Delft University of Technology

Faculty of Civil Engineering and Geosciences

Subfaculty Civil Engineering

Section Sanitary Engineering

CT4470 Drinking water I - Technology

Date   :   24 January 2005

Time   :   9.00-12.00 h

There are 7 questions of equal weight. In all questions it is important to show insight in the influence of process parameters on the treatment step in consideration, in order to be able to optimise design and operation.

During the examination a A4-tje with own notes may **NOT** be used.

If there are uncertainties about the question, do not hesitate to ask the supervisor.

Motivate your answer and check if the answer is complete and practical.

Overview of questions

1.   Aeration
2.   Filtration
3.   Coagulation/flocculation
4.   Softening
5.   Adsorption
6.   Sedimentation
7.   Membrane filtration

General data

Table 1 – Atom mass of important elements in water chemistry.

Element	Atom mass	Element	Atom mass
H	1	S	32
C	12	Cl	35,5
N	14	K	39
O	16	Ca	40
F	19	Mn	55
Na	23	Fe	56
Mg	24	As	75
Al	27	Pb	207
P	31		

Table 2 - Dynamic and kinematic viscosity as function of temperature.

Temperature [°C]	Dynamic viscosity [10^{-3} Pa·s]	Kinematic viscosity [10^{-6} m^2/s]
0	1,79	1,79
5	1,52	1,52
10	1,31	1,31
15	1,15	1,15
20	1,01	1,01
25	0,90	0,90
30	0,80	0,80

Relevant formulas in water chemistry

bij T = 10°C

$CO_2 + 2H_2O$ <--> $H_3O^+ + HCO_3^-$ $K_1 = 3,44 \cdot 10^{-7}$ $pK_1 = 6,46$

$HCO_3^- + H_2O$ <--> $H_3O^+ + CO_3^{2-}$ $K_2 = 3,25 \cdot 10^{-11}$ $pK_2 = 10,48$

$CaCO_3 + CO_2 + H_2O$ <--> $Ca^{2+} + 2HCO_3^-$ $K_a = 4,11 \cdot 10^{-5}$

$NH_3 + H_2O$ <--> $NH_4^+ + OH^-$

$NH_4^+ + 2O_2 + H_2O$ <--> $NO_3^- + 2H_3O^+$

$CH_2O + O_2$ <--> $CO_2 + H_2O$

$H_3O^+ + CaCO_3$ <--> $Ca^{2+} + HCO_3^- + H_2O$

$5CH_2O + 4NO_3^-$ <--> $2N_2 + 4HCO_3^- + CO_2 + 3H_2O$

FeS <--> $Fe^{2+} + S^{2-}$

$SO_4^{2-} + 2CH_2O$ <--> $H_2S + 2HCO_3^-$

$S^{2-} + 2H_3O^+$ <--> $H_2S + 2H_2O$

$2CH_2O$ <--> $CH_4 + CO_2$

$NaOH + Ca^{2+} + HCO_3^-$ <--> $CaCO_3 + Na^+ + H_2O$

$Ca(OH)_2 + Ca^{2+} + 2HCO_3^-$ <--> $2CaCO_3 + 2H_2O$

$4Fe^{2+} + O_2 + 2H_2O + 8OH^-$ <--> $4Fe^{3+} + 12OH^-$

$Fe^{3+} + 3OH^-$ <--> $Fe(OH)_3$

$2Mn^{2+} + O_2 + 4OH^-$ <--> $2MnO_2 + 2H_2O$

Table 3 - k_D values for different gasses as function of temperature.

k_D	0°C	10°C	20°C
Nitrogen	0,023	0,019	0,016
Oxygen	0,049	0,039	0,033
Methane	0,055	0,043	0,034
Carbon dioxide	1,710	1,230	0,942
Hydrogen sulfide	4,690	3,650	2,870
Tetrachloroethene	-	3,380	1,880
Trichloroethene	-	4,100	2,390
Chloroform	-	9,620	5,070

Universal gas constant R = 8,3142 J/(K.mol)

Table 4 – Composition of air in atmosphere (T = 10°C, p = $1 \cdot 10^5$ Pa)

Gas	Volume percentage [%]
Nitrogen	78,1
Oxygen	20,95
Carbon dioxide	0,003
Argon	0,93
Rest gasses	0,0002

Relevant formulae

$c = \dfrac{p}{R \cdot T} \cdot MW$

$\dfrac{dc}{dt} = k_2 \cdot (c_s - c)$

$RQ = \dfrac{Q_l}{Q_w}$

$K = \dfrac{c_e - c_0}{c_s - c_0}$

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

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

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

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

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

$K = 1 - (1 - k)^n$

$I_0 = \dfrac{H_0}{L} = 180 \cdot \dfrac{\nu}{g} \cdot \dfrac{(1 - p_0)^2}{p_0^{\,3}} \cdot \dfrac{v}{d^2}$

$H = 130 \cdot \dfrac{v^{0.8}}{g} \cdot \dfrac{(1 - p_e)^{1.8}}{p_e^{\,3}} \cdot \dfrac{v^{1.2}}{d^{1.8}} \cdot L_e$

$H_{max} = (1 - p) \cdot L \cdot \dfrac{\rho_f - \rho_w}{\rho_w}$

$q_{max} = \dfrac{x}{m} = K \cdot c_s^{\,n}$

$\dfrac{c_0}{c_e} = 1 + \exp\left(k_2 \cdot EBCT \cdot \left(1 - \dfrac{BV \cdot c_0}{q \cdot \rho}\right)\right)$

$BV = \dfrac{Q \cdot T}{V} = \dfrac{T}{EBCT}$

$J = \dfrac{Q}{A_{mem}} = \dfrac{K_w \cdot (TMD - \Delta\pi)}{\nu}$

$TMD = \dfrac{P_f + P_c}{2} - P_p = P_f - \dfrac{\Delta P_{hydr}}{2} - P_p$

$\pi = \sum \dfrac{R \cdot T \cdot c_i \cdot z_i}{MW_i}$

$\gamma = \dfrac{Q_p}{Q_f}$

$Ret = 1 - \dfrac{c_p}{c_f}$

$\beta = \exp\left(\dfrac{J \cdot \delta}{D_i}\right)$

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

$P = \rho \cdot g \cdot Q \cdot \Delta H$

$s_0 = \dfrac{Q}{B \cdot L}$

$r = (1 - p_0) + \dfrac{1}{s_0} \cdot \displaystyle\int_0^{p_e} s\, dp$

$Re = \dfrac{v_0 \cdot R}{\nu}$

$Fr = \dfrac{v_0^{\,2}}{g \cdot R}$

$R = \dfrac{B \cdot H}{B + 2 \cdot H}$

$\tau = \dfrac{\lambda}{8} \cdot \rho_w \cdot v_s^{\,2}$

1.   Aeration and gas transfer

In groundwater treatment aeration and gas transfer is normally needed. Assume that a choice can be made between cascades and spray aerators.

1.1   Which gasses must generally be removed from groundwater and why?

1.2   Mention the advantages and disadvantages of the two different aeration systems.

A cascade is chosen.

1.3   Mention a good configuration of the cascade in order to increase pH and discuss the reasons for your choice.

1.4   A cascade step with a height of 30 cm has a gas removal efficiency of 15%. How many steps are necessary to remove at least 60%?

1.5   The treatment flow is 2000 m^3/h. Determine the net weir length, the chamber width and the chamber depth.

1.6   Draw the cascade.

2.   Filtration

After a cascade aeration a wet filtration step is installed for groundwater treatment.
Flow: 2000 m^3/h
Total surface area: 200 m^2
Filterbed height: 1.5 m
Supernatant water height: 1 m
Filterbed grain size: 1 mm

2.1   Which compounds are removed during the wet filtration step.

2.2   Mention the physical parameters that influence the efficiency of filtration

2.3   Determine clean bed filtration resistance of the filters

2.4   Draw a Lindquist diagram including the course of:
        - hydrostatic pressure
        - pressure during flow through clean bed
        - pressure in clogged bed

2.5   Draw a hydraulic line over the filter before and after back washing

3. Coagulation and flocculation

The following three water types are coagulated with Ferric Chloride

	Watertype A	Watertype B	Watertype C
Suspended solids	very high	low	low
Color	low	high	low
pH	8	6,5	8

3.1 Which coagulation mechanisms are involved during the coagulation of the different water types? Motivate your answer. Give an indication of the iron dose needed (high/low). Why is coagulation still necessary in watertype C?

3.2 During winter time the coagulation/flocculation is not resulting in large iron hydroxide flocks. What is the reason for this and give three ways to improve the performance?

3.3 In the production location of Berenplaat (watercompany Evides), 80 sludge blancket clarifiers (5,7x8,3x3 m) are used for a combined coagulation/flocculation/ sediment-tation. About 2/3 of the sludge blanket clarifier is stirred mechanically (40 W per basin). The water production is 22000 m^3/h. Calculate the G_v-value in the flocculation part of the sludge blanket clarifier.

4. Softening

Water quality:
Ca^{2+}	100 mg/l
Mg^{2+}	6.1 mg/l
HCO_3^-	347.7 mg/l
Na^+	80 mg/l
pH	7

Regulated values:
total hardness = 1.5 mmol/l
concentration $HCO_3^- > 2$ mmol/l
concentration $Na^+ < 5.2$ mmol/l

4.1 What is the total hardness of the water?

4.2 What is the concentration CO_2 in the water?

4.3 Calculate the needed dose of both $Ca(OH)_2$ and NaOH in order to soften to a total hardness of 1,5 mmol/l.
Is there a preferred chemical for the softening in this case? Motivate your answer.
How much of the preferred chemical can be saved by aerating the water thoroughly before the softening process?

5.   Adsorption

The raw water of a surface water treatment plant contains 1.4 µg/l atrazin and 0.8 µg/l of diuron. The Freundlich-constants for diuron and atrazin are given in the table below.

Pesticide	$K [(g/kg)\cdot(m^3/g)]$	n [-]
Diuron	10	0.50
Atrazin	30	0.50

The regulated maximum concentration in the drinking water is 0.1 µg/l.

5.1   Which of the two pesticides is the most difficult to remove, regarding both the concentration as well as the affinity of the pesticide for the activated carbon?

5.2   Explain the difference between a powdered activated carbon (PAC) process and a granular activated carbon (GAC) process regarding the adsorption capacity of the activated carbon.

5.3   How many kg of PAC is needed to treat 10000 m^3 of the raw water (ideal case)?

5.4   How many kg of GAC should be in a column to treat 10000 m^3 of raw water (ideal case)?

5.5   The theoretical adsorption capacity calculated from the Freundlich isotherm is always an overestimation of the adsorbed amount measured in the treatment plants. Give two reasons for this difference in a PAC-process and three reasons in a GAC-process.

6.   Sedimentation

Indicate if the following statements (2.1 to 2.3) are true for false.

6.1   The efficiency of discrete settling is independant of the depth of the settling tank.

6.2   A doubling of the depth of a settling tank has a positive effect on the stability of flow in the settling tank.

6.3   In vertical settling the value of the flow velocity is equal to the surface loading.

A horizontal settling tank is fed with raw water. The water flow is 0,5 m^3/s. The dimensions of the settling tank are L = 50 m, B = 20 m and H = 3 m. The temperature of the water is 10°C.

6.4   Calculate the surface loading, the Reynolds and Froude (Camp) number of this tank.

The cumulative frequency distribution of the settling velocities is given in the table below.

S [mm/s]	0,0	0,2	0,4	0,6
P [%]	0	33,3	66,6	100

6.5   Calculate the removal efficiency of this tank
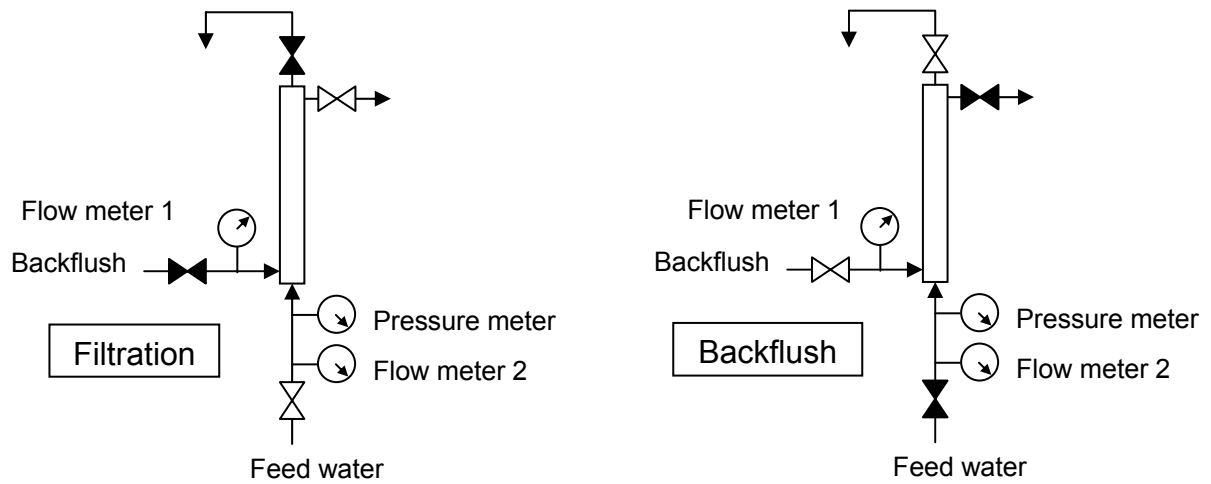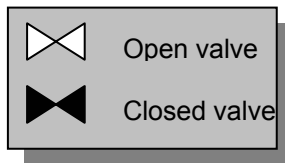
7.   Membrane filtration

An industry treats surface water to process water by means of a double membrane filtration. In the schedule below a schematic drawing of the treatment scheme is given. In the table below the values of some water quality parameters are given of the raw water.
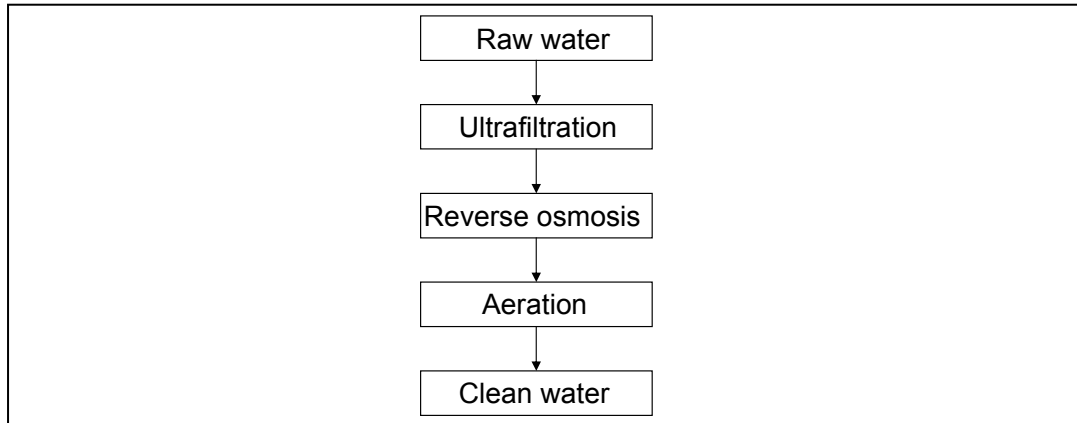
```
          Raw water
             │
             ▼
        Ultrafiltration
             │
             ▼
       Reverse osmosis
             │
             ▼
          Aeration
             │
             ▼
         Clean water
```

Water quality parameter	Raw water	Water quality after ultrafiltration	Water quality after reverse osmosis
Turbidity (FTU)	18		
Suspended solids (g/m^3)	22		
Na^+ (g/m^3)	46		
Ca^{2+} (g/m^3)	70		
HCO_3^- (g/m^3)	87		
SO_4^{2-} (g/m^3)	64		
CO_2 (g/m^3)	0,3		
O_2 (g/m^3)	10		
pH (-)	9		
Sum of pesticides (µg/l)	0,80		

7.1   Give an indication of the water quality after ultrafiltration and reverse osmosis. Fill in the blank spaces in the water quality table.

7.2   The recovery of the reverse osmosis is 80% and the recovery for the ultrafiltration is 95%. How large should the feed flow be to produce 50 m^3/h of permeate.

7.3   Why is the recovery of the ultrafiltration limited to 95%? Why is the recovery of the reverse osmosis limited to 80%?

In the ultrafiltration installation two flow meters (feed flow and backflush flow) and one pressure meter (in the feed flow, just before entering the module) are installed. The permeate flows out of the module at atmospheric conditions. The permeate flux of the module is 100 $l/(m^2 \cdot h)$. In a membrane module 615 membranes of 5.2 mm diameter are placed. The length of the module is 3 meter and the membrane module has an effective membrane area of 30 m^2.

7.4 What values will be read on all three meter during:
- filtration
- back flushing

7.5 The reverse osmosis installation consists of 2:1 staged spiral wound membrane modules. Each module consists of 6 elements. After 6 months in production the permeate flux is lower than at start up. Give explanations for the lower flux and suggest solutions to increase the flux.

CT4470 Drinking water I - Technology

Date   :   24 January 2005
Time   :   9.00-12.00 h

Answers of the exam

**Aeration and gas transfer**

1.1   Methane: to prevent biological growth in filters
           Carbon dioxide: pH neutralisation and avoid excessive dosing of chemicals during softening
           Hydrogen Sulfide: taste and odour

1.2   Cascades: robust, high efficiency, extra elevation height and extra space requirements
           Spray aerator: incorporated in filter, good spreading during dryfiltration, low efficiency.

1.3   For pH increase, carbon dioxide must be removed. The removal efficiency of carbon dioxide per cascade step is independent of fall height, thus many different steps are required.

1.4 $K=1-(1-k)^n$. $K=0,6$; $k=0,15 => n=6$.

1.5   Assume weir loading of 80 m3/h.m => net weir length =2000/80=25 m.
           Weir detph is 2/3*h= 0.2 m

$$t = \sqrt{\frac{2 \cdot h}{g}} \; ; \quad d^3 = \frac{Q_w^2}{g \cdot L_{netto}^2} \; ; \quad v_0 = \frac{Q_w}{L_{netto} \cdot d} \; ; \quad x = v_0 \cdot t \; ; \quad B = 2 \cdot x$$

t=0.247; d=0.0177 m; 0.39 m/s; x=0.097 ; B=0.194 m.
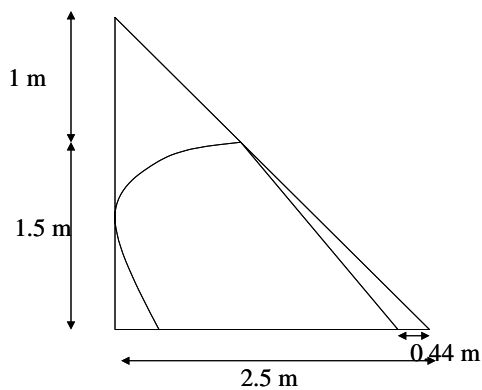

1.6
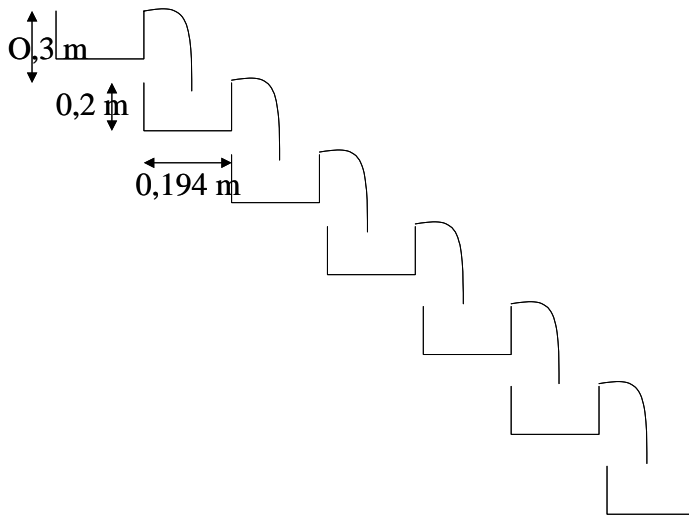
Filtration

2.1   Iron, manganese, ammonium and some times methane

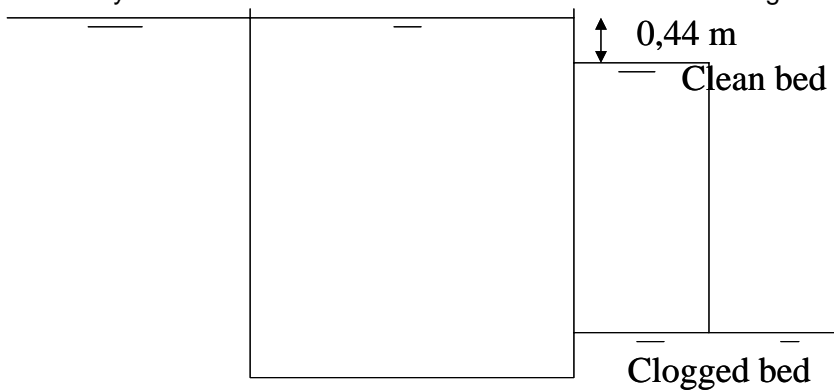2.2   Bed height, grain size, number of layers, filtration velocity

2.3   Assume a temperature of 10oC

$$H = 180\frac{\nu}{g}\frac{(1-p)^2}{p^3}\frac{\nu}{d^2} \quad L = 180\frac{10^{-6}}{9.81}\frac{0.6^2}{0.4^3}\frac{10}{3600.(10^{-3})^2}.1.5 = 0.44 \text{ m}$$

2.4

2.5   Draw a hydraulic line over the filter before and after back washing
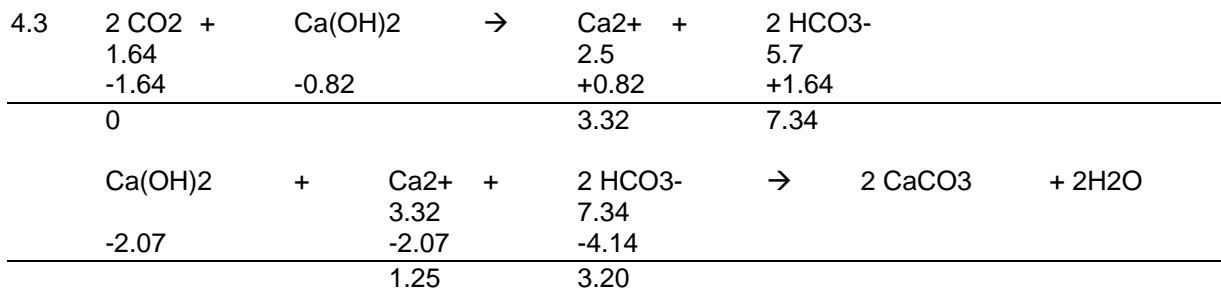

0,44 m

Clean bed

Clogged bed

Coagualtion and flocculation

3.1 Water type A: destabilisation coagulation because of the high suspended solids, not much iron necesasary.
Water type B: adsorptive coagulation remove a part of the color at low pH. High dose of iron needed
Water type C: sweep coagulation high dose needed. Coagulation is also used to remove pathogens.

3.2 The reaction kinetics is slowing down also the shear rate is changing because of the increase of viscosity.
Improvements:
a) find optimal power imput for the steering at low temperatures.
b) Increase the iron dose
c) use a flocculation aid (polymer)
d) mix cold water with water of a higher temperature.

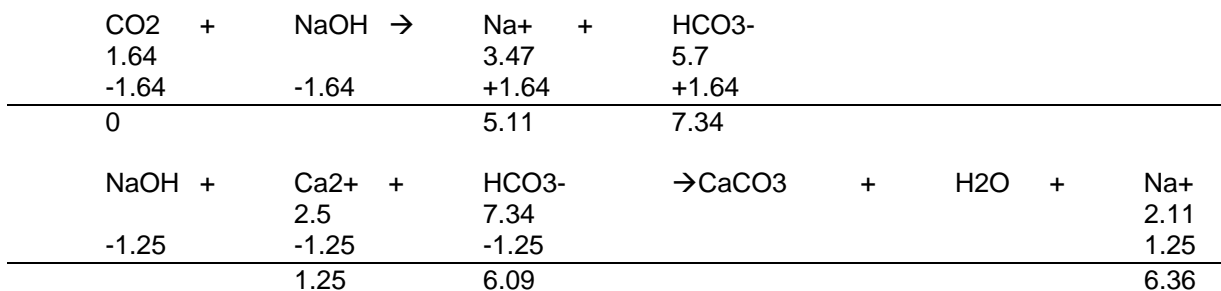3.3 $G_v = (P/(V*u))^{0.5} = (40/(94.6/1000))^{0.5} = 20$ sec^{-1}

Softening

4.1 Ca=2.5 mmol/l; Mg=0.25 mmol/l; total hardness=2.75 mmol/l

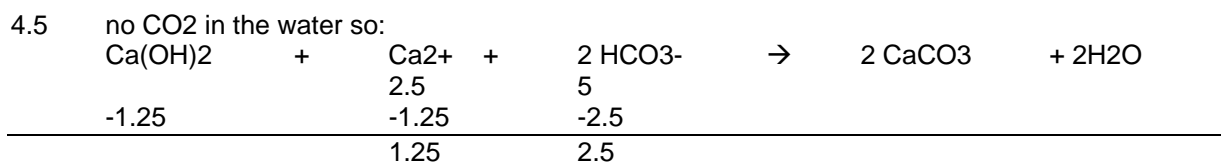4.2 $pH=pK_z+\log(HCO_3/CO_2)$; $\log(HCO_3/CO_2)=7-6.46=0.54$; $CO_2=5.7/3.47=1.64$

4.3

2 CO2 +	Ca(OH)2	→	Ca2+ +	2 HCO3-			
1.64			2.5	5.7			
-1.64	-0.82		+0.82	+1.64			
0			3.32	7.34			

Ca(OH)2	+	Ca2+ +	2 HCO3-	→	2 CaCO3	+ 2H2O	
		3.32	7.34				
-2.07		-2.07	-4.14				
		1.25	3.20				

needed: 0.82+2.07=2.89 mmol/l

CO2 +	NaOH →	Na+ +	HCO3-				
1.64		3.47	5.7				
-1.64	-1.64	+1.64	+1.64				
0		5.11	7.34				

NaOH +	Ca2+ +	HCO3-	→CaCO3	+	H2O	+	Na+
	2.5	7.34					2.11
-1.25	-1.25	-1.25					1.25
	1.25	6.09					6.36

needed: 1.64+1.25=2.89 mmol/l

4.4 Sodium concentration is too high after softening with NaOH, so Ca(OH)2 is preferred.

4.5 no CO2 in the water so:

Ca(OH)2	+	Ca2+ +	2 HCO3-	→	2 CaCO3	+ 2H2O	
		2.5	5				
-1.25		-1.25	-2.5				
		1.25	2.5				

so we save 2.89-1.25=1.64 mmol/l Ca(OH)2

Adsorption

5.1 The K-value of atrazin is 3x higher compared to diuron. This compansates the higher concentration of atrazin.

5.2 PAC is loaded (in the ideal case) until the equilibrium value is about the regulated value (0.1). But in case of breaktrough in GAC most of the activated carbon is loaded (in the ideal case) until the influent value (0.3 diuron). The GAC-activated carbon has a higher loading in case of a breaktrough compared to the wasted PAC.

5.3 Diuron: loading PAC=$10 \times 0.1^{0.5}$=3.2 g diuron/kg activated carbon. We remove 0.8-0.1=0.7 ug/l. This is 7 gram in 10000 m3. So we need 2.2 kg PAC

5.4 Diuron: loading GAC=$10 \times 0.8^{0.5}$=8.9 g diuron/kg activated carbon. We remove before breaktrough 100% of the diuron (block-front) so 0.8 ug/l is 8 gram diuron in 10000 m3. So we need 8/8.9 = 0.9 kg of GAC in the column.

5.5 For PAC: the contact time of the PAC in the process is about 20 minutes not enough to reach an equilibrium adsorption. There is also competition of natural organic matter in the raw water.
For GAC: The front in the column is never a block-front. The rate of adsorption may be too low. Also the NOM in the raw water causes pre-loading.

Sedimentation

6.1 No, the efficiency is dependent on the surface loading and not of the depth

6.2 No, by doubling of the depth the velocity decreases and the hydraulic radius increases. The Froude number thus becomes smaller.

6.3 Yes, in vertical sedimentation $s_o=v_o$

6.4 vo = 0.5/(20·3) = 8.33 mm/s
R = (20·3)/(20+6) = 2.31 m
Re = 8.33·10-3·2.31/(1.31·10-6) = 14690
Fr = (8.33·10-3)2/(9.81·2.31) = 0.3·10-5

6.5 s0 = 0.5/(50·20) = 0.5·10-3 m/s
at s0 = 0.5·10-3 m/s follows po = 83.33

$$r = (1 - p0) + \frac{1}{so} \int_{0}^{po} s\,dp$$

the surface is equal to $0.5 \cdot (0.5 \cdot 10^{-3}) \cdot 0.833 = 0.2082 \cdot 10^{-3}$
it follows that r = $(1-0.833) + 0.2082 \cdot 10^{-3} / 0.5 \cdot 10^{-3}$ = 58.4%

Membrane filtration

7.1

Water quality parameter	Raw water	Water quality after ultrafiltration	Water quality after reverse osmosis
Turbidity (FTU)	18	0.1	0,05
Suspended solids (g/m³)	22	0.1	0,05

Na$^+$ (g/m^3)	46	46	23
Ca^{2+} (g/m^3)	70	70	7
HCO$_3^-$ (g/m^3)	87	87	43
SO$_4^{2-}$ (g/m^3)	64	64	32
CO$_2$ (g/m^3)	0,3	0,3	0,3
O$_2$ (g/m^3)	10	10	10
pH (-)	9	9	8
Sum of pesticides (µg/l)	0,80	0,80	0,04

7.2   Q*0.95*0.8 = 50   =>   Q = 65.8 m3/h

7.3   UF: permeate is needed for cleaning (backwash, forward flush) of installation
         RO: recovery is limited to 80% because at higher recoveries scaling can occur.

7.4   Amem = 30 m2; Qperm = Qfeed = 30*0.1 = 3 m3/h
         Filtration: Flow meter 1:   3 m3/h
                        Flow meter 2:   0 m3/h
                        Pressure meter: 1 bar
         Baskwash   Flow meter 1:   0 m3/h
                        Flow meter 2:   7.5 m3/h
                        Pressure meter: 2.5 bar

7.5   Explanations:
         - fouling: in the first element of the first stage (bio)fouling van occur
         - scaling: in the last elements of the second stage scaling can occur.
         Solitions:
         -     better pre-treatment in case of fouling
         -     increase of cross-flow velocity in case of scaling
         -     dosing of anti-scalants in case of scaling
         -     dosing of acids in case of scaling