Drinking water 1

Aeration

Room 2.99

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Aeration

Contents

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Introduction

goal:

- increase of oxygen O_2 (anaerobic ground water)
  oxidation Fe^{2+} en Mn^{2+}

- decrease of carbon dioxide CO_2 $\rightarrow$ aggressive water $\rightarrow$
  corrosion of pipes

- removal of dissolved gasses e.g. CH_4, H_2S,
  volatile organic compounds (e.g. 1,2 DCP)

location: ground water and bank filtration treatment
(rarely for surface water treatment)

Introduction

Cascades

Introduction

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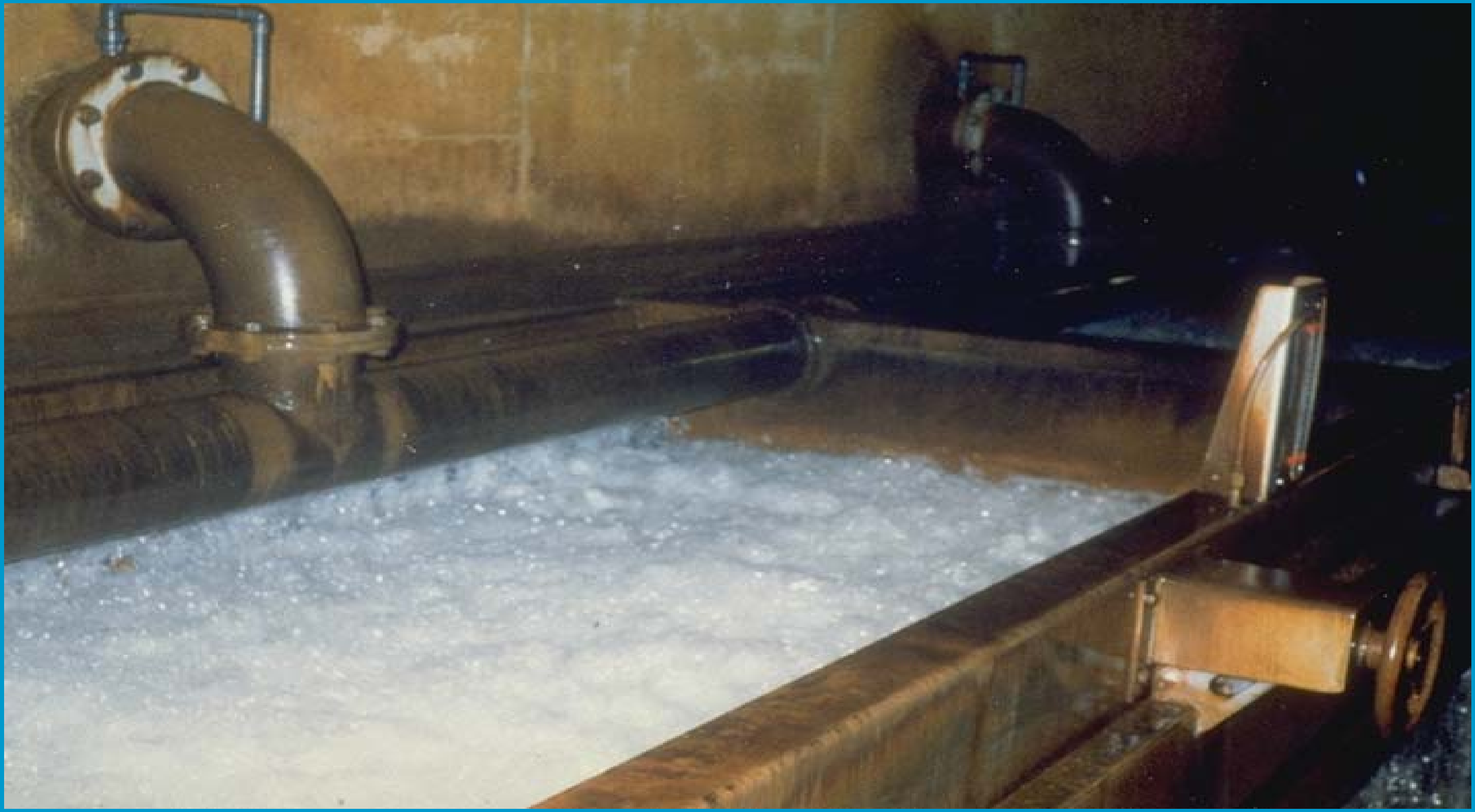
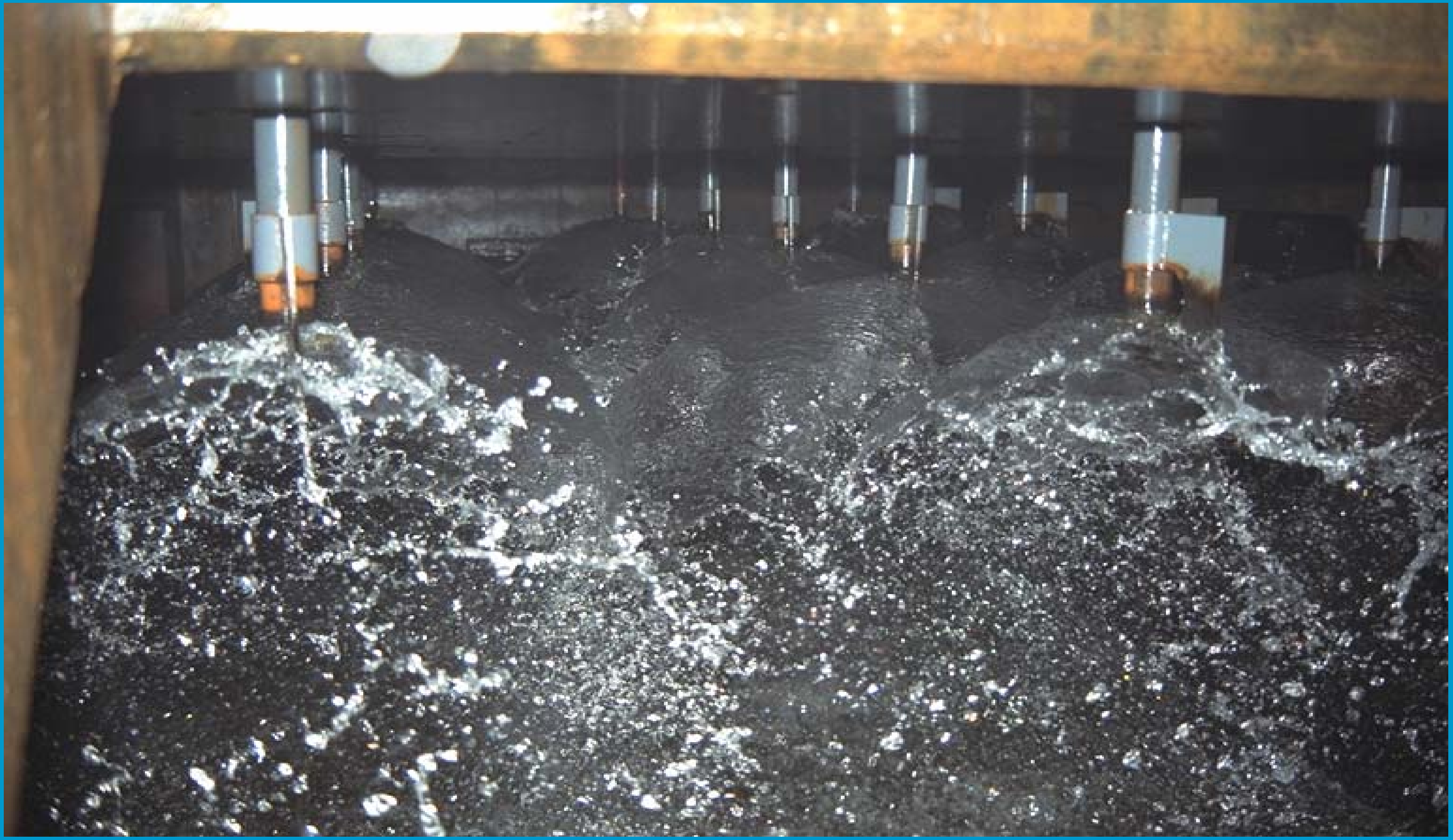
Introduction

Plate aeration

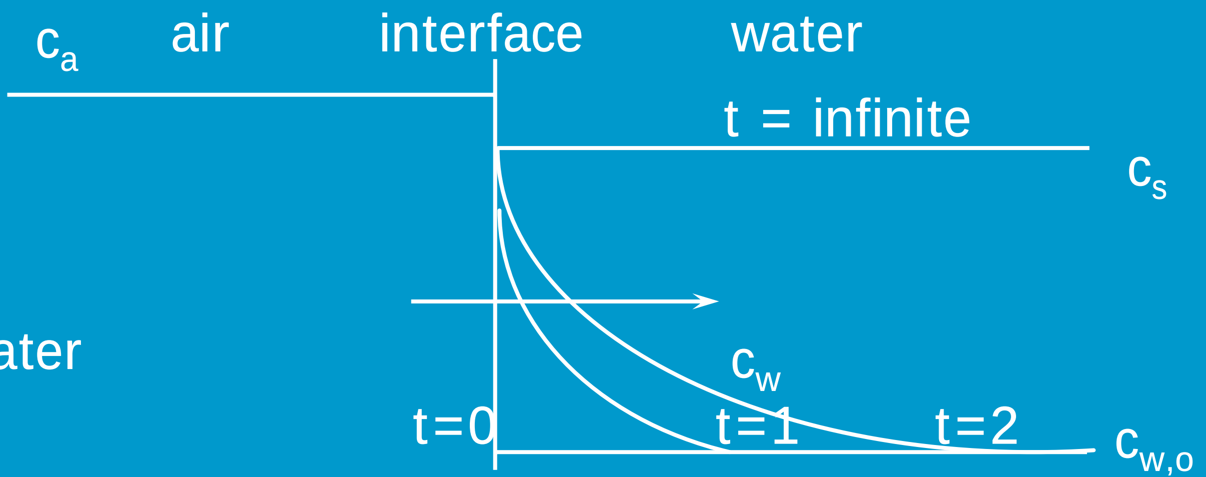


Introduction

Spray aeration



Theory



Solubility of gas in water

$$c_s = k_D \cdot c_a$$

- kind of gas --> k_D
  - high k_D = high solubility , hard to remove
  - low k_D = low solubility , easy to remove
- concentration in the air --> c_a
- temperature T_w
- contaminations

Theory

Henry's law

$$c_s = k_D \cdot c_a$$

c_s = saturation concentration of the gas in water [g/m3]

c_a = concentration of gas in air [g/m3]

k_D= distribution coefficient [-]

k_D	MW	0°C	10°C	20°C
nitrogen (N_2)	28	0.023	0.019	0.016
oxygen (O_2)	32	0.049	0.039	0.033
methane (CH_4)	16	0.055	0.043	0.034
carbon dioxide (CO_2)	44	1.710	1.230	0.942
hydrogen sulfide (H_2S)	34	4.690	3.650	2.870
tetra (C_2Cl_4)	167	-	3.20	1.21
tri (C_2HCl_3)	131.5	-	3.90	2.43
chloroform ($CHCl_3$)	119.5	-	9.0	7.87
ammonia	17	-	0.94	0.76

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Theory

Universal gas law

$$\frac{n}{V} = \frac{p}{R \cdot T}$$

p = partial pressure of the gas [Pa]

V = total gas volume [m3]

n = number of mol of the gas [-]

R = universal gas constant = 8,3142 J/(K*mol)

T = temperature of the gas [K]

$$c_a = \frac{n}{V} \cdot MW = \frac{p \cdot MW}{R \cdot T}$$

MW = molecular weight [g/mol]

Theory

Partial pressure

partial pressure depends on the composition of the air

composition of the air: 78.084% N_2; 20.948% O_2; 0.934% Ar; 0.032% CO_2; 0.002% other gases

partial pressure of oxygen at a standard pressure of 101325 Pa (1 atmosphere) = 0.21*101325 = 21.226 kPa

The saturation concentration for gases at sea level and a water and air temperature of 10°C is:

O_2 = 11.3; CO_2 = 0.79
N_2 = 17.9; CH_4 = 0 mg/l

Theory

Question 1 (1)

What is the saturation concentration of carbon dioxide in water (pressure = 101325 Pa, T = 10°C)?

Gas	Distribution coefficient k_D	Volume percentage [%]
CO_2	1.23	0.034

Partial pressure of carbon dioxide is $0.00034 \cdot 101325 = 34.45$ Pa.

MW = 44 g/mol, T = 283K.

Theory

Question 1 (2)

Concentration carbondioxide in air:

$$c_a = \frac{p \cdot MW}{R \cdot T} = \frac{34.45 \cdot 44}{8{,}3142 \cdot 283} = 0.64\ \mathrm{mg/l}$$

Checking units

Pa = N/m^2; J = N·m

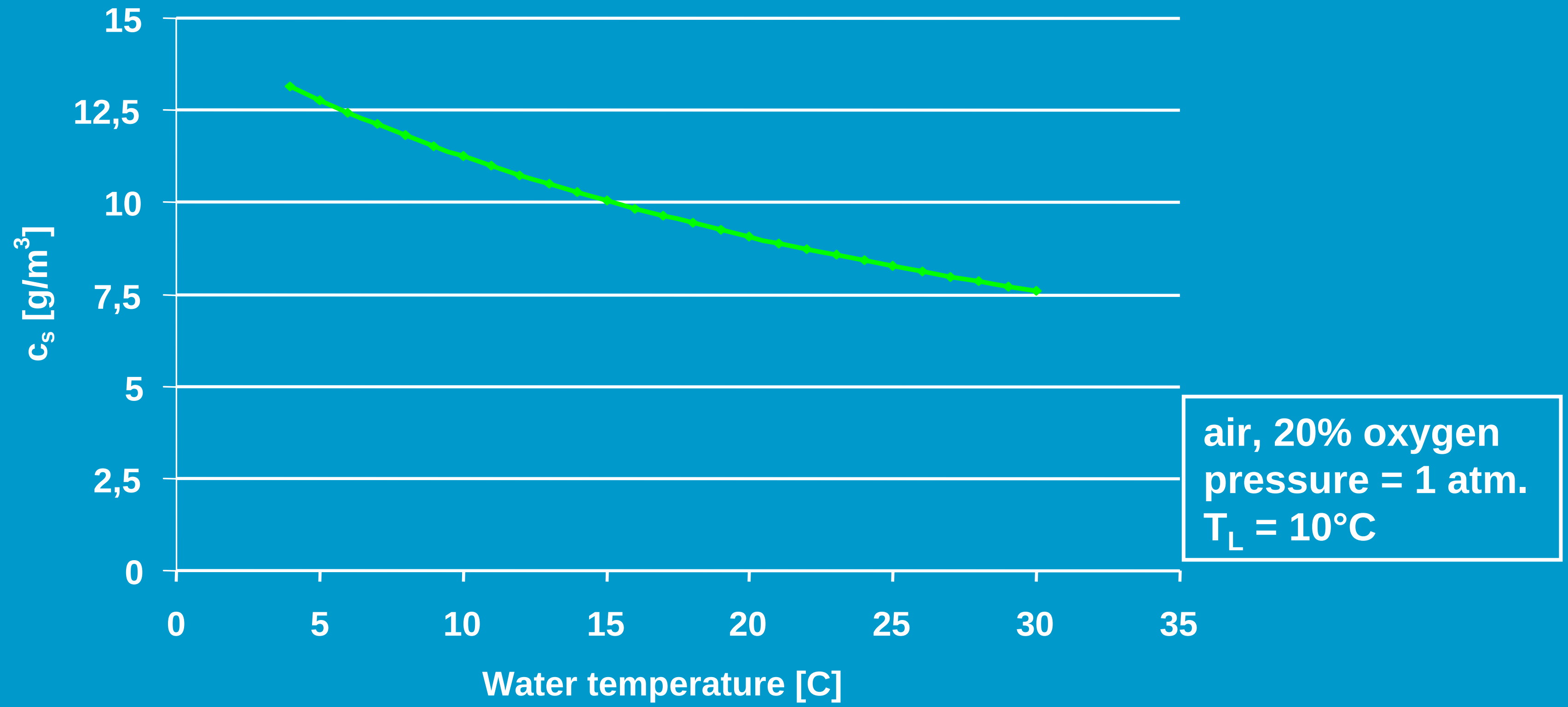
$$c_a = \frac{p \cdot MW}{R \cdot T} = \frac{Pa \cdot \frac{g}{mol}}{\frac{J}{K \cdot mol} \cdot K} = \frac{\frac{N}{m^2} \cdot \frac{g}{mol}}{\frac{N \cdot m}{K \cdot mol} \cdot K} = \frac{g}{m^3} = \frac{mg}{l}$$

The saturation concentration of carbon dioxide in water is thus:

$c_s = 1.23 \cdot 0.64 = 0.79$ mg/l

Theory

Saturation concentration



Saturation concentration oxygen:

at Mt Everest, pressure = 0.1 bar, c_s = 1.1 g/m^3

at 100 m under sea water level, pressure = 10 bar, c_s = 113 g/m^3

Theory

Maximum concentration O_2

Air, 1 atm	9.5 mg/l	cascades
Air, 10 atm	95 mg/l	deep shaft aeration
Pure oxygen	45 mg/l	

In water about 10 mg/l O_2

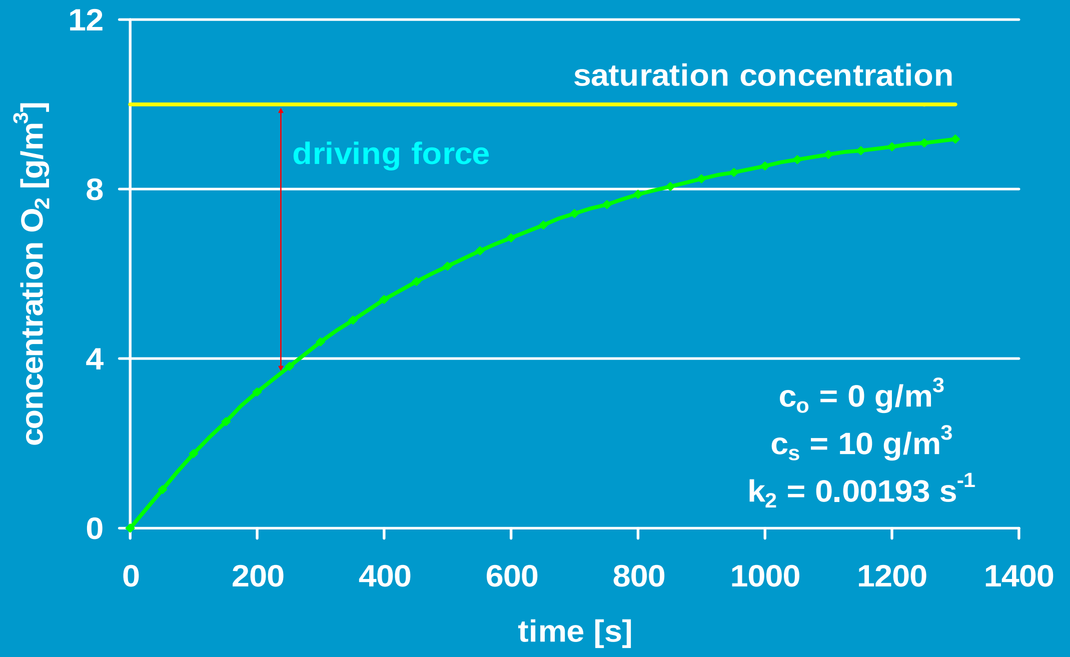
conversion of 1 mg/l Fe^{2+} uses 0.14 mg/l O_2

conversion of 1 mg/l Mn^{2+} uses 0.29 mg/l O_2

conversion of 1 mg/l NH^{4+} uses 3.55 mg/l O_2

With wastewater BOD of 100-500 mg/l $\rightarrow$ surface aeration

Theory



Kinetics

$$\frac{dc}{dt} = k_2 \cdot (c_s - c_w)$$

k_2 = device dependent parameter,

k_2 = depends on interface renewal

integration $c_w = c_{w,o}$ at $t = 0$ gives:

$$c_w = c_s - (c_s - c_{w,o}) \cdot \exp(-k_2 \cdot t)$$

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Theory

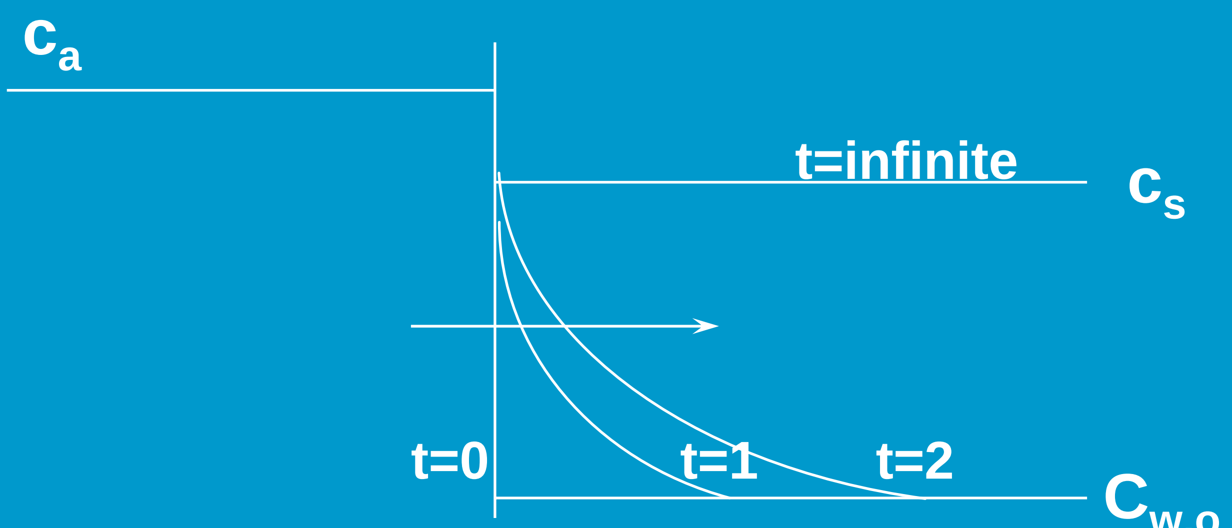
Mass balance

$$Q_a \cdot c_{a,o} + Q_w \cdot c_{w,o} = Q_a \cdot c_{a,e} + Q_w \cdot c_{w,e}$$

$$RQ = \frac{Q_a}{Q_w} = \frac{c_{w,e} - c_{w,o}}{c_{a,o} - c_{a,e}}$$

Basic equations

Basic equations



Equilibrium	$c_s = k_D \cdot c_a$
Kinetics	$\frac{dc}{dt} = k_2 \cdot (c_s - c_w)$
Mass balance	$\Delta c_w = \Delta c_a \cdot RQ$

Theory

$$K = \frac{c_{w,e} - c_{w,o}}{c_s - c_{w,o}}$$

K = efficiency of aeration

Calculations with constant gas concentrations in the air (RQ = infinite)

1. Plugflow $K_1 = 1 - \exp(-k_2 \cdot t)$

2. Mixing $K_2 = \dfrac{1}{1 + \dfrac{1}{k_2 \cdot t}}$

Theory

Question 2 (1)

Calculate the contact time if an efficiency of 90% is required with spray aeration and with cascades in an open room and the k_2=0,02?

An efficiency of 90% means a K-value of 0.9. The systems are open therefore the mass balance is negligible. For spray aeration:

$$K_1 = 1 - \exp(-k_2 \cdot t)$$

The equation for cascades is:

$$K_2 = \frac{1}{1 + \frac{1}{k_2 \cdot t}}$$

Theory

Question 2 (2)

$$K_1 = 1 - \exp(-k_2 \cdot t) \Rightarrow t = -\frac{\ln(1-K_1)}{k_2} = -\frac{\ln(0.1)}{0.02} = 115 \text{ seconds}$$

$$K_2 = \frac{1}{1+\frac{1}{k_2 \cdot t}} \Rightarrow t = \frac{1}{k_2 \cdot \left(\frac{1}{K_2} - 1\right)} = \frac{1}{0.02 \cdot \left(\frac{1}{0.9} - 1\right)} = 450 \text{ seconds}$$

Theory

Calculations with changing gas concentrations in the air

3. Plug flow cocurrent
   (air and water downwards)

$$K_3 = \frac{1 - \exp\left(-k_2 \cdot t \cdot \left(1 + \frac{k_D}{RQ}\right)\right)}{1 + \frac{k_D}{RQ}}$$

4. Plug flow countercurrent
   (air upwards, water downwards)

$$K_4 = \frac{1 - \exp\left(-k_2 \cdot t \cdot \left(1 - \frac{k_D}{RQ}\right)\right)}{1 - \frac{k_D}{RQ} \cdot \exp\left(-k_2 \cdot t \cdot \left(1 - \frac{k_D}{RQ}\right)\right)}$$

5. Complete mixing

$$K_5 = \frac{1}{1 + \frac{1}{k_2 \cdot t} + \frac{k_D}{RQ}}$$

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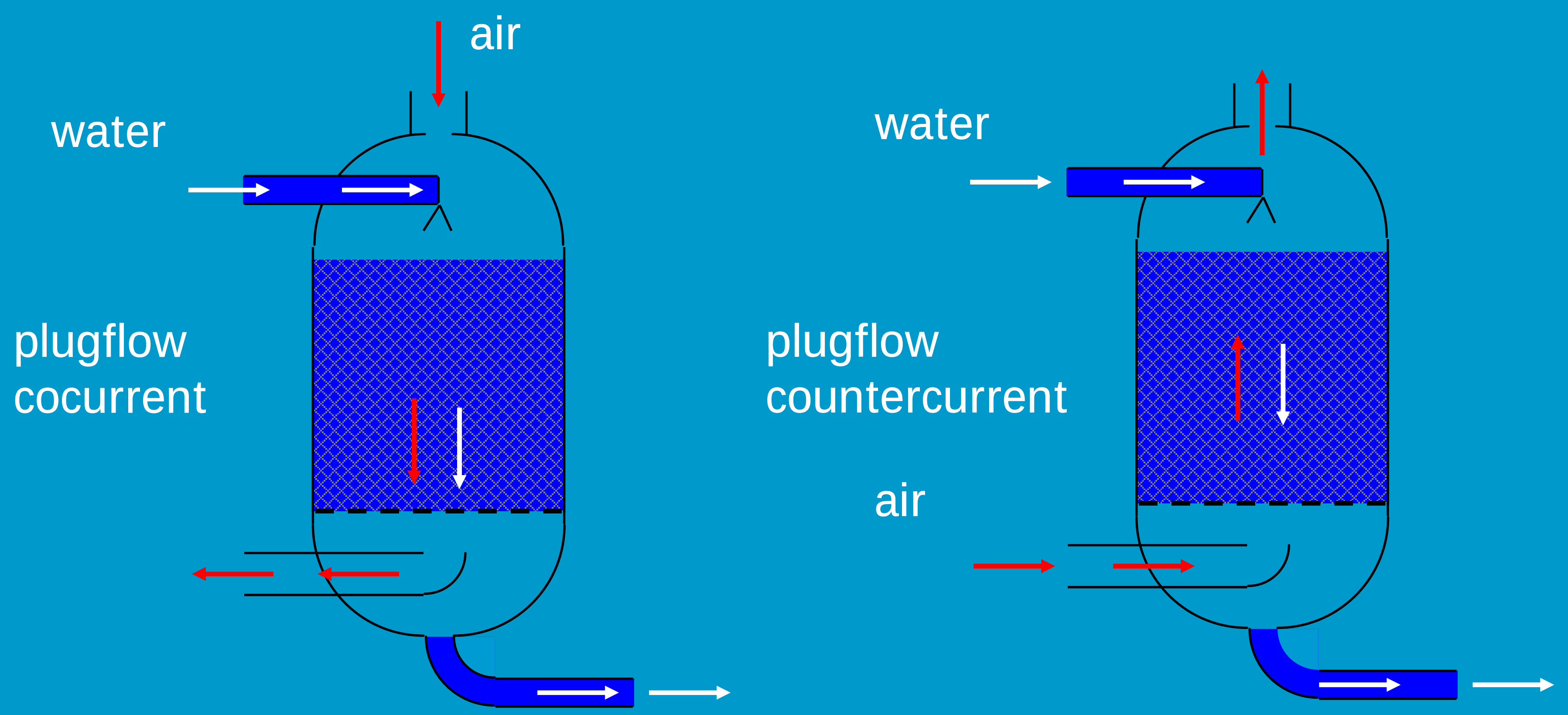
Theory



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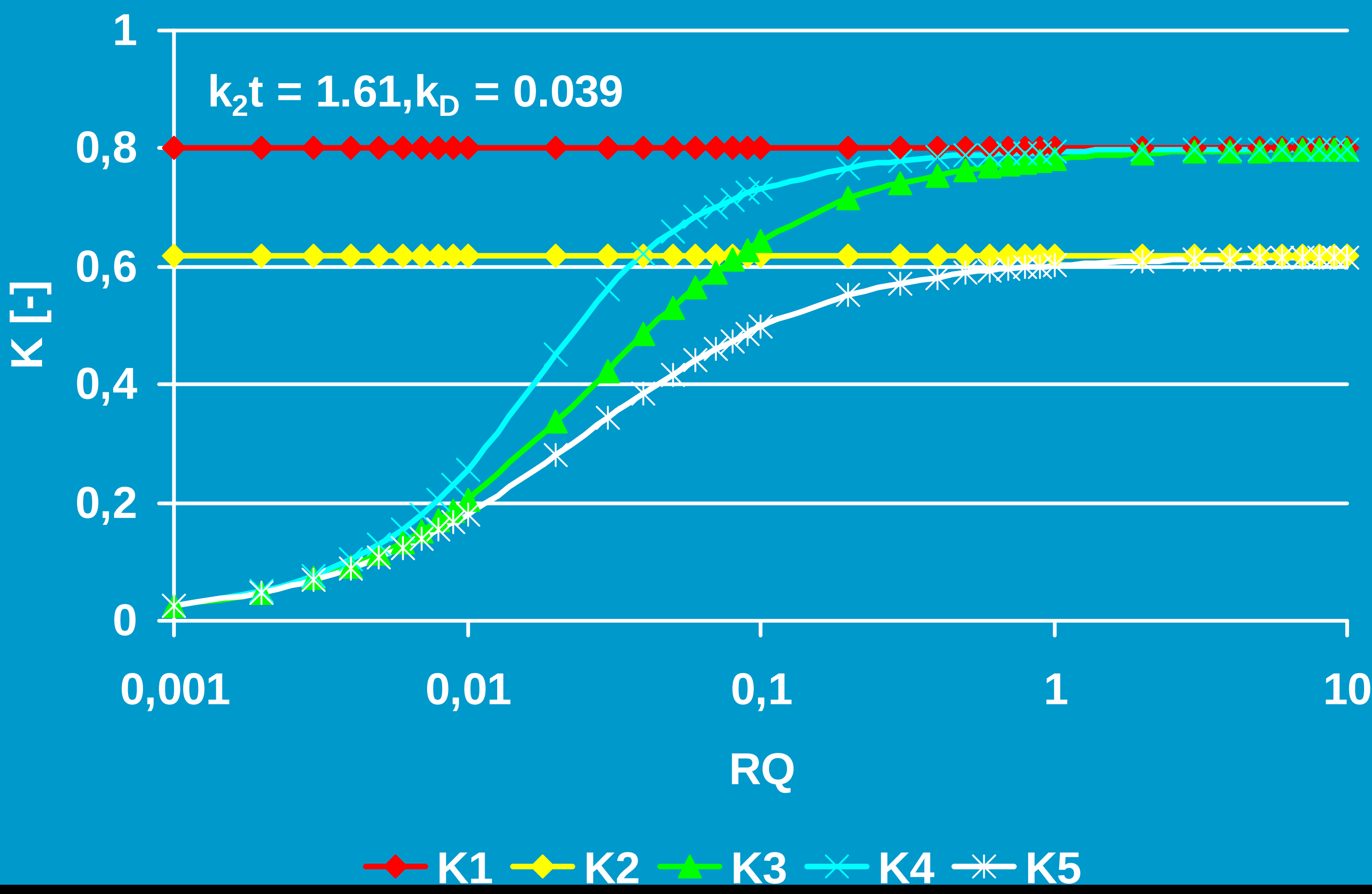
Theory

Maximum efficiencies as function of RQ



Theory

Air/water ratio

Minimum RQ for K = 0.9 (complete mixing, t = infinite)

O_2	RQ = 0.35
CH_4	RQ = 0.39
CO_2	RQ = 11.1
$CHCl_3$	RQ = 86.6

System	RQ	Drinking water	Waste water
Cascades	0.4	O_2	-
tower aeration	5 – 100	CO_2, $CHCl_3$	$CHCl_3$
plate aeration	20 – 60	CH_4, CO_2, O_2	-
spray aeration	0.5	O_2, (CO_2)	-
shaft aeration	0.1 - 0.4	O_2	O_2
surface aeration	> 5	-	O_2

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Cascades

Efficiency

$$K = \frac{1}{1 + \frac{1}{k_2 \cdot t} + \frac{k_D}{RQ}}$$

theoretical

$K = f(h, n)$

practical

$RQ = 0.4$

$K > 95$ % for CH_4, O_2

$K = 60 - 70\%$ for CO_2

Surface loading: 50 - 100 $m^3/(m^2*h)$

Total height: 2 - 7 m (per step 0.3 - 0.6 m)

Energy consumption: 10 - 30 Wh/m^3

Visually attractive, robust, insensitive for calamities

Cascades

Cascades

Efficiency per step

$$K = \frac{c_{w,e} - c_{w,o}}{c_s - c_{w,o}} = 1 - (1 - k)^n$$

K = total efficiency

k = efficiency per step, k = f (h, kind of gas)

n = number of steps

h (m)	0.2	0.4	0.6	0.8	1.0	1.2
k_{O2} (%)	14	25	36	46	51	55
k_{CO2} (%)	14	14	15	15	15	15
k_{CH4} (%)	14	27	37	48	56	62

Cascades

Question 3

Removal of methane from ground water with cascades. The cascade has 5 steps, total drop height = 2 m. Concentration of methane in the raw water is 0.8 mg/l, after first step 0.58 mg/l, saturation value of methane in water = 0 mg/l.
What is the efficiency for removal of methane after 5 steps?.
The efficiency of one step is calculated with:

$$k = \frac{c_{w,e} - c_{w,o}}{c_s - c_{w,o}}$$

In this case c_o = 0.8 mg/l, c_e = 0.58 mg/l en c_s = 0 mg/l.

$$k = \frac{c_{w,e} - c_{w,o}}{c_s - c_{w,o}} = \frac{0.58 - 0.8}{0 - 0.8} = 0.27$$

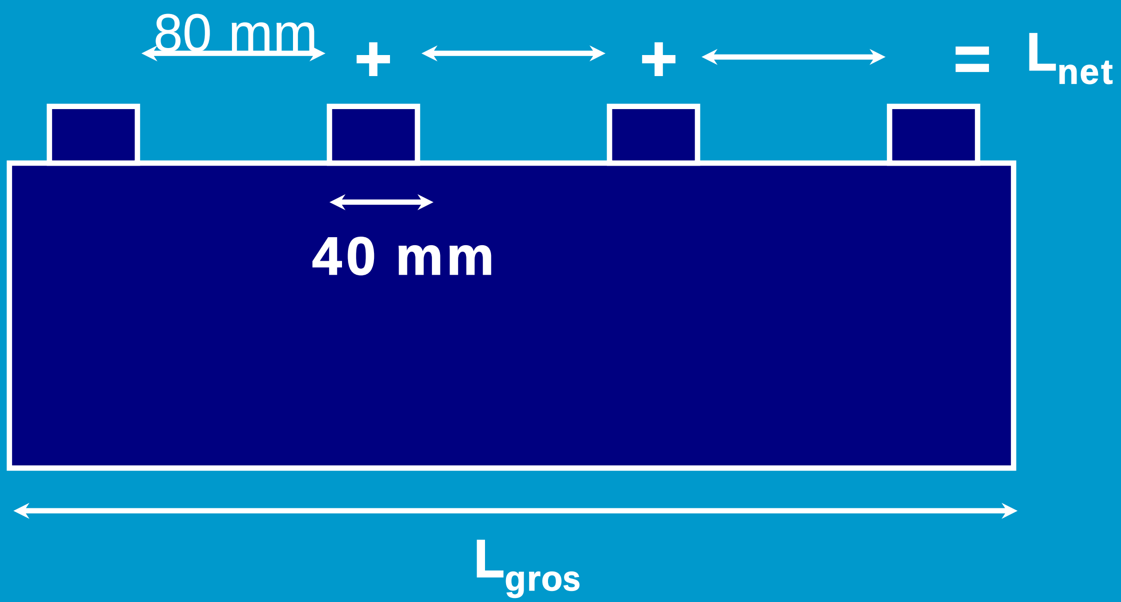
There are 5 steps. Total efficiency of the cascades:

$$K = 1 - (1 - k)^n = 1 - (1 - 0.27)^5 = 0.79$$

Cascades

Weir load

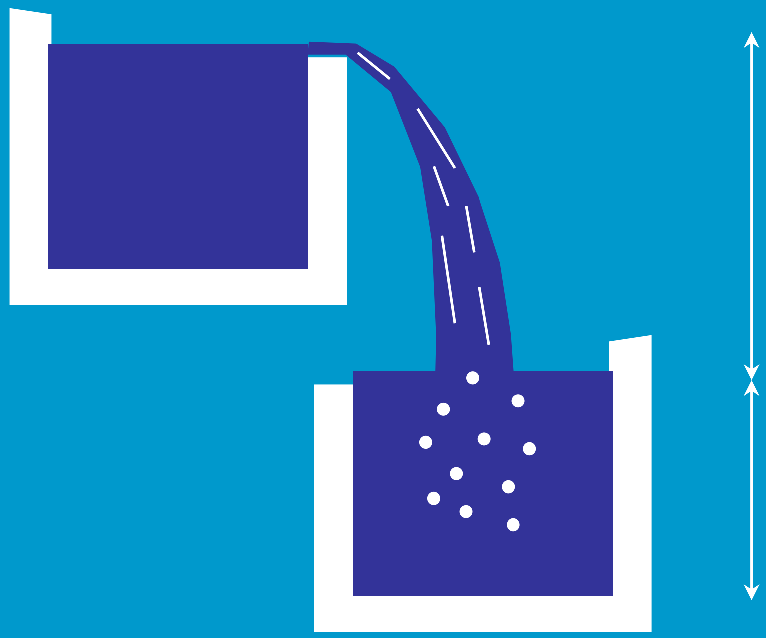
$$\text{weir load } q = \frac{Q}{L_{net}}$$



weir load for O_2, CH_4 en CO_2: 200 $m^3/(m*h)$

Cascades

Gutter depth



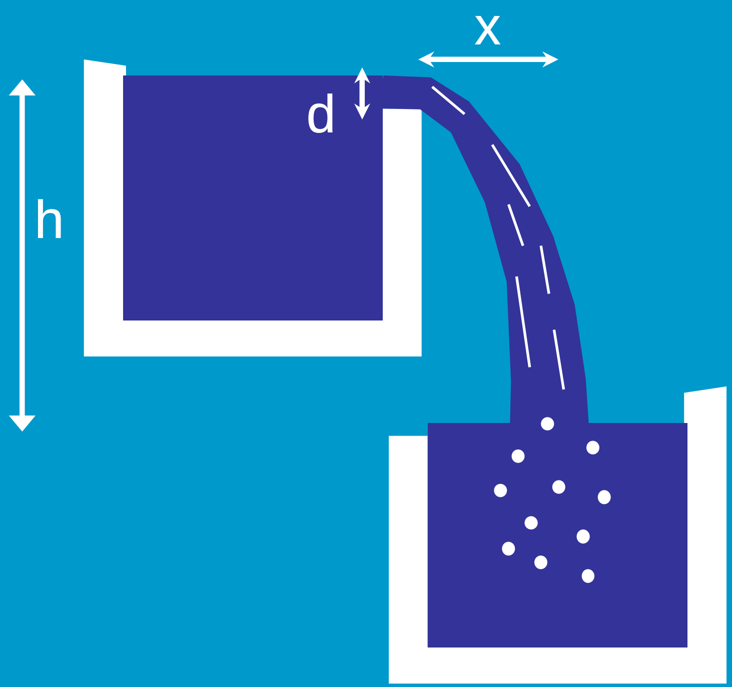
h = drop depth [m]

H = gutter depth [m]

H = 2/3*h

Cascades

Gutter width



trajectory

$$h = \frac{1}{2} \cdot g \cdot t^2 \qquad t = \sqrt{\frac{2h}{g}}$$

full weir

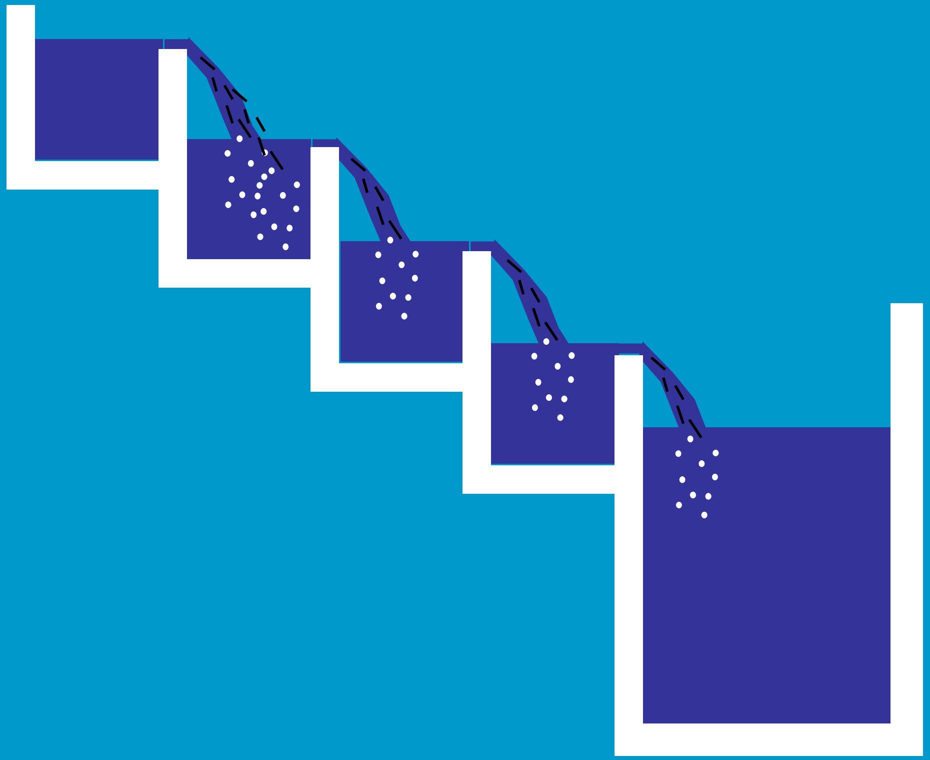
$$d^3 = \frac{Q^2}{g \cdot L_{net}^{\ 2}}$$

$$x = v_o \cdot t$$

$$v_o = \frac{Q}{L_{net} \cdot d}$$

Cascades

Cascades next to each other

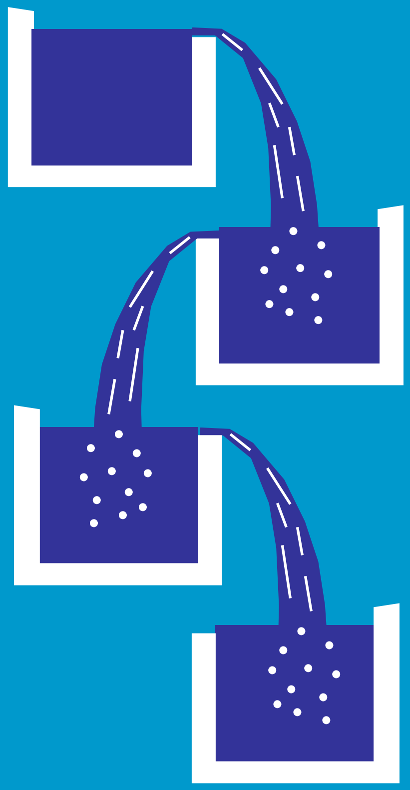


Cascades

Cascades next to each other

Cascades

Cascades on top of each other



Cascades

Cascades on top of each other

Tower aeration

Efficiency	K = (h, RQ)
	RQ (O_2, CH_4) = 1 - 5
	RQ (CO_2) = 20
	RQ = 50-100 for tri and tetra
	K > 90-99%
Surface load	40 - 100 $m^3/(m^2*h)$
Packing height	3 - 5 m
Total height tower	5 - 7 m
Sensitive to fouling	backwash

Countercurrent has a higher efficiency, however co-current systems are also used:

- CO_2 removal not too high because of calcification
- with countercurrent flooding can occur (RQ > 100)

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Tower aeration

Question 4 (1)

A co-current tower aerator has a RQ of 5 and a contact time of 20 s. What is the CO_2 concentration after aeration if the influent concentration is 65 mg/l and the saturation concentration for carbondioxide in water is 1,0 mg/l? For the distribution coefficient (k_D) of CO_2 a value of 1.2 can be used and for the device dependent parameter k_2 a value of 0.2 s^{-1} can be used.

$$c = c_0 + (c_s - c_0) \cdot \frac{1 - e^{\left[-k_2 \cdot t \cdot \left(1 + \frac{k_D}{RQ}\right)\right]}}{1 + \frac{k_D}{RQ}} = 65 + (1 - 65) \cdot \frac{1 - e^{\left[-0.2 \cdot 20 \cdot \left(1 + \frac{1.2}{5}\right)\right]}}{1 + \frac{1.2}{5}} = 13.74 \text{ mg/l}$$

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Tower aeration

Question 4 (2)

The height is increased from 6 to 8 m.

Drop speed = h/t = 6/20 = 0.3 m/s. Tower of 8 m, contact time h/v = 8/0.3 = 26.67 s. The effluent concentration is:

$$c = c_0 + (c_s - c_0) \cdot \frac{1 - e^{\left[-k_2 \cdot t \cdot \left(1 + \frac{k_D}{RQ}\right)\right]}}{1 + \frac{k_D}{RQ}} = 65 + (1 - 65) \cdot \frac{1 - e^{\left[-0.2 \cdot 26.67 \cdot \left(1 + \frac{1.2}{5}\right)\right]}}{1 + \frac{1.2}{5}} = 13.45 \text{ mg/l}$$

Tower aeration

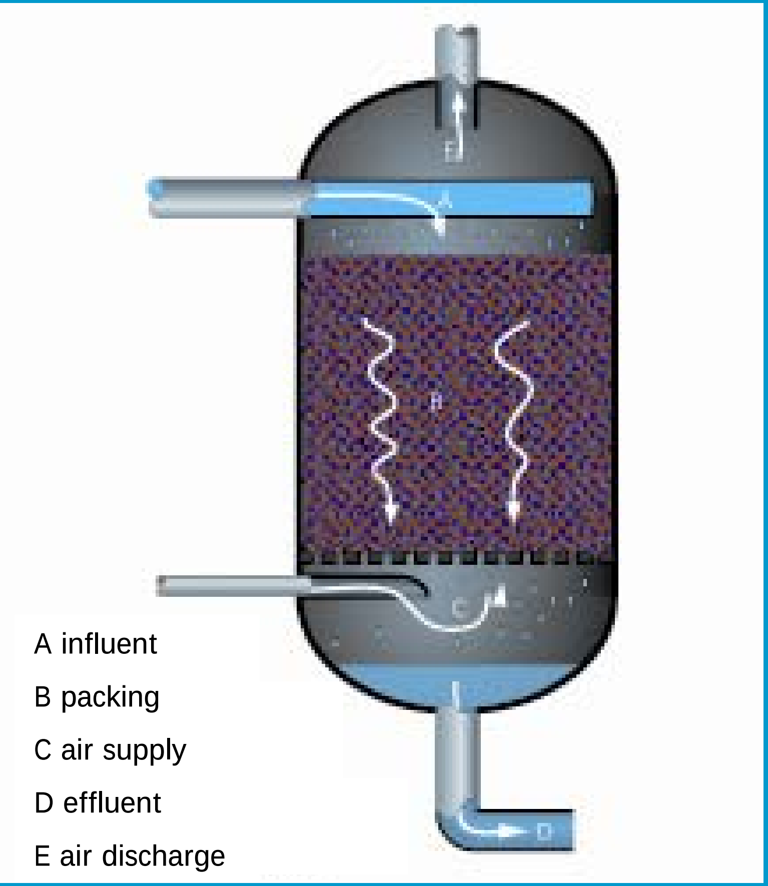
Question 4 (3)

What is the efficiency of counter current tower aeration for a tower with a height of 6 m (drop time 20 s)?

$$K_4 = \frac{1 - e^{\left[-k_2 \cdot t \cdot \left(1 - \frac{kD}{RQ}\right)\right]}}{1 - \frac{k_D}{RQ} \cdot e^{\left[-k_2 \cdot t \cdot \left(1 - \frac{k_D}{RQ}\right)\right]}} = \frac{1 - e^{\left[-0.2 \cdot 20 \cdot \left(1 - \frac{1.2}{5}\right)\right]}}{1 - \frac{1.2}{5} \cdot e^{\left[-0.2 \cdot 20 \cdot \left(1 - \frac{1.2}{5}\right)\right]}} = 0.963 \quad \text{mg/l}$$

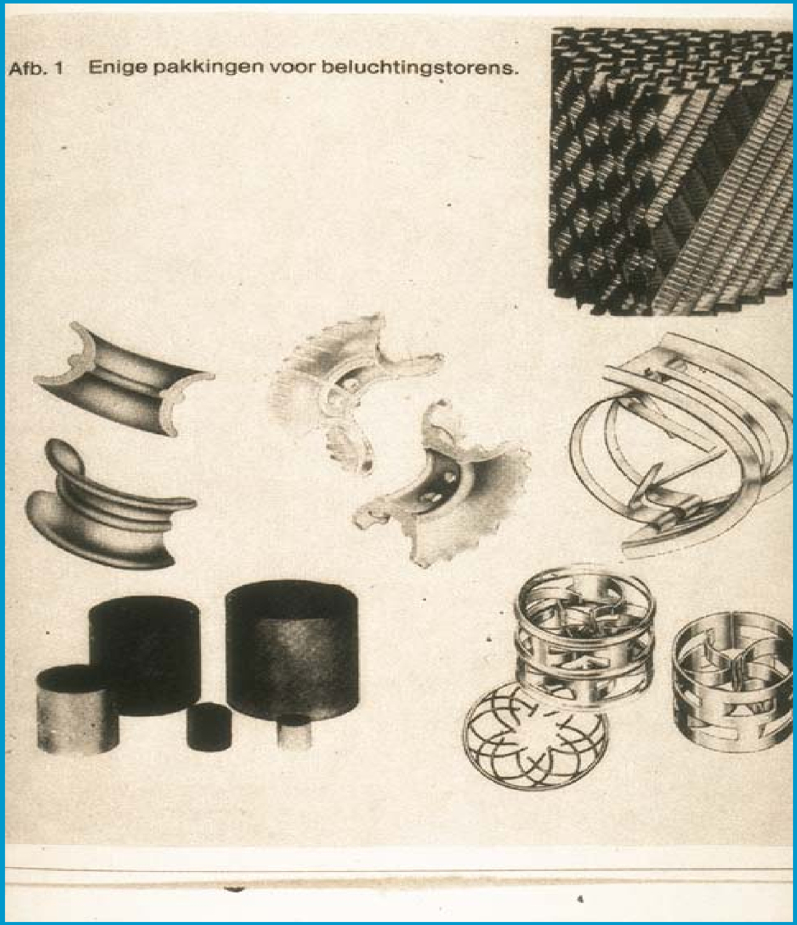
Tower aeration

Principle of tower aerators



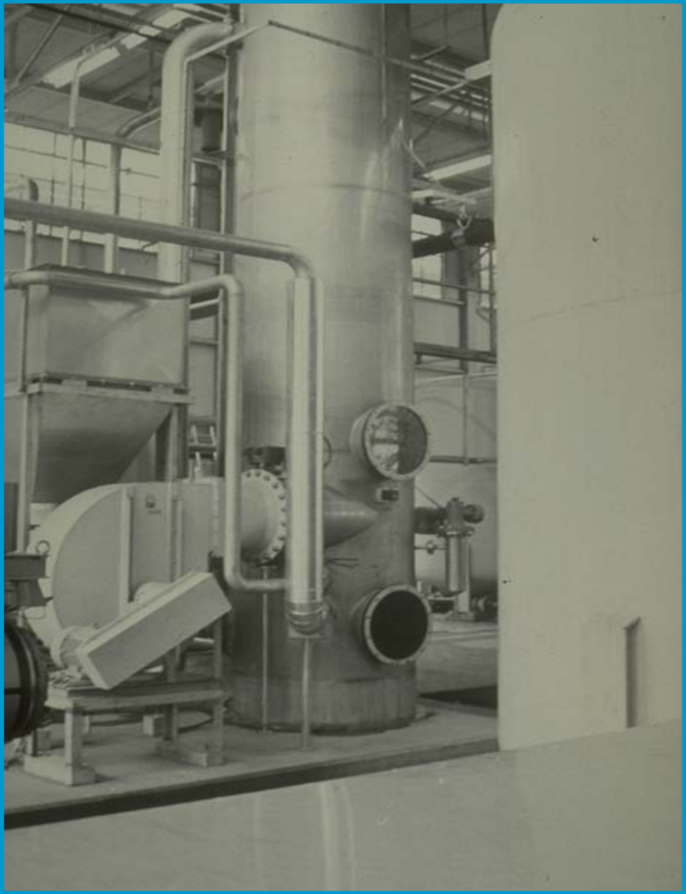
Tower aeration

Packing materials



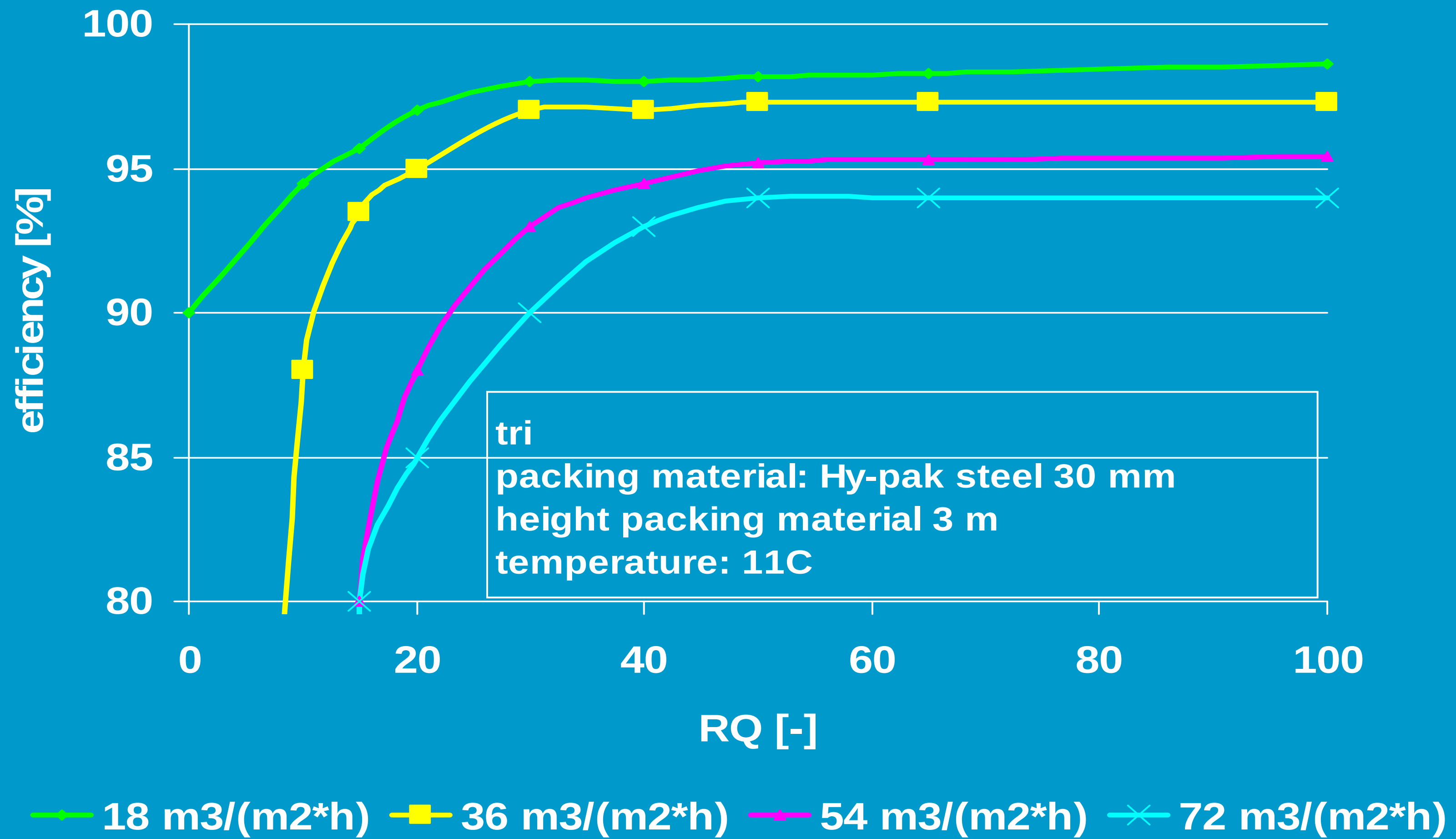
Tower aeration

Construction



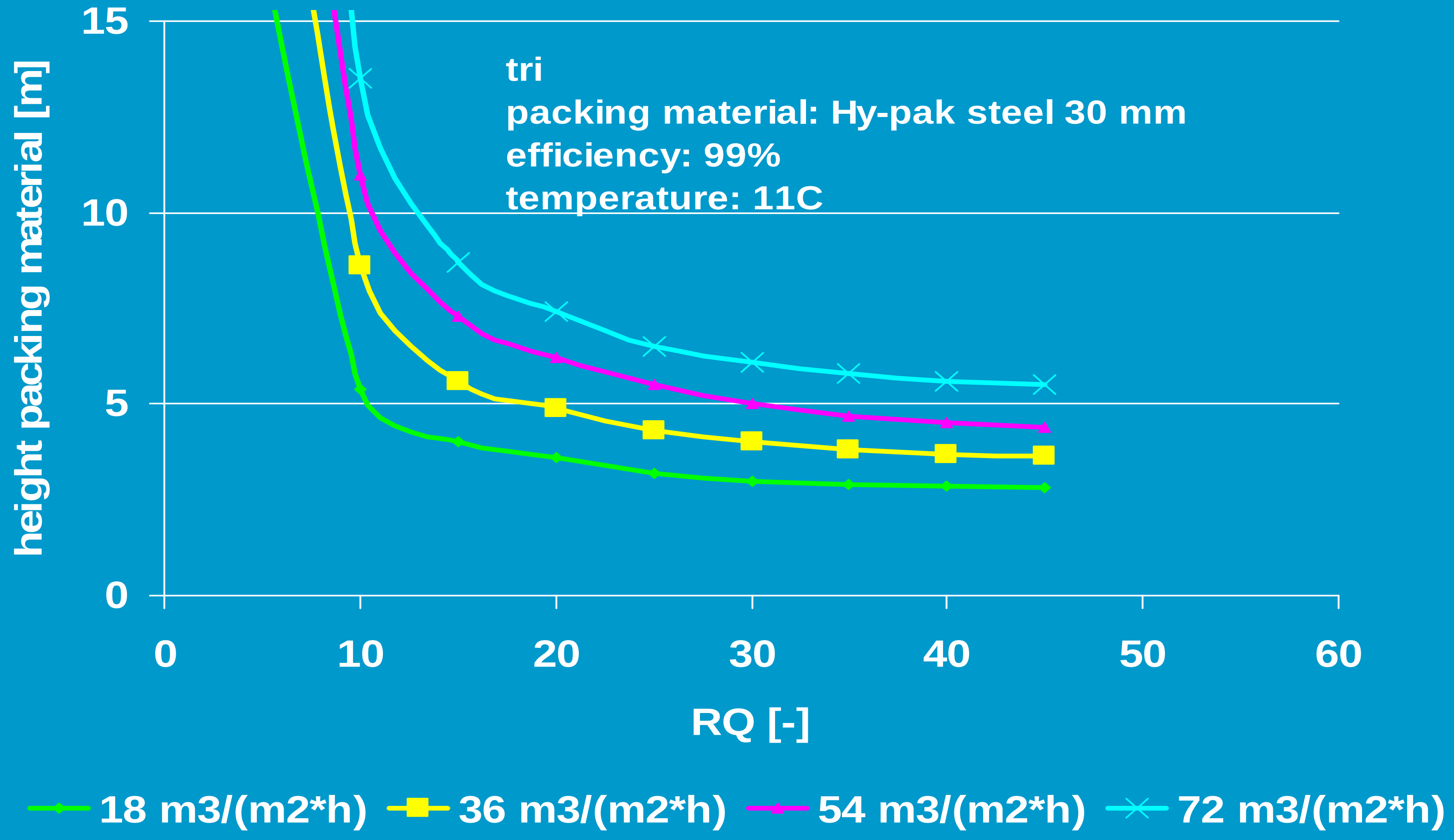
Tower aeration

Variable RQ



Tower aeration

Variable RQ and h



Tower aeration

Efficiency calculations for different heights of a co-current tower-aerator at RQ = 10

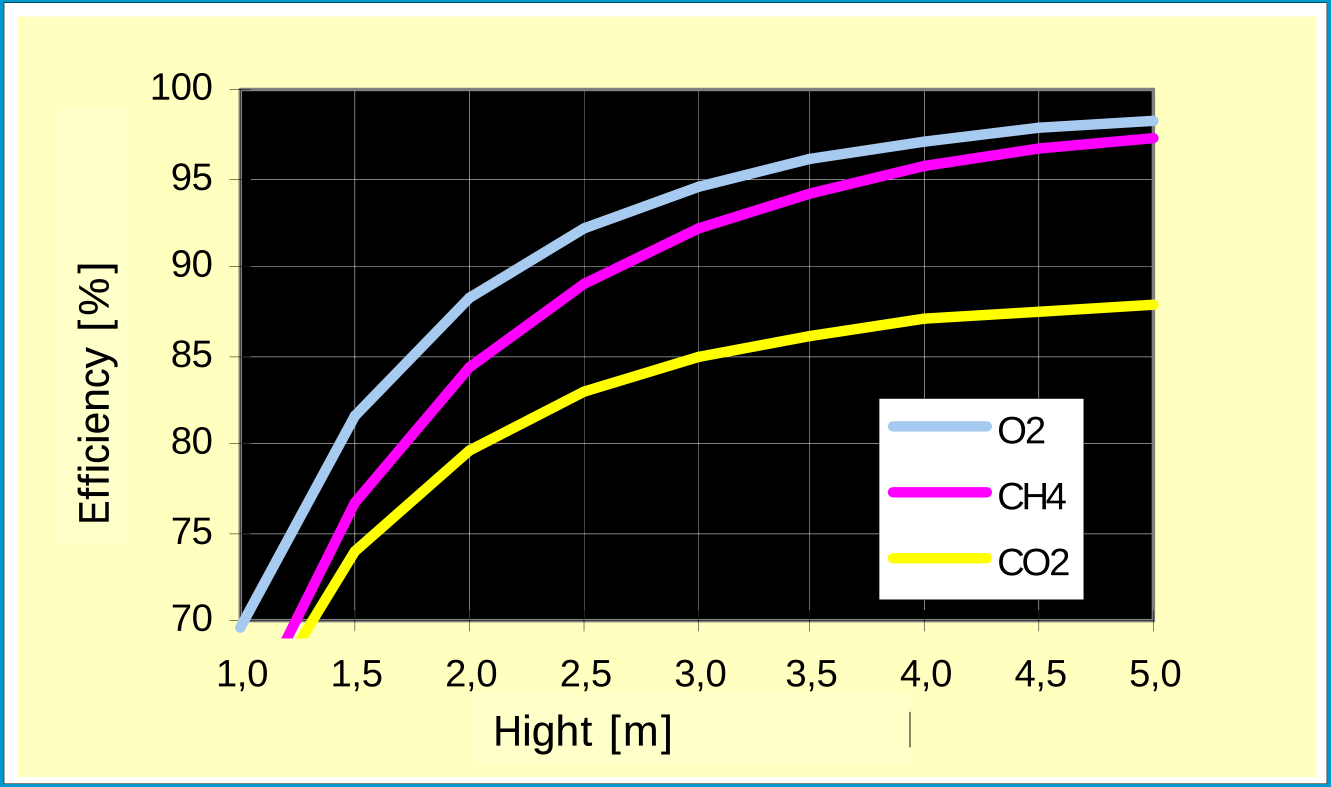


Plate aeration

Efficiency	K = f (RQ, t)
	RQ = 20 - 60
	K = 80% CO_2
	K > 90% CH_4 en O_2
Surface load:	30 $m^3/(m^2*h)$
Energy use:	30 - 40 Wh/m^3
	(water 0.5 m; air 0.15 m)

Sensitive to fouling

Construction in existing filters possible, condensation

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Plate aeration

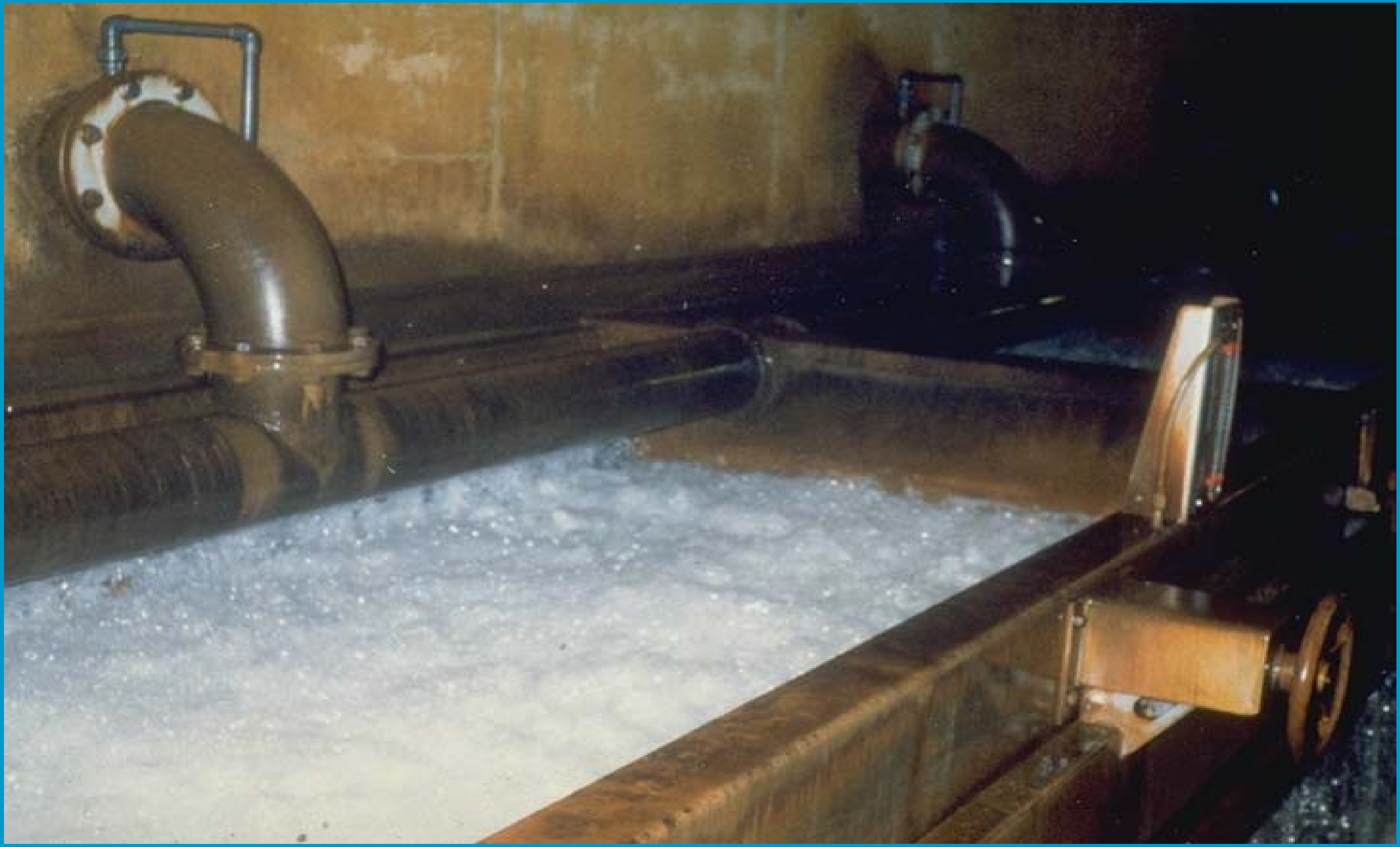


Plate aeration

Spray aeration

Type of sprayers

- upward or diagonally upward fixed sprayers
- plate sprayers

Amsterdam nozzle

Dresden nozzle

Spray aeration

Efficiency:

$$K = 1 - \exp(-k_2 \cdot t) = 1 - \exp\left(-k_2 \cdot \sqrt{\frac{2 \cdot h}{g}}\right)$$

K = 60 - 80% CO_2,
K = 65 - 85% O_2

Surface loading: 3-10 $m^3/(m^2*h)$
same as surf. load of rapid sand filtration, therefore above each other

Drop height: ca. 2m
Pressure drop: Dresden 0.5 m H_2O, Mist 10.0 m H_2O, Amsterdam 5.0 m H_2O
Energy use: Dresden 10 Wh/m^3, Mist 50 Wh/m^3 Amsterdam 30 Wh/m^3

Sensitive to fouling, visually attractive

Spray aeration

Question 5 (1)

The oxygen concentration of water is 5 mg/l. After spray aeration it is 7.5 mg/l (drop height of the sprayers = 0.5 m). The saturation concentration of oxygen is 10 mg/l. What is the oxygen concentration if the drop height is increased to 1 m?

The sprayer = perfect plugflow. The efficiency is:

$$K_1 = 1 - \exp(-k_2 \cdot t)$$

With a drop height of 0.5 m the efficiency of the system is 50%. The drop time of a water drop is:

$$t = \sqrt{\frac{2 \cdot h}{g}} = \sqrt{\frac{2 \cdot 0.5}{10}} = 0.32 \text{ seconds}$$

The device bound parameter k_2 is now calculated with the equation of plugflow:

$$K_1 = 1 - \exp(-k_2 \cdot t) \Rightarrow k_2 = -\frac{\ln(1 - K_1)}{t} = 2.19 s^{-1}$$

Spay aeration

Question 5 (2)

If the drop height is 1 m, the drop time is 0.45 s. The efficiency with a drop height of 1 m is now:

$$K_1 = 1 - \exp(-k_2 \cdot t) = 1 - \exp(-2.19 \cdot 0.45) = 0.63$$

An efficiency of 63% means an effluent concentration of:

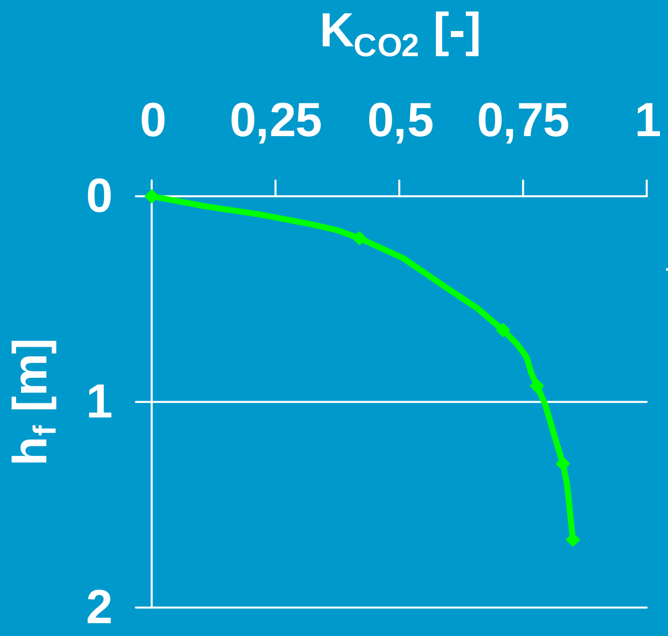
$$c_e = K \cdot (c_s - c_o) + c_o = 0.63 \cdot (10 - 5) + 5 = 8.15 \text{ mg/l}$$

What is the oxygen concentration if 2 sprayers with each a dropheight of 0,5 m are placed in series?

The efficiency of the first sprayer is 50%, the efficiency of the second sprayer is 50% too, the total efficiency is therefore 75% or an effluent concentration of 8.75 mg/l O_2.

Spray aeration

Dresden nozzle



Influence of discharge and depth on the efficiency for removal of CO_2 at 16 °C.

Discharge	drop height [m]			
[10^{-3} m^3/s]	0.65	0.95	1.30	1.65
0.80	0.70	0.77	0.82	0.86
1.03	0.65	0.76	0.80	0.83
1.33	0.61	0.65	0.75	0.76
1.61	0.62	0.70	0.73	0.74

Spray aeration

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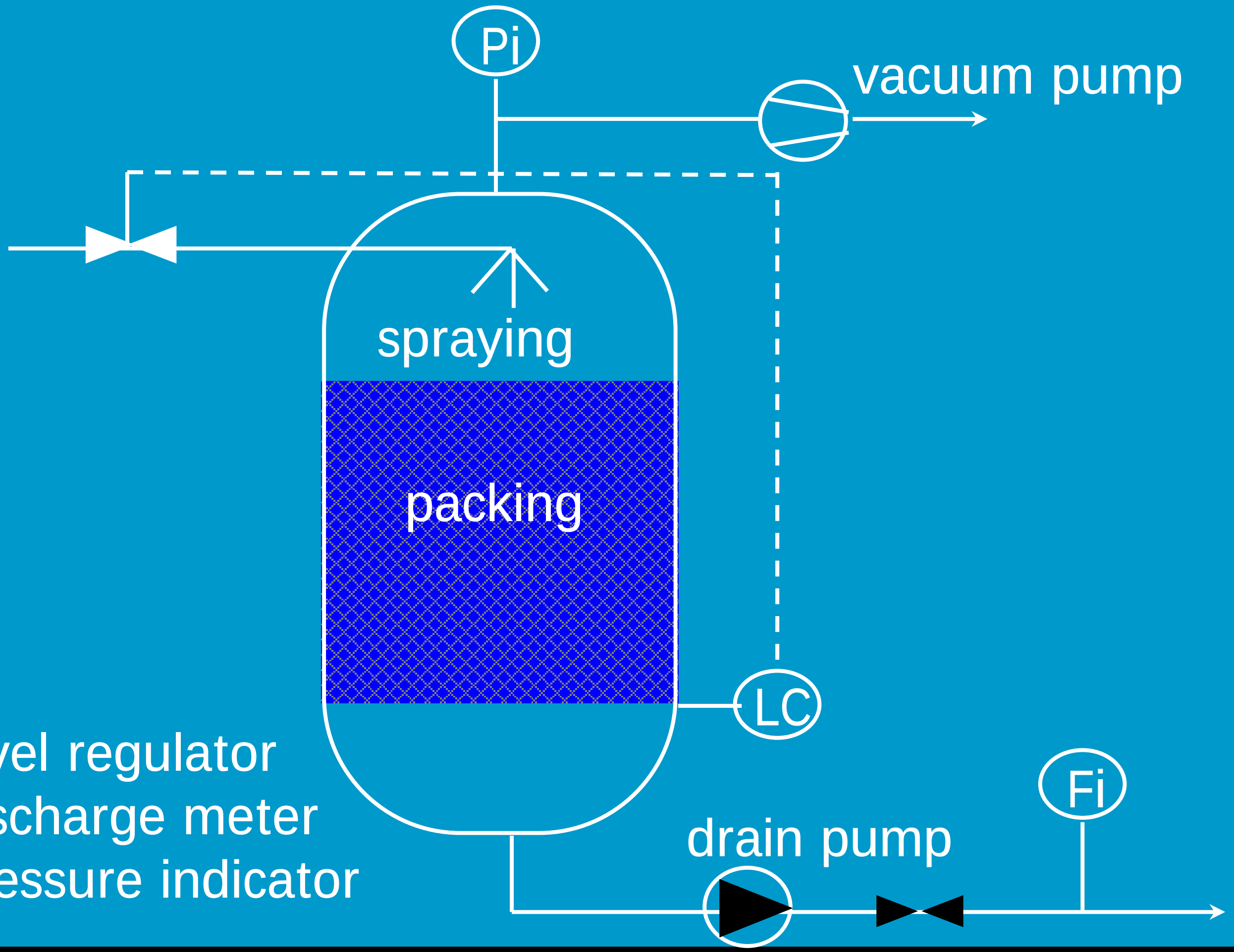
Other types

Vacuum degasification



LC level regulator
Fi discharge meter
Pi pressure indicator

Other types

Vacuum degasification

Efficiency	K = f (P), P = vacuum pressure RQ = 0 mostly O_2, N_2 removal less for CO_2 removal
Surface load	40 - 100 $m^3/(m^2 * h)$

Little discharge variation possible

Energy use:	high energy use 1600 Wh/m^3 (expensive)

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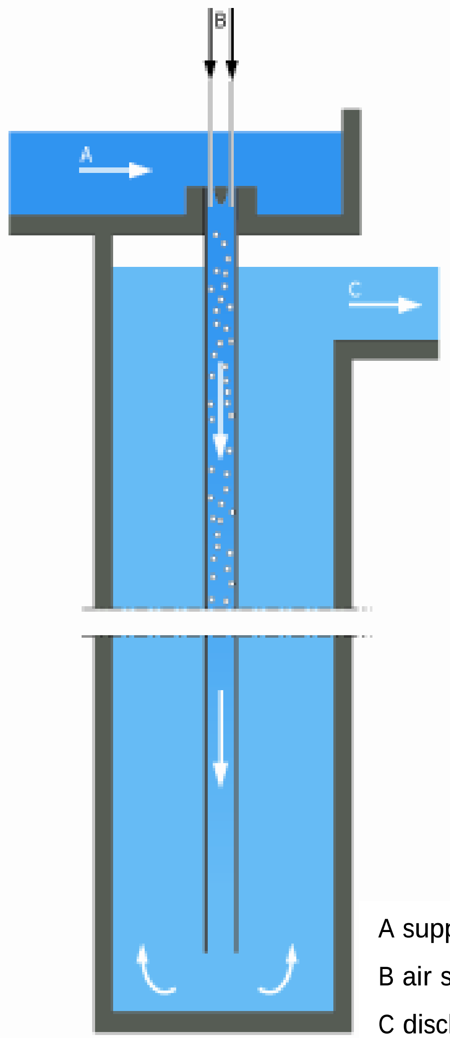
Other types

Deep well aeration



A supply of raw water

B air supply

C discharge aerated water

Other types

Deep well aeration

Efficiency	K = f (RQ, h), RQ = DH ≈ 0.3 - 0.4 h = 20 m DH = 1 m H_2O K = > 100% O_2
Surface load	1000 $m^3/(m^2 * h)$

Little discharge variation possible

Energy use:	5 Wh/m^3

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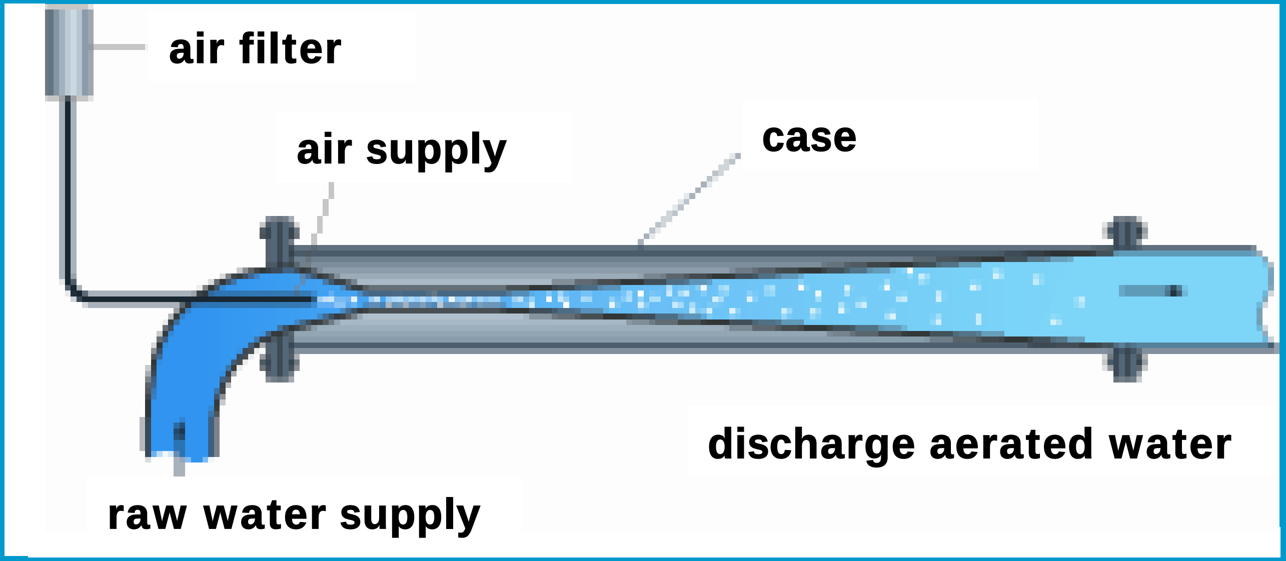
Other types

Venturi



Other types

Venturi

Efficiency $K = f(RQ = DH)$
$RQ = 0.2 - 0.4$
$DH = 5 - 8$ m H_2O
$K = 80 - 95\% O_2$

uses not much space, inexpensive

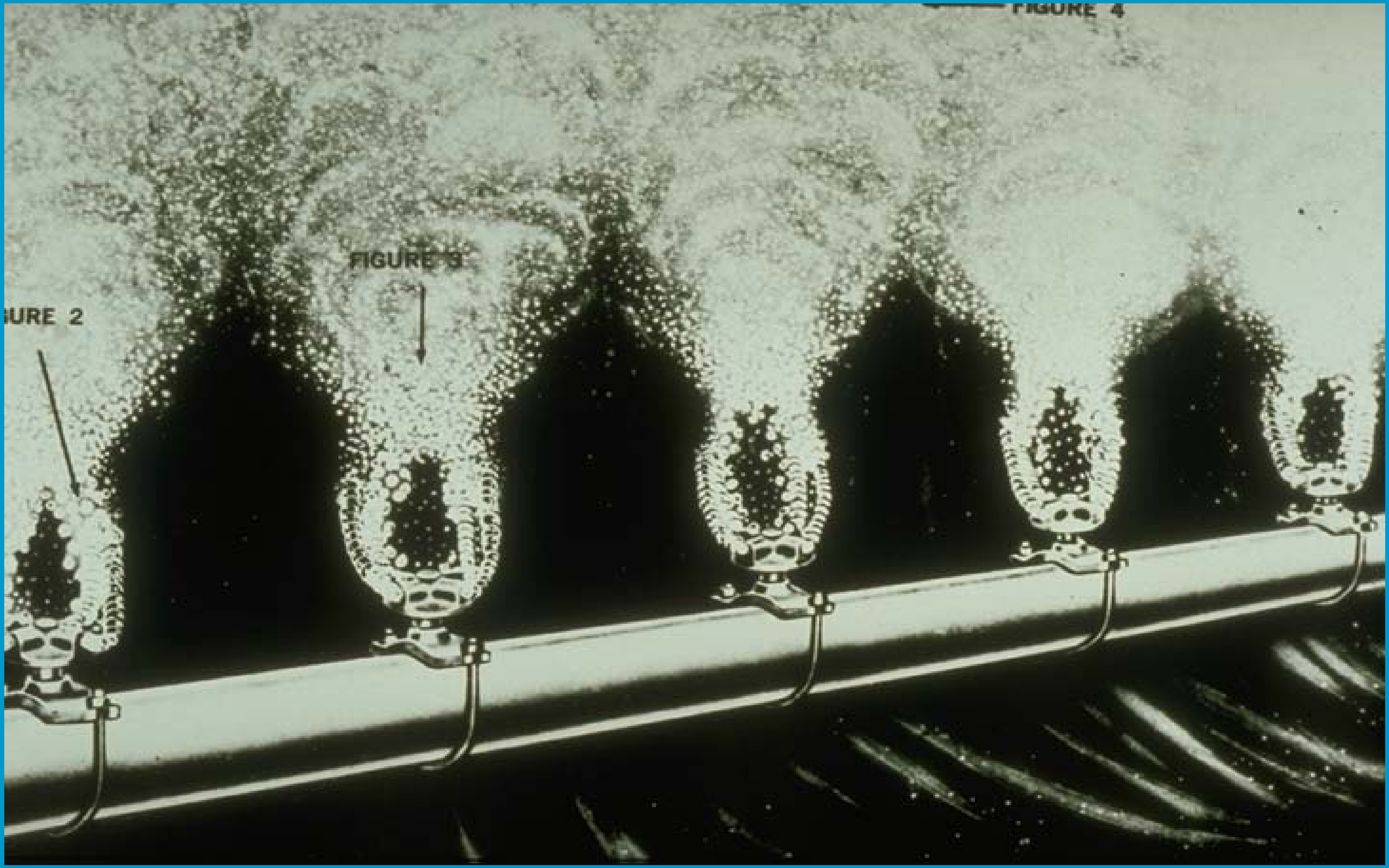
Regulating effect rapid sand filtration, little discharge variation

Energy use: 20 - 30 Wh/m^3

TU Delft

Other types

Bubble aeration



Other types

Surface aeration