Delft University of Technology
Faculty of Civil Engineering and Geosciences
Subfaculty Civil Engineering
Section Sanitary Engineering

CT4471 Drinking water I - Technology

Date : 4 November 2005
Time : 14.00-17.00 h

There are 7 times 4 **True-False** statements of equal weight. In all statements 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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

1. Aeration and gas transfer

1.1 Aeration of groundwater is mainly meant to remove carbon dioxide, methane and ammonia.

1.2 From theory it can be concluded that removal of carbon dioxide by cascades is independent of fall height.

1.3 Removal of carbon dioxide is 15% per cascade step. Then removal of 5 cascade steps in series is 75%.

1.4 When pH is 6.46 (at temperature 10 ^{0}C) and HCO_3^- is 2 mmol/l then CO_2 concentration is 2 mmol/l.

2. Filtration

2.1 At ground water pumping station Ridderkerk of Hydron-ZH the first filters are dry-filters. This is probably because of the high methane concentration in the influent water.

2.2 At pumping station Scheveningen of DZH mainly iron is removed. The filtration velocity is 5 m/h, the sand grains have a diameter of 1 mm, the porosity is 40%, the bed height is 1.5 m and the water temperature is 10 ^{0}C. Then the clean bed resistance of the filterbed is 18 cm.

2.3 For the filters mentioned in statement 2.2 the backwash velocity has to be 42 m/h to reach 20% expansion (assuming a sand density of 2650 kg/m^3).

2.4 The maximum pore filling of the filters mentioned in statement 2.2 is 80% and the density of the flocs is 5 kg/m^3. Then 1.6 kg of iron flocs can be stored in 1 m^3.

3. Coagulation and flocculation

3.1 Sweep coagulation is normally applied when suspended solids concentration in influent water is high.

3.2 After coagulation and floc formation the water is normally pumped to a floc removal device.

3.3 When water temperature drops from 20 ^{o}C to 10^{o}C, the power input in the floc formation unit should increase with a factor 1.3.

3.4 During coagulation the pH of the water will drop, making the water more acid.

4. Softening

4.1 At groundwater pumping station Ridderkerk lime is used for softening. The reason for that is the low buffering capacity of the incoming water.

4.2 At groundwater pumping station Ridderkerk split treatment is not applied. One of the reasons could be that the magnesium concentration in the incoming water is high.

4.3 At Amsterdam water Supply the incoming calcium concentration is 2 mmol/l. Reduction of calcium to 1.25 mmol/l is necessary. In a pellet reactor the maximum softening depth is 0.5 mmol calcium/l. The by-pass ratio can thus be 50%.

4.4 At Amsterdam Water Supply, the pressure loss over a expanded pellet bed of 50 cm is 40 cm. The density of the pellets is 2700 kg/m^3. Then the porosity of the expanded bed is 53%.

5. Adsorption

5.1 At groundwater pumping station Ridderkerk GAC is applied. In the past the 4 filters were operated in a Pseudo moving bed mode (2x2 filters). Nowadays the 4 filters are operated in parallel. This most probably because of the higher removal efficiency of the parallel operated filters.

5.2 A filter of 150 m^3 is loaded with an influent concentration of 2 µg/l atrazin and a flow of 500 m^3/h. The density of the carbon is 500 kg/m^3. The maximum saturation of the carbon is determined by the following Freundlich constants: n=0.5 and K = 30 (g/kg)·(m^3/g)^n. The maximum amount of Atrazin stored in the filter (assuming a steep adsorption front) is thus 10 kg.

5.3 The number of Bedvolumes of the filter of statement 5.2 is 36000, the run time of the filter is 450 days.

5.4 When the influent concentration of Atrazin increases to 4 µg/l, the maximum amount of Atrazin stored in the filter of statement 5.2 will increase with a factor 1.4.

6. Sedimentation

6.1 The removal efficiency of a horizontal flow tank with the dimensions (L x W x H) 20 x 4 *3 m^3 that treats a flow of 86.4 m^3/h with the settling characteristics of tabe 6.1 is 50%.

Table 6.1. 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

6.2 The flow in the horizontal flow settling tank mentioned in statement 6.1 is stable and turbulent (temperature is 10 ^{0}C).

6.3 By placing a vertical baffle in the flow direction in the tank, turbulence decreases and stability increases.

6.4 The length of the outlet gutter of a horizontal flow settling tank should be equal to the width of the settling tank.

7. Membrane filtration

7.1 For the treatment of backwash water ultrafilters are applied in order to remove Natural organic matter (NOM).

7.2 At Heineken factory, water from DZH is chosen (instead of water from Hydron-ZH) to feed the Spiral Wound Reverse Osmosis installation, because of its low calcium and silica content. This is mainly to avoid scaling of the membranes.

7.3 At Heineken factory the Spiral Wound Reverse Osmosis plant is partially by-passed. This is mainly because of the sodium content. Assuming 100% retention of sodium, an influent concentration of 36 mg/l and a required sodium content in the Heineken beer of 10 mg/l the by-pass ratio is 28%.

7.4 At Heineken factory, the Spiral Wound Reverse Osmosis installation consist of a "christmas tree" configuration in three stages. In these configurations the recovery of all the three stages is normally the same.

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Answers of exam

1. Aeration and gas transfer

1.1. **False**, ammonia is not removed during aeration

1.2. **True**, because of the high Kd-value of carbon dioxide, removal is determined by mass balance and not by kinetics and removal is thus independent of fall height.

1.3. **False**. k=0.15 and $K=1-(1-k)^5=0.55$

1.4. **True**. pH=pK1+log(HCO3/CO2) = > 6.46-6.46=0 = log(HCO3/CO2) => CO2=2 mmol/l.

2. Filtration

2.1. **False**. The first filters are dry-filters and this is because of the high **ammonia** concentration in the influent water.

2.2. **False**. $H = 180 \frac{\nu}{g} \frac{(1-p)^2}{p^3} \frac{v}{d^2} L = 180 \frac{1e-6}{9.81} \frac{(1-0.4)^2}{0.4^3} \frac{5/3600}{1e-3^2} 1.5 = 0.22m$

2.3. **False** . pe = 0.5; $v = (180 \frac{g}{130\nu^{0.8}} 1.65 \frac{(p)3}{(1-p)^{0.8}} \frac{d^{\wedge 1.8}}{})^{1/1.2} = 56m^3/h$

2.4. **True**. Total pore volume for flocs is 0.4*0.8 = 0.32 m^3/m^3. mass of flocs is 0.32*5=1.6 kg/m^3

3. Coagulation and flocculation

3.1 **False**. Sweep coagulation is normally applied when suspended solids concentration in influent water is **low**.

3.2 **False**. Pumping will break-up the flocs, so the water will flow by gravity.

3.3 **True**. To keep the same G-value, the power input should compensate for the higher viscosity.

3.5 **True**. Because of the formation of iron hydroxide flocs the water becomes more acid.

4. Softening

4.1 **False**. Using lime more HCO_3^- is used than when caustic soda is used and thus the buffering capacity will be lowered more. Low buffering capacity of the incoming water thus is not the reason.

4.2 **True**. Because of high magnesium concentrations spilt treatment cannot be applied. Softening only removes calcium till a maximum of 0.5 mmol/l

4.2 **True**. 0.5*0.5+2*0.5= 1.25 mmol/l

4.3 **True**. H=1.7*(1-p)*L => 1-p=0.47.

5. Adsorption

5.1 **False**. The removal efficiency of Pseudo moving bed filters is better, but probably there was a hydraulic problem.

5.2 **True**. The total amount of atrazine stored is maximally $q=30*500*150*0.002^{0.5}$= 10kg/filter

5.3 **True**. T=BV*V/Q=36000*150/(500*24)=450 days

5.4 **True**. When atrazin concentration increases with factor 2 the loading capacity increases with factor $2^n=2^{0.5}=1.4$.

6. Sedimentation

6.1 **False.** The surface loading s_o=Q/A=144/80=1.08m/h=0.3mm/s. P_0=50%. The removal in a horizontal flow tank however is higher than 50%, in this case 75%.

6.2 **False**. v_0=86.4/12/3600=0.002m/s. R=12/10. Re=2400 and Fr=3.4 e-7. => turbulent and unstable.

6.3 **True**. R becomes 0.75 => Re = 1500 and Fr = 5.4 e-7.

6.4 **False**. Because of resuspension the outlet device should have a length several times times the width of the tank.

7. Membrane filtration

7.1 **False**. Ultrafilters do not remove dissolved organic mattter and back wash water normally does not contain organic matter.

7.2 **True**. Calcium and silica can give scaling of the membranes (mainly when the concentrations are high due to concentration polarization and in the later stages of the membrane filtration installation) which affect the recovery.

7.3 **True**. 0.28*36=10 mg/l

7.4 **False**. The recovery in later stages is lower, because the feed pressure in the later stages is lower because of higher hydraulic and osmotic pressure losses.