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10

Bulking sludge

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10.1 INTRODUCTION

Overall, a good separation (settling) and compaction (thickening) of activated sludge in the secondary clarifier are necessary conditions to guarantee a good and efficient operation of the wastewater treatment plant. When there is excessive growth of filamentous bacteria, the settling properties of the sludge are strongly reduced. This phenomenon, described as bulking sludge, is a common and long-standing problem for activated sludge processes where suspended solids cannot be retained in the settler and compaction is hampered affecting the overall efficiency of the plant.

Chapter 10 on bulking sludge in the textbook *Biological Wastewater Treatment: Principles, Modelling and Design* (Chen *et al*., 2020) presents an overview of relevant historical aspects of the development of activated sludge systems and their relationship with the occurrence of filamentous bulking sludge. Fundamentals on the relationship between morphology and ecophysiology are analysed as well as the identification of the filamentous bacteria involved. Different theories formulated to explain the filamentous bulking sludge are discussed on the basis of lab- and full-scale observations and remedial actions to control and suppress the growth of filamentous organisms are presented. Finally, recent developments in mathematical modelling and aerobic granular sludge are introduced.

10.2 LEARNING OBJECTIVES

After the successful completion of this chapter, the reader will be able to:

- Understand how the sludge volume index is related to the settler area.
- Understand which factors govern the sludge volume index value and how to minimize sludge volume index by process design and operation.

- Calculate the sludge loading rate and contact time of a given selector and apply the selector design guidelines for typical operating conditions and influent flow characteristics of a conventional activated sludge wastewater treatment plant.
- Relate control of bulking sludge to aerobic granular sludge formation.

10.3 EXAMPLES

Wastewater treatment plant under study

Consider a conventional activated sludge wastewater treatment plant (WWTP), named WWTP1. The influent characteristics and the WWTP design and operating conditions are summarized in Table 10.1.

Table 10.1 Influent characteristics and WWTP design and operating conditions. Note that the subscript 'in' here refers to the influent, while the subscript 'i' refers to the selector compartment (i=1,2,3).

Description	Symbol	Value	Unit
Influent flow rate	Q_{in}	14,500	m^3/d
Influent total COD concentration	COD_{in}	816	10^{-3} kgCOD/m
Influent biodegradable COD concentration	$COD_{b,in}$	636	-
Readily biodegradable COD fraction of the influent biodegradable COD	f_{SS}	0.3	-
Influent total Kjeldahl nitrogen concentration	TKN_{in}	50	$gN.m^{-3}$
Influent orthophosphate concentration	$P_{IN,in}$	13	$gP.m^{-3}$
Total reactor volume	V_R	14,650	m^3
Volume of the 1st compartment in the selector	V_{S1}	250	m^3
Volume of the 2nd compartment in the selector	V_{S2}	500	m^3
Volume of the 3rd compartment in the selector	V_{S3}	1,000	m^3
Sludge retention time	SRT	8	d
Total suspended solids mass	MX_{TSS}	51,000	kgTSS
Sludge VSS:TSS ratio	f_{VT}	0.85	kgVSS/kgTSS
Sludge underflow recycle ratio	s	1:1	-

In what follows, the selector design will be assessed for a plant with organic matter removal only (Example 10.3.1), a plant where biological nitrogen removal via nitrification-denitrification takes place in a Modified Ludzack-Ettinger (MLE) process configuration (Example 10.3.2) and a plant where the aerobic selector is replaced by an anaerobic selector (Example 10.3.3).

Aerobic selector design

Example 10.3.1

The WWTP under study has been designed for organic matter removal (only). To this end, all tanks are aerobic, including the three selector compartments (Figure 10.1). A minimum oxygen concentration of 2 g/m^3 is maintained along the aerobic tanks.

1. What is the sludge loading rate (SLR) in each of the three compartments of the aerobic selector?
2. What is the actual contact time in the aerobic selector?

3. Based on the previous operational data and on the selector design guidelines recommended for aerobic selectors in municipal wastewater treatment systems (Table 10.2 in the textbook Chen *et al.,* 2020), does the aerobic selector provide favourable conditions to reduce the occurrence of filamentous bulking sludge? If not, (how) can this be remedied?

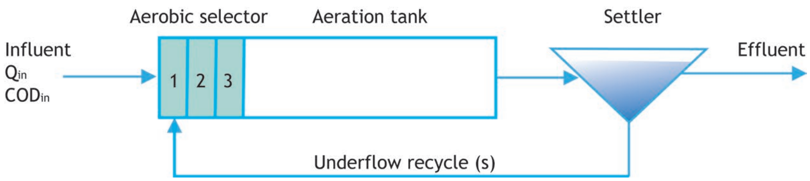

Figure 10.1 Layout of a WWTP with aerobic selector (Example 10.3.1). 'Comp.' refers to 'compartment'. The same configuration holds for the WWTP with anaerobic selector from Example 10.3.3, only then the selector compartments are not aerated, resulting in anaerobic conditions.

Solution

All calculations discussed below are provided in the spreadsheet 'Chapter 10 Design examples.xlsx' on the sheet 'aerobic selector'.

1. The sludge loading rate in selector compartment i (SLR_i, in kgCOD/kgTSS.d) is calculated as the ratio between the incoming COD load ($FCOD_i$, in kgCOD/d) and the TSS mass in that selector compartment (MX_{TSSi}, in kg TSS):

$$SLR_i = \frac{FCOD_i}{MX_{TSSi}} \quad (10.1)$$

The amount of TSS in selector compartment i is calculated according to Eq. 10.2, assuming an even distribution of the TSS over all the reactor compartments, *i.e.,* the three selector compartments (with volume V_{Si}, i=1,2,3) and the bioreactor (with volume V_R):

$$MX_{TSS,i} = V_{Si} / V_R \cdot MX_{TSS} \quad (10.2)$$

which yields:

$$MX_{TSS,1}: 250\ m^3 / 14{,}650\ m^3 \cdot 51{,}000\ kgTSS = 870\ kgTSS \quad (10.3)$$

$$MX_{TSS,2}: 500\ m^3 / 14{,}650\ m^3 \cdot 51{,}000\ kgTSS = 1{,}741\ kgTSS \quad (10.4)$$

$$MX_{TSS,3}: 1{,}000\ m^3 / 14{,}650\ m^3 \cdot 51{,}000\ kgTSS = 3{,}481\ kgTSS \quad (10.5)$$

Note: the TSS concentration is the same everywhere, in the reactor as well as in all the selector compartments, and is calculated as:

$$X_{TSS} = MX_{TSS} / V_R \qquad (10.6)$$

$$X_{TSS} = 51{,}000 \text{ kgTSS} / 14{,}650 \text{ m}^3 = 3.5 \text{ kgTSS/m}^3 \qquad (10.7)$$

The COD load on the first selector compartment equals the influent COD load:

$$FCOD_1 = FCOD_{in} = Q_{in} \cdot COD_{in} \qquad (10.8)$$

which amounts to:

$$FCOD_1 = 14.5 \cdot 10^6 \text{ l/d} \cdot 816 \text{ mgCOD/l} = 11{,}832 \text{ kgCOD/d} \qquad (10.9)$$

The COD load on the second selector compartment should strictly speaking be calculated as the influent COD load minus the load of COD which has been degraded in the first selector compartment. However, it is not exactly known how much COD is degraded in each selector compartment. In fact, the selector design guidelines (Table 10.2 in the textbook) are such that only the readily biodegradable COD is converted. In this example, the readily biodegradable COD load amounts to:

$$FRBCODin = Q_{in} \cdot f_{SS} \cdot COD_{b,in} \qquad (10.10)$$

$$FRBCODin = 2{,}769 \text{ kgCOD/d} \qquad (10.11)$$

which represents 23 % of the influent load. Given that the fraction of readily biodegradable COD only represents a relatively small fraction of the influent COD load, the COD load on the second and third selector compartment will be approximated by the influent COD load:

$$FCOD_3 = FCOD_2 = FCOD_1 = FCOD_{in} \qquad (10.12)$$

The sludge loading rates in the three selector compartments are thus calculated from Eq. 10.1 as:

$$SLR_1 = \frac{FCOD_1}{MX_{TSS1}} = \frac{11{,}832 \text{ kgCOD/d}}{870 \text{ kg/TSS}} = 13.6 \text{ kgCOD/kgTSS.d} \qquad (10.13)$$

$$SLR_2 = \frac{FCOD_2}{MX_{TSS2}} = \frac{11{,}832 \text{ kgCOD/d}}{1{,}741 \text{ kg/TSS}} = 6.8 \text{ kgCOD/kgTSS.d} \qquad (10.14)$$

$$SLR_3 = \frac{FCOD_3}{MX_{TSS3}} = \frac{11{,}832 \text{ kgCOD/d}}{3.481 \text{ kg/TSS}} = 3.4 \text{ kgCOD/kgTSS.d} \qquad (10.15)$$

2. The actual contact time in the i^{th} aerobic selector compartment is equal to the actual hydraulic residence time, $HRT_{a,i}$ (d) in that compartment:

$$HRT_{a,i} = V_{Si} / (Q_{in} \cdot (1+ s)) \qquad (10.16)$$

which is calculated as:

$$HRT_{a,1} = 250\ m^3 / 14{,}500\ m^3/d / (1 + 1) \cdot 24\ h/d \cdot 60\ min/h = 12\ min \quad (10.17)$$

$$HRT_{a,2} = 500\ m^3 / 14{,}500\ m^3/d / (1 + 1) \cdot 24\ h/d \cdot 60\ min/h = 25\ min \quad (10.18)$$

$$HRT_{a,3} = 1{,}000\ m^3 / 14{,}500\ m^3/d / (1 + 1) \cdot 24\ h/d \cdot 60\ min/h = 60\ min \quad (10.19)$$

Thus, the total contact time in the aerobic selector is 87 min.

3. The selector design guidelines for aerobic selectors in municipal wastewater treatment systems are listed in Table 10.2. The single parameter that remains to be calculated is the floc loading in the first compartment. The floc loading expresses the mass of organic matter per mass of TSS and is calculated as the total COD concentration entering the first selector compartment, taking into account the dilution by the recycle flow, divided by the total suspended solids concentration, according to Eq. 10.20:

$$\text{Floc loading in first selector compartment} = COD_{in} / (1 + s) / X_{TSS} \quad (10.20)$$

In this case, Eq. 10.20 is evaluated as:

$$\text{Floc loading in first selector compartment} = 816\ g\ COD/m^3 / (1 + 1) / 3.5\ kgTSS/m^3 = 117\ gCOD/kgTSS \quad (10.21)$$

Table 10.2 Comparison between operational data of the wastewater treatment plant under study and the selector design guidelines recommended for aerobic selectors. Calculations are provided in the spreadsheet 'Chapter 10 Design examples.xlsx' on the sheet 'aerobic selector'.

Parameter	Design value (guideline)	WWTP1		WWTP1b (adjusted selector volume)	
Number of compartments	≥ 3	3	✓	3	✓
Contact time (min) total - compartment 1 - compartment 2 - compartment 3	 10-15	 87 12 25 50	✗	 14 2 3 8	✓
SLR (kgCOD.kg/TSS.d) - compartment 1 - compartment 2 - compartment 3	 12 6 3	 13.6 6.8 3.4	✓	 85 43 21	✗
Floc loading in first compartment ($gCOD/kgTSS$)	50-150	117	✓	117	✓
DO concentration (gO_2/m^3)	≥ 2	Not specified => should be ≥ 2	✓	Not specified => should be ≥ 2	✓

Conclusion:
Comparing the design guidelines recommended for aerobic selectors in municipal wastewater treatment systems with the values for the WWTP1 under study, it is clear that several requirements are met: the number of compartments is satisfactory and so are the sludge loading rates in the selector compartments and the floc loading in the first compartment. One can also assume that the DO concentration will be kept sufficiently high ($DO > 2\ gO_2/m^3$).

However, the total contact time in the selector is much too high (6-8 times): 87 minutes whereas the recommended time is 10-15 minutes. As such, the aerobic selector is not likely to provide favourable conditions to reduce the occurrence of filamentous bulking sludge.

How can this be remedied?
The total contact time in the selector should be reduced by a factor 6-8, which means that the total volume of the three selector compartments should be reduced accordingly, to 200-300 m^3 instead of the current 1,750 m^3. Assume for instance V_{S1}=40 m^3, V_{S2}=80 m^3 and V_{S3}=160 m^3 (total selector volume 160 m^3); however, then the sludge loading rate becomes 6-8 times too high (see Table 10.2 and the Excel file, case WWTP1b). Since it is not an option to increase the TSS concentration by the same factor, it seems that this cannot be remedied.

Anoxic selector design

Example 10.3.2

The WWTP under study is upgraded to achieve biological nitrogen removal via nitrification-denitrification in a MLE process configuration (WWTP2). An average nitrate concentration (S_{NO3-}) of 25 mg N/l is reached in the beginning of the selector through an internal recirculation flow (a) of 2:1 with respect to the influent flow rate.

Would the selector comply with the design guidelines for anoxic selectors (Table 10.2 in the textbook)? If not, what additional design and operational modifications would be required to meet the guidelines?

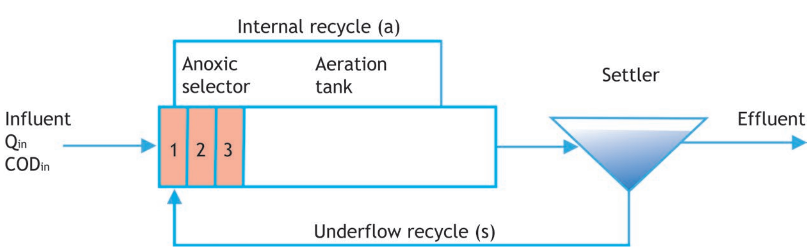

Figure 10.2 Layout of a WWTP with anoxic selector (Example 10.3.2). 'Comp.' refers to 'compartment'.

Solution

The selector design guidelines recommended for aerobic selectors in municipal wastewater treatment systems are listed in Table 10.3. The sludge loading rate (SLR) remains unchanged compared to Example 10.3.1 as the COD load and X_{TSS} remain constant. All the calculations are provided in the spreadsheet 'Chapter 10 Design examples.xlsx' on the sheet 'anoxic selector'.

The contact time in the ith selector compartment $HRT_{a,i}$ (d) is calculated through Eq. 10.22, taking into account the internal recycle ratio a:

$$HRT_{a,i} = V_{Si} / (Q_{in} \cdot (1 + s + a)) \quad (10.22)$$

which is calculated as:

$$HRT_{a,1} = 250\ m^3 / 14{,}500\ m^3/d / (1 + 1 + 2) \cdot 24\ h/d \cdot 60\ min/h = 6\ min \quad (10.23)$$

$$HRT_{a,2} = 500\ m^3 / 14{,}500\ m^3/d / (1 + 1 + 2) \cdot 24\ h/d \cdot 60\ min/h = 12\ min \quad (10.24)$$

$$HRT_{a,3} = 1{,}000\ m^3 / 14{,}500\ m^3/d / (1 + 1 + 2) \cdot 24\ h/d \cdot 60\ min/h = 25\ min \quad (10.25)$$

Thus, the total contact time in the anoxic selector is 43 min. It is half of the contact time compared to the case of the aerobic selector, because of the internal recycle.

The ratio between the amount of readily biodegradable COD consumed and the amount of nitrate consumed is calculated as:

$$(RBCOD / NO_3^-\text{-}N)_{consumed} = COD_{b,in} \cdot f_{SS} / S_{NO3} \quad (10.26)$$

$$(RBCOD / NO_3^-\text{-}N)_{consumed} = 636\ gCOD/m^3 \cdot 0.3 / 25\ gN/m^3 = 8\ gCOD/gN \quad (10.27)$$

Table 10.3 Comparison between operational data of the wastewater treatment plant under study and the selector design guidelines recommended for anoxic selectors. Calculations are provided in the spreadsheet 'Chapter 10 Design examples.xlsx'on the sheet 'anoxic selector'.

Parameter	Design value (guideline)	WWTP2		WWTP2c	
Number of compartments	≥ 3	3	✓	3	✓
Contact time (min) total - compartment 1 - compartment 2 - compartment 3	 45-60	 43 6 12 24	✓	 56 8 16 32	✓
SLR (kgCOD.kg/TSS.d) - compartment 1 - compartment 2 - compartment 3	 6 3 1.5	 13.6 6.8 3.4	✗	 6.1 5.2 2.6	(✗)
$(RBCOD / NO_3^-\text{-}N)_{consumed}$ (gCOD/gN)	7-9	8	✓	8	✓

Comparing the obtained values with the design guidelines for anoxic selectors, it appears that the only criterion which is not met is the one for the sludge loading rates in the selector compartments, which are approximately two times too high. The solution would be to double the reactor volume or to double the MLSS concentration or a combination of both (see Eq. 10.1).

Since the contact time in the selectors is at the low end, the selector compartment values could be increased by 30 % and still meet the guideline, obtaining a contact time of approximately 60 min (43 min · 1.30 = 56 min). The resulting volume of the three compartments is then V_{S1} = 325 m^3, V_{S2} = 650 m^3, V_{S3} = 1,300 m^3. In order to further decrease the SLR to the recommended values of 6, 3 and 1.5 kgCOD/kgTSS.d respectively, the MLSS concentration needs to be increased as well. Increasing the MLSS concentration to X_{TSS} = 6 kgTSS/m^3 (corresponding with a total suspended solids mass MX_{TSS} = 87,500 kgTSS) results in an adequate sludge loading rate in the first selector compartment; however, the sludge loading rates in the second and third reactor compartments are still too high. This could theoretically be solved by further increasing the MLSS concentration; however, this does not seem realistic, a value of X_{TSS} = 6 kg/TSS.m^3 already being very (or even too) high.

Anaerobic selector design

Example 10.3.3

The WWTP under study (WWTP1) is modified in order to incorporate an anaerobic selector instead of an aerobic one (Figure 10.1). It can be assumed that there is no internal recirculation rate sent to the selector, so neither oxygen nor nitrate enters the selector.

1. Which modifications must be made to meet the guidelines for anaerobic selectors (Table 10.2 in the textbook).
2. What will be the unaerated mass fraction?

Solution

1. Guidelines for anaerobic selectors

Table 10.4 compares the operational data and the selector design guidelines recommended for anaerobic selectors in municipal wastewater treatment systems. The contact time remains unchanged compared to Example 10.3.1 *i.e.,* the case without internal recycle to the selector, and meets the corresponding guideline for anoxic selectors. All the calculations are provided in the spreadsheet 'Chapter 10 Design examples.xlsx' on the sheet 'anaerobic selector'.

The only additional criterion that needs to be checked is the ratio between influent readily biodegradable COD (*i.e.,* the sum of VFAs and fermentable COD) and influent phosphate (Eq. 10.28):

$$(COD_{VFA+fermentable} / PO_4^{-3}\text{-}P)_{in} = COD_{b,in} \cdot f_{SS} / P_{IN,in} \quad (10.28)$$

which is calculated as:

$$(COD_{VFA+fermentable} / PO_4^{-3}\text{-}P)_{in} = 636 \text{ gCOD/m}^3 \cdot 0.3 / 13 \text{ gP/m}^3 = 15 \text{ gCOD/gP} \quad (10.29)$$

and adheres to the corresponding design guideline.

Table 10.4 Comparison between operational data of the wastewater treatment plant under study and the selector design guidelines recommended for anaerobic selectors. Calculations are provided in the spreadsheet 'Chapter 10 Design examples.xlsx' on the sheet 'anaerobic selector'.

Parameter	Design value (guideline)	WWTP1	
Number of compartments	≥ 3	3	✔
Contact time (min)	60-120	87	✔
$(COD_{VFA+fermentable} / PO_4^{3-}\text{-}P)_{in}$ (gCOD/gP)	9-20	15	✔

Conclusion: the anaerobic selector fulfils the guidelines and thus yields favourable conditions to reduce the occurrence of bulking sludge.

2. Unaerated sludge mass fraction

The unaerated sludge mass fraction amounts to:

$$f_{XT} = V_{S,tot,\ anaerobic} / V_{tot} \tag{10.30}$$

and is calculated as:

$$f_{XT} = (250 + 500 + 1{,}000)\ m^3 / 14{,}650\ m^3 = 0.12 \text{ or } 12\ \% \tag{10.31}$$

Note that it is assumed here that the WWTP does not contain an anoxic zone, otherwise the anoxic tank volume would need to be considered in the calculation of the unaerated sludge mass fraction.

10.4 EXERCISES

Bulking sludge characteristics (exercises 10.4.1-10.4.3)

Exercise 10.4.1

Explain what the sludge volume index (SVI) is and its practical relevance.

Exercise 10.4.2

Explain what bulking sludge is and its consequences for process performance.

Exercise 10.4.3

To what extent is bulking sludge related to the SVI?

Causes and remediation of bulking sludge (exercises 10.4.4-10.4.7)

Exercise 10.4.4

Describe the diffusion-based selection theory and the kinetic selection theory to explain the occurrence of bulking sludge. Discuss how these theories relate to each other.

Exercise 10.4.5

Explain the storage selection theory.

Exercise 10.4.6
What are the main non-specific methods to control bulking sludge? What drawbacks do these methods have?

Exercise 10.4.2.7
Describe the principle of specific methods to control bulking sludge. What is the principle behind these methods? How are they established in practice?

Selectors to control bulking sludge - relation with granular sludge (exercises 10.4.8-10.4.10)

Exercise 10.4.8
Explain the principle of selectors to control bulking sludge.

Exercise 10.4.9
Discuss the implementation of selectors through their main design parameters.

Exercise 10.4.10
Describe how aerobic granular sludge relates to bulking sludge.

ANNEX 1: SOLUTIONS TO EXERCISES

Bulking sludge characteristics (solutions 10.4.1-10.4.3)

Solution 10.4.1

The sludge volume index (SVI, in ml/g) is an empirical measure of the sludge settling characteristics, expressing the volume taken by one gram of sludge after 30 minutes of settling. The SVI is obtained by having a sludge sample settling in a 1-liter measurement cylinder for 30 minutes. The volume of the sludge layer is read and divided by the original suspended solids content of the sludge sample.

Practical relevance: the SVI has a direct and strong effect on the required settler (surface) area. For instance, an increase in the SVI from 100 to 150 ml/g will result in almost double the required settler area (Figure 10.3).

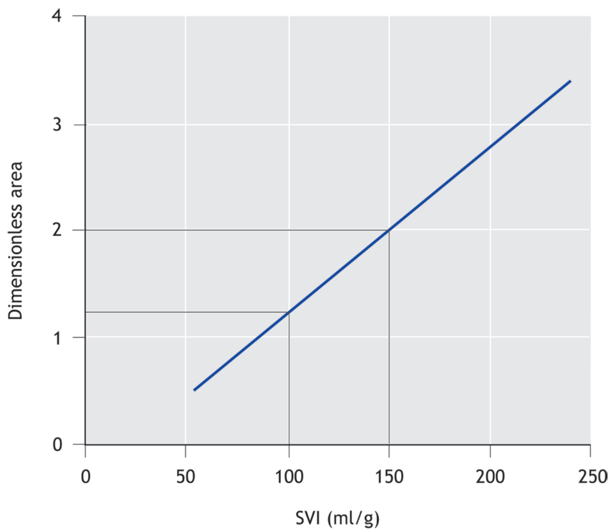

Figure 10.3 Relation between sludge volume index and surface area needed for a settler according to the STOWA design guidelines for settlers (STOWA, 1994). Figure reproduced from Chen *et al.* (2020).

Solution 10.4.2

- 'Bulking sludge' refers to the excessive growth of filamentous bacteria in an activated sludge process, to such an extent that suspended solids cannot be maintained in the settler. Indeed, filamentous bacteria result in open and porous sludge flocs, which experience hindered settling.
- Note 1: bulking sludge is an operational or empirical problem, there is not an exact scientific index to distinguish bulking sludge from non-bulking sludge.
- Note 2: the volume fraction of filamentous bacteria in the activated sludge community which causes settling problems could be minor. Volume fractions of 1-20 % are sufficient to cause bulking sludge.

Solution 10.4.3

- In practice, bulking sludge is associated with a high SVI. However, there is no generally accepted 'critical value' above which bulking sludge occurs, *i.e.* in the sense that it causes settler failure.
- In the Netherlands for instance, an SVI above 120 ml/g is already considered bulking sludge.

Causes and remediation of bulking sludge (solutions 10.4.4-10.4.7)

Solution 10.4.4

- *Diffusion-based selection theory.*
  Filamentous bacteria can easily grow outside the flocs, which means that the filamentous bacteria observe a higher substrate concentration than the floc-formers inside the floc. As a result, diffusion-dominated conditions (*i.e.*, low substrate concentrations) typically result in the growth of open, filamentous structures.
- *Kinetic selection theory.*
  This theory regards filamentous microorganisms as K strategists, *i.e.,* characterized by a higher affinity (lower affinity constant K_S) and a lower maximum growth rate than floc-forming bacteria, the latter being r strategists. In systems where the substrate concentration is low (typically $C_S < K_S$), as in continuously-fed completely mixed systems, filamentous bacteria have a higher specific growth rate than floc-forming bacteria, and thereby win the competition for substrate. In systems where the substrate concentration is high, as in plug-flow reactors and sequencing batch reactor (SBR) systems, floc-forming bacteria will dominate.
- *Relation between diffusion-based selection theory and kinetic selection theory.*
  K_S is typically used in activated sludge processes as an apparent mass transfer parameter, lumping substrate affinity and diffusion resistance. As such, the kinetic selection theory and the diffusion-based selection theory effectively both describe growth limited by diffusion at low substrate concentration. Indeed, the lower mass transfer resistance experienced by filamentous bacteria will translate into a lower K_S, classifying them as K strategists.

Solution 10.4.5

Microorganisms generally store substrate under high substrate concentrations, certainly when they undergo feast/famine conditions as usually occurs in a wastewater treatment plants. Non-filamentous (floc-forming) microorganisms are traditionally supposed to have a higher storage ability than filamentous ones. The storage ability gives them a competitive advantage in highly dynamic activated sludge systems such as plug-flow reactors, SBR and selector systems. Even though storage and regeneration may not be prime selection factors against filamentous bacteria, they do play a key role in selector-like systems because the high loading conditions and plug-flow conditions to prevent diffusion limitations also induce the storage response by the floc-forming bacteria. The prime selection factors for filamentous bacteria causing bulking sludge are generally accepted to be diffusion-based and/or kinetic selection (see Exercise 10.4.8).

Solution 10.4.6

- Non-specific methods comprise the use of oxidants to destroy filamentous bacteria causing bulking sludge. Examples are chlorination, ozonation and the application of hydrogen peroxide. They do not specifically target filamentous bacteria but make use of the fact that filamentous bacteria are placed mostly outside the floc and are therefore more susceptible to oxidants than the floc-forming bacteria.
- Drawbacks: (*i*) non-specific methods do not remove the causes for the excessive growth of filamentous microorganisms and their effect is therefore only transient; (*ii*) when using oxidants, there are environmental and ecotoxicological concerns about the potential formation of undesirable by-products such as halogenated organic components, and (*iii*) other micro-organisms could also be affected by the

oxidants, given that this method is non-specific. If slow-growing bacteria such as nitrifiers were to be affected, they would take a long time to recover, resulting in a suboptimal effluent quality.

Solution 10.4.7

- Specific methods are preventive methods which favour the growth of floc-forming bacteria at the expense of filamentous bacterial structures. Finding the right environmental conditions to achieve this is a challenge in activated sludge plants, but when successful, it enables the permanent control of bulking sludge.
- Preventive actions are based on the idea that the substrate conversion should not be limited by diffusion. This requires that readily biodegradable substrates are consumed at high substrate concentrations, such that the substrate uptake rate is close to its maximum value (at least $q_s/q_{smax} > 0.6$ and preferably $q_s/q_{smax} > 0.8$). In addition, the oxygen concentration should also be non-limiting (typically $O_2 > 1$ mg/l), at least during the period where readily biodegradable substrate is available. This is largely ensured by a properly designed plug flow or compartmentalized selector tank.

Selectors to control bulking sludge - relation with granular sludge (solutions 10.4.8-10.4.10)

Solution 10.4.8

In order to ensure that substrate conversion is not limited by diffusion and thus prevent bulking sludge, a high uptake rate and (almost) complete removal of readily biodegradable organics should be established in the entrance part of the activated sludge process. This initial part of the biological reactor, characterized by a plug-flow hydraulics (*i.e.,* a low dispersion number) and by an adequate macro-gradient of substrate, is termed the selector. The selector can also be a small initial zone of the reactor which receives the influent and sludge return flows, as long as it leads to a high uptake rate and almost complete removal of readily biodegradable organics.

Solution 10.4.9

- Selectors need to consist of at least three compartments to ensure sufficient plug-flow behaviour.
- Selectors can be aerobic, but also anoxic or anaerobic. In an aerobic selector, the oxygen concentration should be sufficiently high ($O_2 > 2$mg/l) as verified with an oxygen sensor in the first compartment. The entrance of oxygen into anoxic or anaerobic selectors needs to be avoided at all times. A low DO in the selector leads to oxygen gradients and growth of filamentous bacteria (low DO bulking).
- The sludge loading rate (SLR, kgCOD/kgTSS.d) needs to be kept close to a prescribed value[1], which depends on the selector type (higher SLR for aerobic than for anoxic selectors, not specified for an anaerobic one) and decreases along the selector path (highest SLR in the first selector compartment). The SLR needs to be high enough to avoid substrate limitation and low enough to enable full conversion of readily biodegradable substrate.
- The contact time needs to be kept within a certain prescribed range[1], which depends on the selector type (increases for aerobic $\geq$ anoxic $\geq$ anaerobic), load, temperature and influent readily biodegradable COD fraction. The contact time needs to be sufficiently long to ensure complete conversion of readily biodegradable substrate. On the other hand, too long contact times may result in a too low concentration of substrate, favouring the growth of filamentous microorganisms.
- For an aerobic selector, the floc loading (in kgCOD/kgTSS) needs to be in a certain range[1].
- The design of an anoxic selector is primarily based on the ratio of readily biodegradable organics to nitrate (RBCOD / NO_3^--N), which needs to be higher than the typical value for direct denitrification, taking into

[1] Values and ranges are specified in the examples 10.3.1-10.3.3.

account that an important fraction of readily biodegradable COD is converted into storage products. Nitrate needs to be in surplus in the anoxic reactor, even though periods with temporarily anaerobic conditions are not harmful.

- For anaerobic selector design, the ratio of readily biodegradable COD (VFA and fermentable COD) to phosphate needs to be kept within a certain range to make sure that hardly any readily biodegradable COD enters the main aeration basin.
- For anaerobic selector design, the main criterion is that readily biodegradable COD (VFA and fermentable COD) is fully converted under anaerobic conditions.
- Mixing conditions in anoxic and anaerobic conditions are not critical. Also, carry-over of readily biodegradable organics into the aerated stage is much less detrimental than in aerobic conditions. This is based on the experimental work by Martins (2004).

Solution 10.4.10

Aerobic granular sludge is the opposite phenomenon to bulking sludge. Granular sludge is formed when substrate conversion is not limited by diffusion. For aerobic granules to be formed, the removal of readily biodegradable organics should take place with minimal substrate gradients over the sludge floc or under fully anaerobic conditions. Anaerobic selectors are particularly suitable to promote aerobic granular sludge formation since they select phosphate and glycogen accumulating bacteria (PAO and GAO), given that ordinary heterotrophic filamentous bacteria are unable to grow under anaerobic conditions. The relatively low maximum growth rates of PAO and GAO result in lower substrate and oxygen uptake rates, which means that substrate/oxygen uptake rather than diffusion is the rate-limiting-step. Moreover, diffusion limitation is minimized since growth takes place on substrate stored within the cell.

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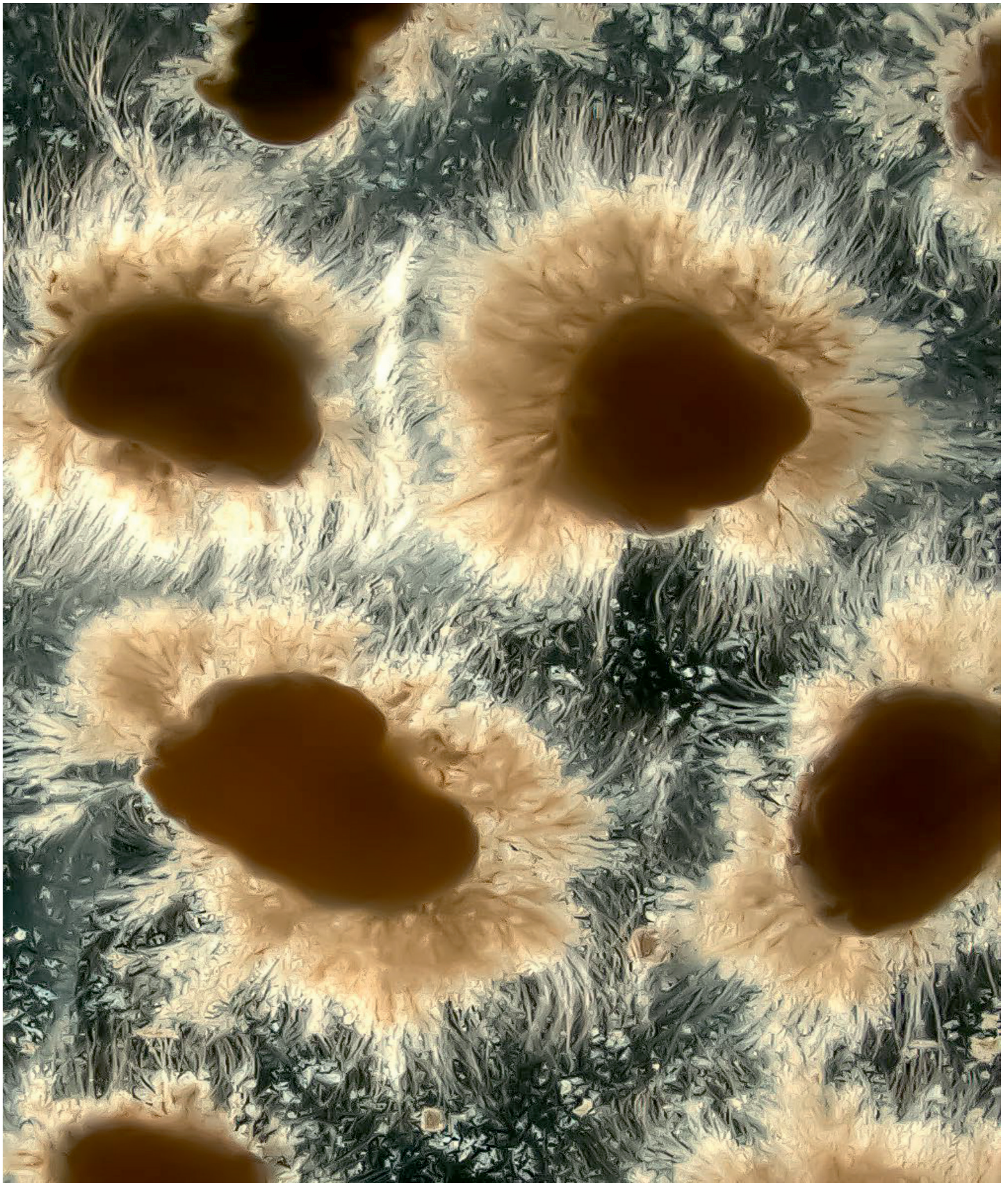
NOMENCLATURE

Abbreviation	Description
DO	Dissolved oxygen
RBCOD	Readily biodegradable COD
SRT	Sludge retention time (sludge age)
SLR	Sludge loading rate
SVI	Sludge volume index
TSS	Total suspended solids
VFAs	Volatile fatty acids
VSS	Volatile suspended solids
TSS	Total suspended solids

Symbol	Description	Unit
a	Mixed liquor recycle ratio (Q_a / Q_{in})	-
$COD_{b,in}$	Influent biodegradable COD concentration	$kgCOD/m^3$
COD_{in}	Influent total COD concentration	$kgCOD/m^3$
C_S	Substrate concentration	g/m^3
f_{SS}	Influent readily biodegradable fraction of the influent biodegradable COD	-
$f_{SU,CODin}$	Soluble unbiodegradable fraction of total influent COD	-
$f_{XU,CODin}$	Particulate unbiodegradable fraction of total influent COD	-
f_{XT}	Unaerated sludge mass fraction in the reactor	-
f_{VT}	Ratio of VSS over TSS of the sludge	gVSS/gTSS
$FCOD_{b,in}$	Daily load of influent biodegradable COD	kgCOD/d
$FCOD_{in}$	Daily load of influent COD	kgCOD/d
$FCOD_i$	Daily load of COD on the i^{th} selector compartment	kgCOD/d
$FRBCOD_{in}$	Daily load of influent readily biodegradable COD	kgCOD/d
$FRBCOD_i$	Daily load of readily biodegradable COD on the i^{th} selector compartment	kgCOD/d
HRT_a	Actual hydraulic retention time	d
K_S	Half-saturation constant for substrate	g/m^3
MX_{TSS}	Mass of solids in the bioreactor	kgTSS
$MX_{TSS,i}$	Mass of solids in the i^{th} selector compartment	kgTSS
$P_{IN,in}$	Influent orthophosphate concentration	gP/m^3
Q_a	Mixed liquor recycle flow rate = internal recycle flow rate	m^3/d
Q_{in}	Influent flow rate	m^3/d
Q_s	Sludge recycle flow rate	m^3/d
$RBCOD_{in}$	Influent readily biodegradable COD concentration	$kgCOD/m^3$
SRT	Sludge retention time	d
s	Sludge underflow recycle ratio (Q_s/Q_{in})	-
SLR	Sludge loading rate	kgCOD/kgTSS.d
SLR_i	Sludge loading rate of the i^{th} selector compartment	kgCOD/kgTSS.d
S_{NO3}	Nitrate concentration	kgN/m^3
TKN_{in}	Influent total Kjeldahl nitrogen (TKN) concentration	kgN/m^3
V_{Si}	Volume of the i^{th} selector compartment	m^3
V_R	Volume of bioreactor	m^3



Low concentrations of RBCOD in the influent may even lead to filamentous outgrowth in aerobic granular sludge when also the oxygen transport rate to the biofilm is limiting. This dual oxygen and COD limitation have a negative impact on the settling rate, stability and process performance. This problem has been overcome in Nereda® technology by applying an anaerobic feed of sewage allowing full uptake of readily degradable COD before aeration starts (photo: M. de Kreuk).