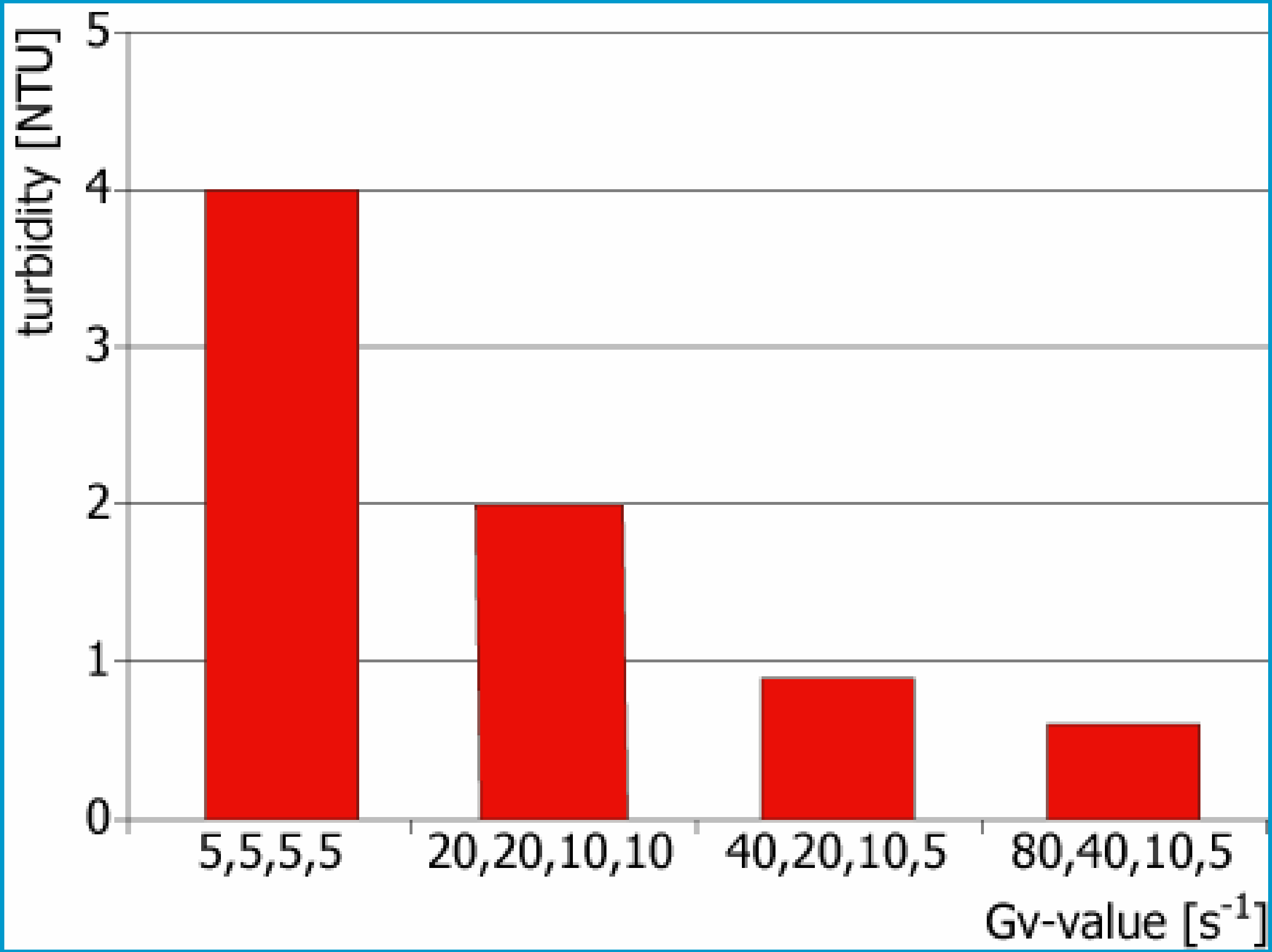
Variation in velocity gradient G_v



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Flocculators

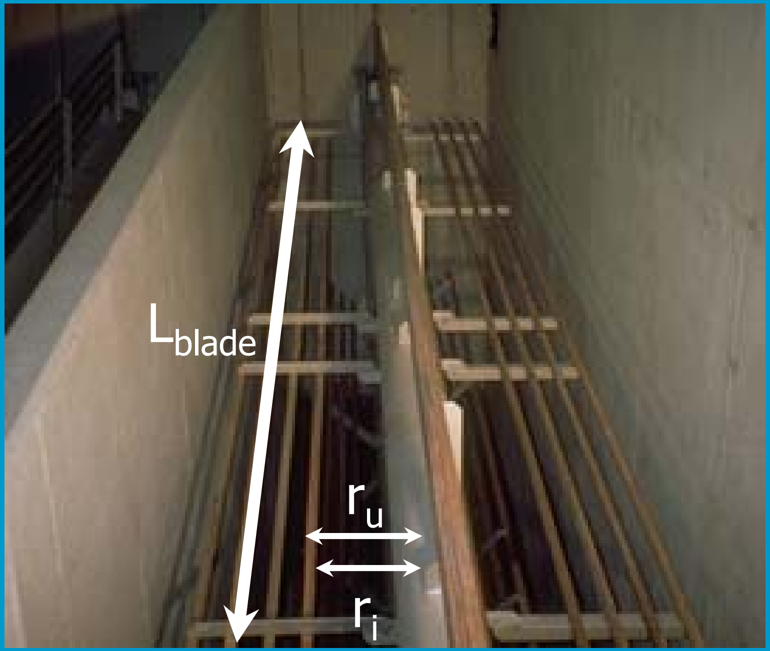
$$G_v = \sqrt{\frac{P}{V \cdot \eta}}$$

$$P = \rho_w \cdot \pi^3 \cdot (1 - k_2)^3 \cdot N^3 \cdot \sum C_d \cdot L_{blad} \cdot \left(r_u^{\,4} - r_i^{\,4}\right)$$

$$G = \text{constant} \cdot \sqrt{N^3}$$

Design parameters:
L_{blade}, C_d, r_u, r_i, k_2

Operating parameters: N



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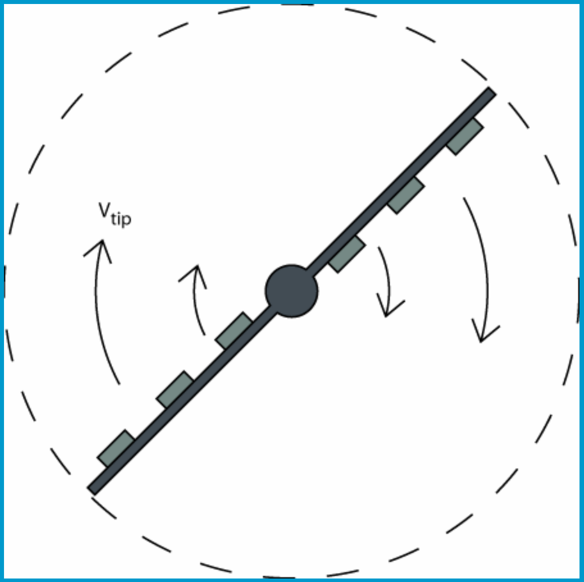
Tip velocity



$$v = 2 \cdot \pi \cdot r \cdot N$$

N = 4 rotations/min

v_{max} = 1 m/s

$$\Rightarrow r < \frac{v}{2 \cdot \pi \cdot N} < \frac{1}{2 \cdot \pi \cdot \frac{4}{60}} < 2.4\text{m}$$

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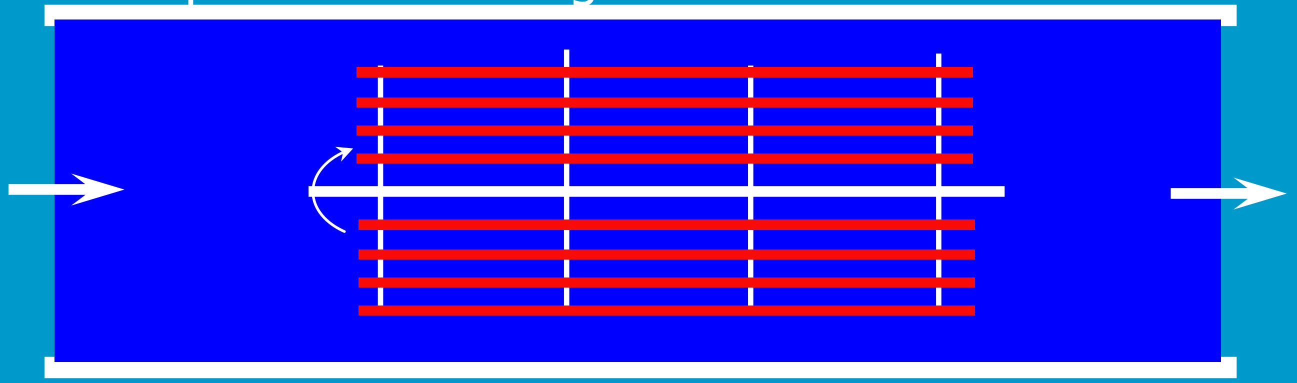
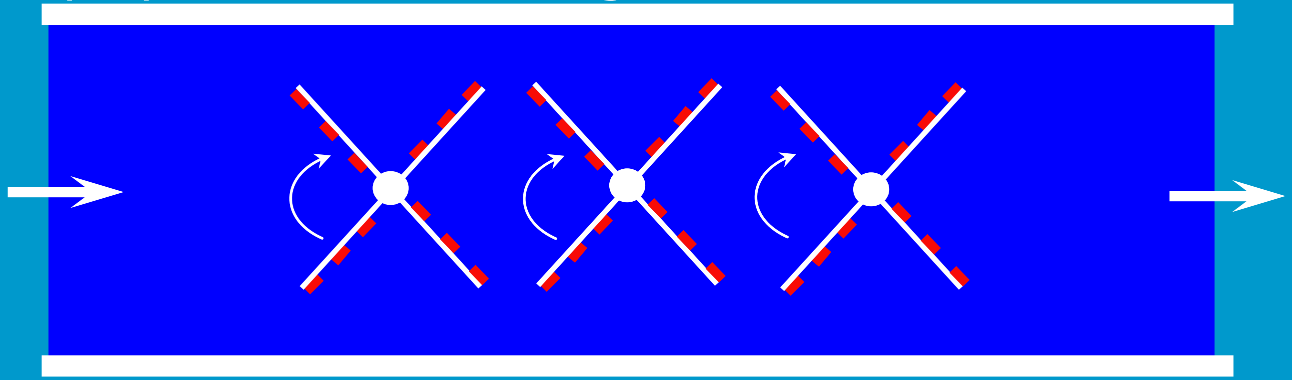
Short circuit flow due to flocculators

flow parallel to stirring axis = no short circuit flow



Short circuit flow due to flocculators

flow perpendicular to stirring axis = short circuit flow



flow velocity = 0.03 m/s, tip velocity = 1 m/s

→ water velocity –0.97 tot 1.03 m/s

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Floc break-up

avoiding floc break-up:
- more compartments with different G_v value
- tip velocity less than 1 m/s results in maximum width of 5 m

approaching plug flow:
- compartments with large L/B ratio (L/B >= 3)
- water flow parallel to axis of stirring device

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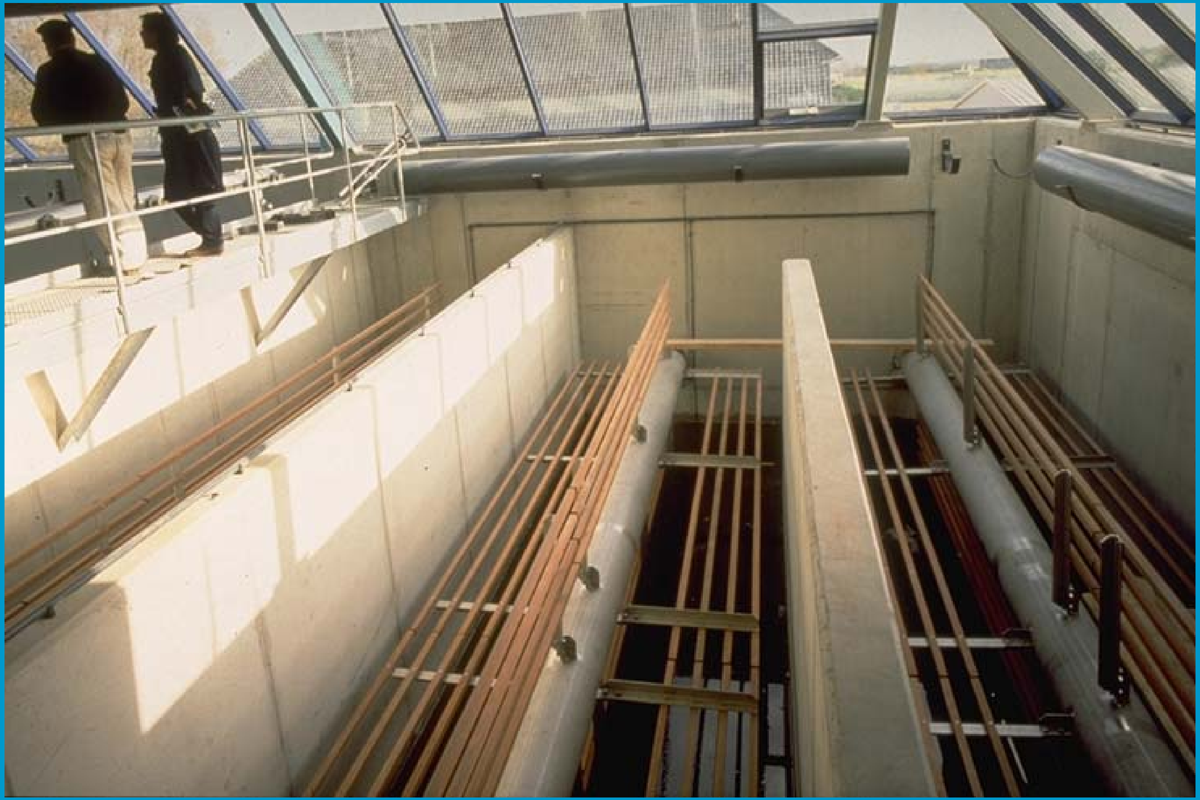
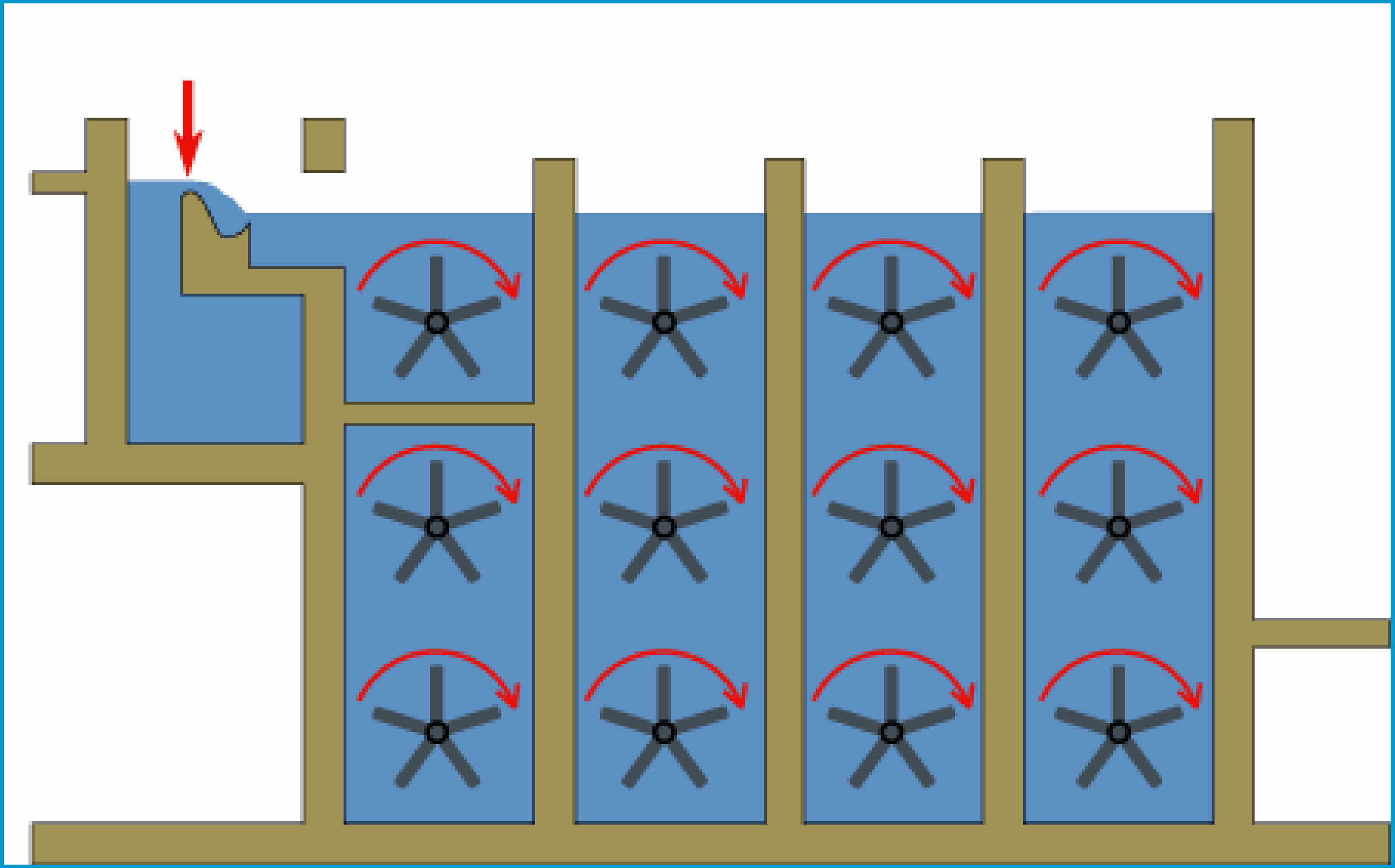
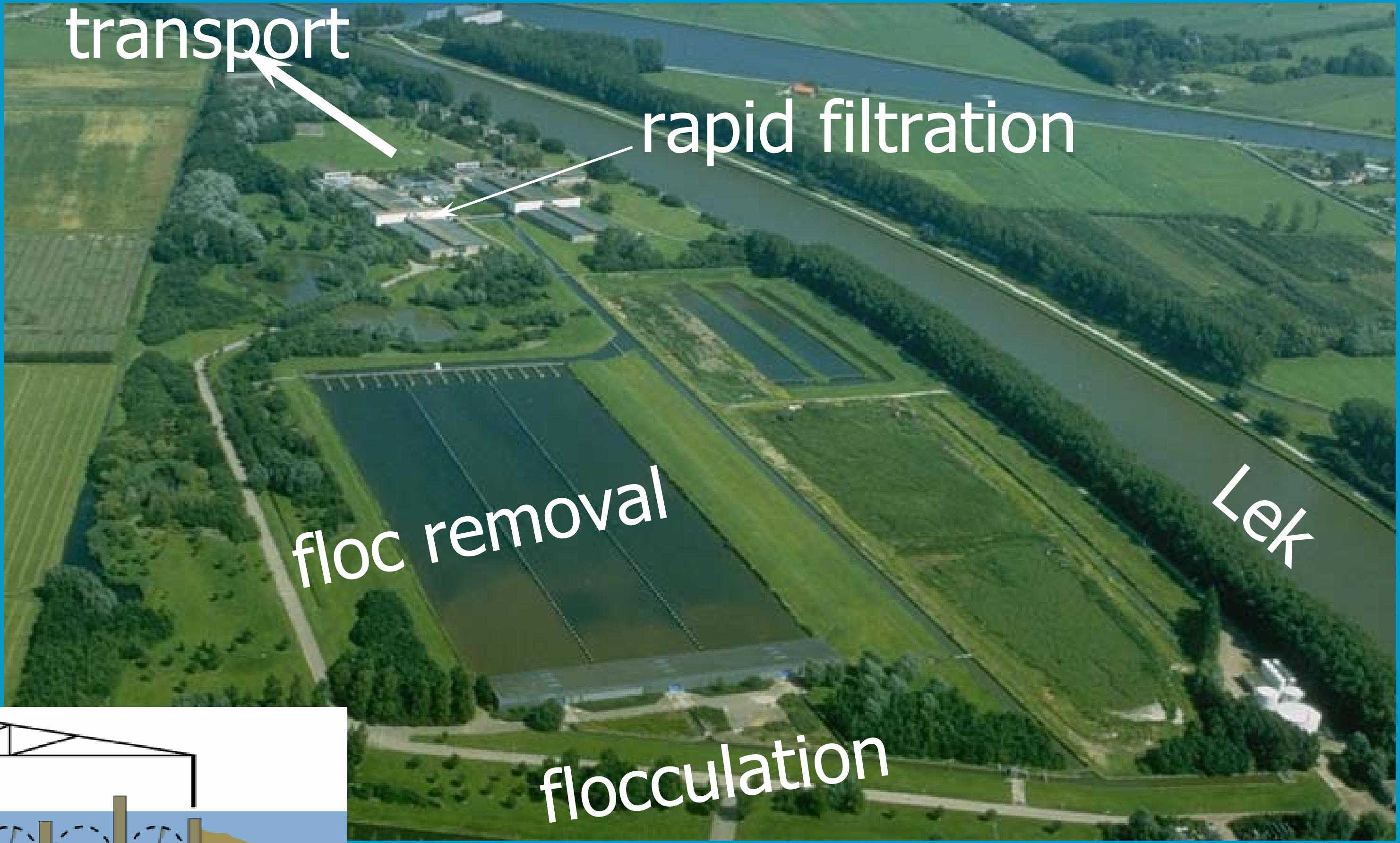
Well designed flocculator

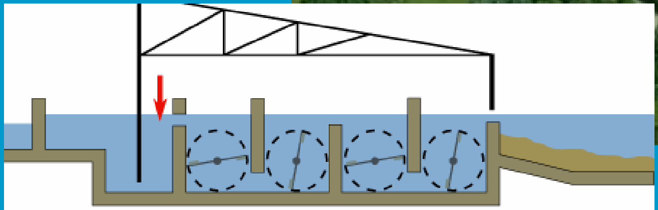


Well designed flocculator



Flocculation: practice





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Flocculation: practice

Dutch practice

	WRK I-II	WRK III	Braakman
Flocculation time minimum [min]	17		19
Flocculation time maximum [min]	30		24
Number of compartments	4	5	3
Width [m]	4	11.6	2.5
Depth [m]	4	6.3	6.8
Length [m]	18	3	2.5
Direction of flow	vertical	horizontal	vertical
Rotations of stirring device [rpm]	0 - 4	0 - 12	1 - 8
G_v value [s^{-1}] per comp.	0 – 20		10 – 110
Direction axis to flow	perpendicular	parallel	parallel

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Optimal design parameters flocculation installations

Coagulation

- mixing time 1-10 sec
- velocity gradient mixing > 1,500 sec^{-1}

Flocculation

- flocculation time = 30 minutes
- 3 - 4 compartments
- Length/width ratio = 3 to 6
- axis stirring device parallel to water flow
- velocity gradient flocculation 100 → 10 sec^{-1}
- rotations: 1 - 8 rpm
- maximum tip velocity 0.9 m/s

Special constructions

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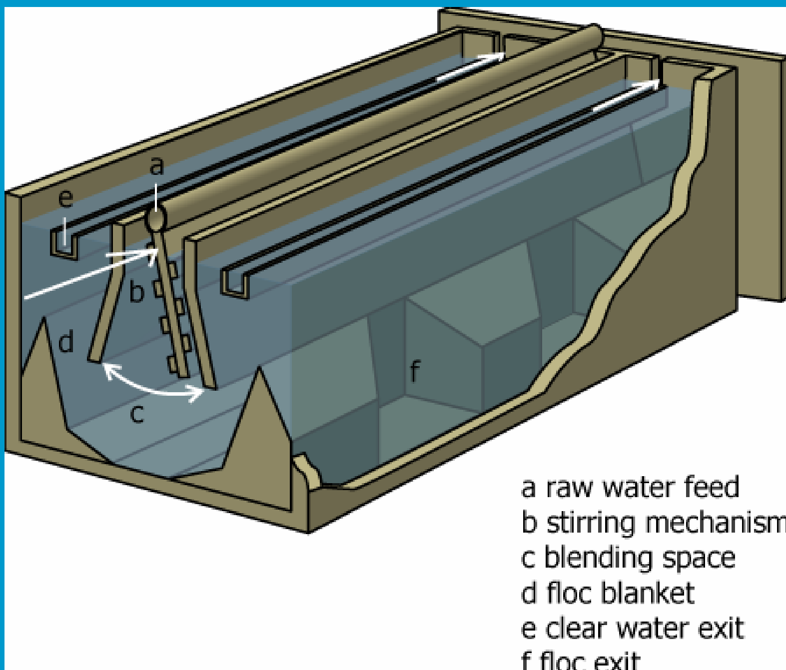
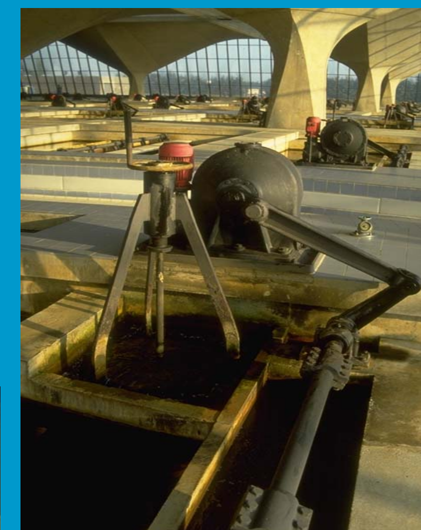
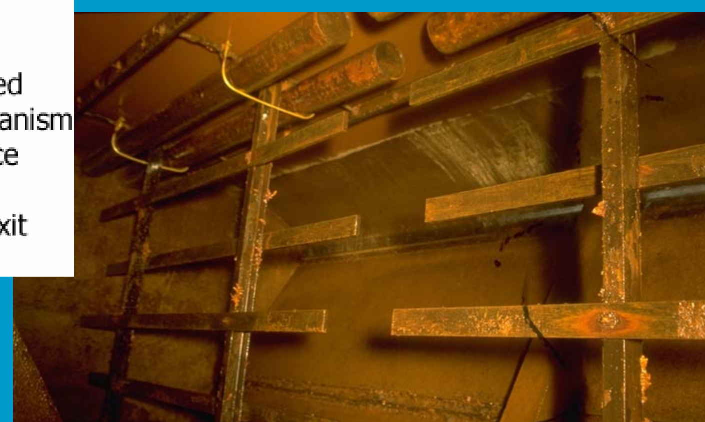
Sludge blanket installation Berenplaat







Sludge blanket installation Bombay

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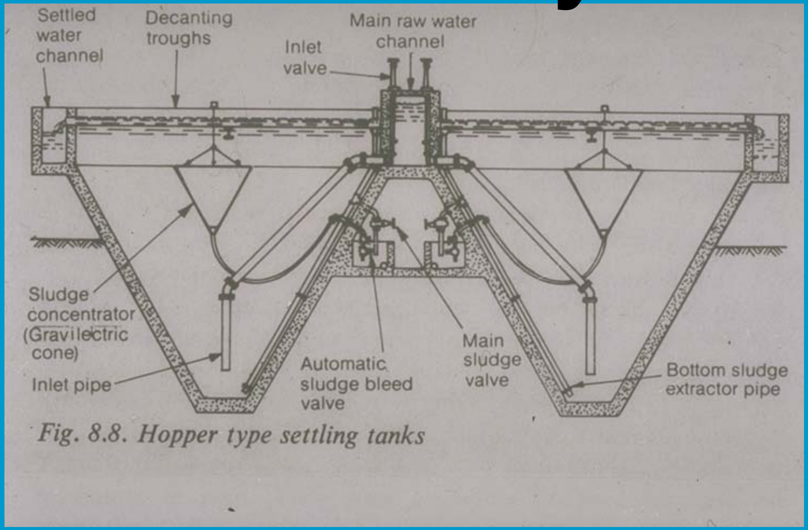
Sludge blanket installation Bombay



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Hydraulic flocculation

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