doi: 10.2166/9781789062304_0357

11

Aerobic granular sludge

Laurence Strubbe, Merle de Kreuk, Edward J.H. van Dijk, Mark C.M. van Loosdrecht and Eveline I.P. Volcke

11.1 INTRODUCTION

Chapter 11 on aerobic granular sludge (AGS) in the main textbook *Biological Wastewater Treatment: Principles, Modelling and Design* (Chen *et al.,* 2020) introduces the principles, underlying processes, the functionality of the (biological) mechanisms and the implementation of AGS design in different situations. The examples, questions and exercises given here will guide you through the procedures and considerations related to AGS reactor design, operation, and control. An appropriate process control shows how the daily variations in batches are handled by adjusting the batch length and the scheduling.

The questions relate to the general background of the AGS system, the principles of the formation of AGS and how this is translated into the reactor operation. In addition, this chapter relates the dynamics of a typical cycle to the biological conversions in the granules. The influence of process operation conditions and influent characteristics are also discussed in order to achieve a nitrification/denitrification process that is balanced at all times. Fluctuations and control options are identified. Finally, resource recovery aspects are addressed.

11.2 LEARNING OBJECTIVES

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

- Identify the main characteristics of aerobic granular sludge processes and the differences with respect to conventional activated sludge processes.
- Discuss the prerequisites for the granulation process and the selection of aerobic granular sludge.
- Interpret the dynamics of a typical cycle: aerated/non-aerated periods, corresponding processes, and spatial distribution (substrate, redox zones, etc.) in the granules.

© 2023 Laurence Strubbe. This is an Open Access book chapter distributed under a Creative Commons Attribution Non Commercial 4.0 International License (CC BY-NC-ND 4.0), (https://creativecommons.org/licenses/by-nc-nd/4.0/). The chapter is from the book *Biological Wastewater Treatment: Examples and Exercises*, Carlos M. Lopez-Vazquez, Damir Brdjanovic, Eveline I.P. Volcke, Mark C.M. van Loosdrecht, Di Wu and Guanghao Chen (Eds).

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

- Quantify conversion rates in aerobic granular sludge processes for typical influent characteristics and reactor operating conditions.
- Quantify and interpret the influence of process operation conditions (dissolved oxygen concentration, temperature) and influent characteristics (*e.g.*, VFA in influent) on organic matter and nutrient removal.
- Identify typical control strategies to account for influent flow and composition dynamics.
- Dimension and compare an aerobic granular sludge plant with and without a buffer tank for given influent characteristics.
- Apply the principle of batch scheduling in a typical example.
- Describe resource recovery options for AGS plants.

11.3 EXAMPLES

Additional information A1: Design of an AGS reactor based on hydraulic constraints
Two hydraulic constraints need to be considered for the design of an aerobic granular sludge (AGS) reactor.

1) The first hydraulic constraint relates to the volume exchange ratio (VER, in %), *i.e.*, the ratio between the volume fed during a new batch cycle (V_{batch}, in m^3) and the total reactor volume ($V_{reactor}$, in m^3):

$$VER = V_{batch} / V_{reactor} \cdot 100\ \% \tag{11.1}$$

in which:

$$V_{batch} = Q \cdot t_{feed} \tag{11.2}$$

with

Q = Influent flow rate (m^3/h)
t_{feed} = Feeding phase duration (h)

The VER is limited to a maximum value, VER_{max} = 65 %, to prevent the influent being mixed with effluent during the (plug-flow) feeding phase:

$$VER \leq VER_{max} = 65\ \% \tag{11.3}$$

The hydraulic constraint regarding the VER is typically applied to determine the minimum reactor volume or at least to check whether the given reactor volume meets the hydraulic constraint.

2) The second hydraulic constraint deals with the upflow velocity in the reactor (v_{upflow}, in m/h):

$$v_{upflow} = \frac{Q}{\frac{V_{reactor}}{H}} \tag{11.4}$$

in which:

H = Reactor height (m)

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

The upflow velocity in the reactor is limited to a maximum value of 5 m/h (Eq. 11.5) to prevent sludge being spilled into the effluent during plug-flow feeding:

$$v_{upflow} \leq 5 \text{ m/h} \tag{11.5}$$

Eq. 11.5 is typically applied to determine the reactor height for a given reactor volume. This condition needs to be fulfilled under all conditions, so it is evaluated under peak wet weather conditions as the worst-case scenario.

Eq. 11.3 and Eq. 11.5 thus constitute the two hydraulic constraints that need to be fulfilled in the design of an AGS reactor.

Additional information A2: Design of an AGS reactor based on biological constraints
In addition to the hydraulic constraints, there is also a biological constraint which needs to be fulfilled for the design of an AGS reactor, namely regarding the sludge loading rate.

The sludge loading rate (SLR, kgCOD/kgTSS.d) is calculated by Eq. 11.6 (rearrangement of Eq. 11.7 from Chen *et al.*, 2020):

$$SLR = \frac{Q \cdot COD}{\frac{t_{react,day}}{24} \cdot X_{TSS} \cdot V_{reactor} \cdot n_{reactor}} \tag{11.6}$$

in which:

COD = Influent COD concentration (kgCOD/m^3)
$t_{react,day}$ = Total reaction time per day (h)
X_{TSS} = Mixed liquor suspended solids or sludge concentration (kgTSS/m^3)
$n_{reactor}$ = Number of reactors (-)

The sludge loading rate needs to be limited to 0.4 kgCOD/kgTSS.d at moderate temperatures to ensure that nitrification takes place:

$$SLR \leq 0.4 \text{ kgCOD/kgTSS.d} \tag{11.7}$$

Example 11.3.1

Design and upgrading of an AGS system without a buffer tank

A new wastewater treatment plant needs to be built to serve 300,000 people equivalent (PE), taking into a wastewater production of 150 L/d.PE, a daily peak flow factor of 1.5 (S_F^{PDWF}) and a wet weather peak flow factor (S_F^{PWWF}) of 3.0. The incoming wastewater has a COD concentration of 500 g/m^3.

It has been decided to build an AGS system without a buffer tank, operated in batch mode. The feeding phase (t_{feed}) takes 60 minutes, the aeration phase ($t_{aeration}$) 140 minutes and the settling phase ($t_{settling}$) 20

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

minutes. The schedule for the settling phase holds during average dry weather flow (DWF) as well as peak dry weather flow (PDWF) conditions.

The task is to answer the following questions:

a) Calculate the dry weather flow rate (Q_{DWF}), peak dry weather flow rate (Q_{PDWF}) and peak wet weather flow rates (Q_{PWWF}) (all in m^3/h). With this information, determine the reactor volume (for one AGS reactor) based on the hydraulic constraint concerning the volume exchange ratio.
b) Calculate the number of AGS reactors required.
c) Calculate the sludge loading rate (SLR, in kgCOD/kgTSS.d) in the reactors, for the average dry weather flow as well as the daily peak flow. To do this, assume a typical total suspended sludge concentration in the reactor.
d) Is this sludge loading rate low enough for nitrification to take place during increased temperatures of 25 °C?
e) Calculate the maximum upflow velocity in the reactor, assuming a reactor height of 8 m. Evaluate the obtained value.
f) Do you recommend any adjustments in the design or operation?

Once the AGS system has been constructed, the situation in the catchment area changes: an additional sewer system, characterised by a very high peak wet weather flow (PWWF) over dry water flow rate (DWF), is connected to this treatment plant. As a result, the average daily flow rate increases to 2,200 m^3/h, while the peak wet weather flow increases to 8,800 m^3/h.

g) Describe the consequences of these increased flow rates and envisage in a qualitative way what could be done to be able to treat all of the influent?

Solution

a) Reactor volume

The dry weather flow rate (Q^{DWF}) is the average collected sewage flow rate during periods without rain, consisting of wastewater from households as well as industrial effluents. It is calculated by Eq. 11.8.

$$Q^{DWF} = 150 \cdot 10^{-3}\ m^3/d.PE \cdot 300{,}000\ PE \cdot (1/24)\ d/h = 1{,}875\ m^3/h \quad (11.8)$$

The peak dry weather flow rate or daily peak flow rate (Q^{PDWF}) is the maximum flow rate during one day, which is calculated by multiplying the dry weather flow rate with the peak flow factor (Eq. 11.9):

$$Q^{PDWF} = S_F^{PDWF} \cdot Q^{DWF} \quad (11.9)$$

which in this case becomes:

$$Q^{PDWF} = 1.5 \cdot 1{,}875\ m^3/h = 2{,}813\ m^3/h \quad (11.10)$$

The peak wet weather flow rate (Q^{PWWF}) is the peak flow rate during rainy weather, which determines the maximum hydraulic load expected to reach the wastewater treatment plant. The peak wet weather flow rate is calculated from the dry weather flow rate and the wet weather peak flow factor (Eq. 11.11):

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

$$Q^{PWWF} = S_F^{PWWF} \cdot Q^{DWF} \tag{11.11}$$

In this case:

$$Q^{PWWF} = 3 \cdot 1{,}875\ m^3/h = 5{,}625\ m^3/h \tag{11.12}$$

Taking into account the hydraulic constraint concerning the VER (Eq. 11.3), the definition of VER (Eq. 11.1), the reactor volume is determined by Eq. 11.13:

$$V_{reactor} \geq V_{batch} \cdot 100\ \% / 65\ \% \tag{11.13}$$

which, taking into account Eq.11.2, is equivalent to Eq. 11.14:

$$V_{reactor} \geq Q \cdot t_{feed} \cdot 100\ \% / 65\ \% \tag{11.14}$$

The feeding phase duration (t_{feed}) is fixed at 1 hour during DWF and PDWF conditions. The corresponding volume fed during a cycle (V_{batch}, Eq. 11.2) is the highest under PDWF conditions, and so is the corresponding minimum reactor volume.

As a result, the reactor volume is calculated from Eq. 11.14 for PDWF conditions, as:

$$V_{reactor} = Q^{PDWF} \cdot t_{feed} \cdot 100\ \% / 65\ \% = 2{,}813\ m^3/h \cdot 1\ h / 0.65 = 4{,}328\ m^3 \approx 4{,}500\ m^3 \tag{11.15}$$

Setting the reactor volume at 4,500 m^3 to comply with the peak dry weather flow, the VER during average dry weather is calculated (from Eq. 11.1 and Eq. 11.2) as:

$$VER = V_{batch}^{DWF} / V_{reactor} \cdot 100\ \% = Q^{DWF} \cdot t_{feed} / V_{reactor} \cdot 100\ \% = 1{,}875\ m^3/h \cdot 1\ h / 4{,}500\ m^3 = 42\ \% \tag{11.16}$$

A VER of 42 % during the average dry weather flow would be appropriate and ensures that during the daily peak flow, the effective VER will stay within the hydraulic limits of 65 %. However, during peak wet weather conditions, the feeding time will need to be reduced to maintain the VER below the maximum value of 65 %.

b) <u>Number of reactors</u>

The number of reactors is determined by taking into account that feeding is continuous, so:

$$n_{reactors} \cdot t_{feed} = t \tag{11.17}$$

in which t denotes the total cycle duration (h), which equals to:

$$t = t_{feed} + t_{react} + t_{settle} \tag{11.18}$$

Where:

t_{react} = Reaction phase duration (h)
t_{settle} = Time for sludge settling (h)

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

By combining Eq. 11.17 and Eq. 11.18, the required number of reactors is determined as:

$$n_{reactors} = \frac{t}{t_{feed}} = \frac{t_{feed} + t_{react} + t_{settle}}{t_{feed}} \tag{11.19}$$

In this case:

$$n_{reactors} = \frac{(60 + 140 + 20)\,\text{min}}{60\,\text{min}} = 3.67 \tag{11.20}$$

The resulting number needs to be rounded to the highest whole number, so at least four reactors are required to ensure the influent can be fed to one of the reactors.

c) <u>Sludge loading rate</u>
The sludge loading rate is calculated by Eq. 11.6.

$$SLR = \frac{Q \cdot COD}{\frac{t_{react,day}}{24} \cdot X_{TSS} \cdot V_{reactor} \cdot n_{reactor}} \tag{11.6}$$

A typical MLSS concentration for granular sludge is:

$$X_{TSS} = 8\ \text{kgTSS/m}^3 \tag{11.21}$$

The total reaction time per day is calculated by Eq. 11.22:

$$t_{react,day} = n_{cycles} \cdot t_{react} \tag{11.22}$$

where n_{cycles} denotes the number of cycles per day and per reactor (-), which is determined by Eq. 11.23:

$$n_{cycles} = \frac{24}{t} = \frac{24}{t_{feed} + t_{react} + t_{settle}} \tag{11.23}$$

In this case:

$$n_{cycles} = \frac{24\ \text{h/d}}{(60 + 140 + 20)\,\text{min}} \cdot 60\ \text{min/h} = 6.5\ \text{cycles/d} \tag{11.24}$$

The total reaction time per day is thus calculated (by substituting Eq. 11.24 in Eq. 11.22) as:

$$t_{react.day} = \frac{6.5\ \text{cycles/d} \cdot 140\ \text{min/cycle}}{60\ \text{min/h}} = 15\ \text{h/d} \tag{11.25}$$

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

With this information, the sludge loading rate at average dry weather flow is calculated (by substituting Eq. 11.25 and Eq. 11.21 in Eq. 11.6) as:

$$SLR^{DWF} = \frac{1{,}875\ m^3/h \cdot 24\ h/d \cdot 500\ gCOD/m^3}{\frac{15\ h/d}{24\ h/d} \cdot 8{,}000\ gTSS/m^3 \cdot 4{,}500\ m^3 \cdot 4} = 0.25\ kgCOD/kgTSS.d \tag{11.26}$$

while the sludge loading rate at daily peak flow becomes:

$$SLR^{PDWF} = \frac{2{,}813\ m^3/h \cdot 24\ h/d \cdot 500\ gCOD/m^3}{\frac{15\ h/d}{24\ h/d} \cdot 8{,}000\ gTSS/m^3 \cdot 4{,}500\ m^3 \cdot 4} = 0.38\ kgCOD/kgTSS.d \tag{11.27}$$

d) Biological constraint

Nitrification occurs for sludge loading rates up to 0.4 kgCOD/kgTSS.d at moderate temperatures, while higher temperatures can enable nitrification even under higher loading rates. In this example, the SLR in average dry weather conditions and in peak dry weather conditions are both lower than 0.4 kgCOD/kgTSS.d, which means that the biological constraint is definitely fulfilled during elevated temperatures. Therefore, in this example, the hydraulic constraint set by VER_{max} = 0.65 % (Eq. 11.3) is more limiting than the biological constraint.

e) Maximum upflow velocity

The maximum upflow velocity is reached under peak wet weather conditions and is calculated from Eq. 11.4:

$$v_{upflow} = \frac{Q_{PWWF}}{\frac{V_{reactor}}{H}} = \frac{5.625\ m^3/h}{\frac{4{,}500\ m^3}{8\ m}} = 10\ m/h \tag{11.28}$$

The upflow velocity exceeds the maximum of 5 m/h imposed by the hydraulic constraint Eq. 11.5.

f) Adjustments in design and operation

In order to meet the hydraulic constraint regarding the maximum upflow velocity during peak wet weather conditions and thus make sure that no sludge is spilled into the effluent during rainy weather, one option would be to increase either the reactor aspect ratio (*i.e.*, the ratio between the reactor height and diameter) or the AGS reactor volume. The maximum allowable reactor height is determined by construction restrictions and typically does not exceed 10-12 meters. Assume that the reactor height needs to be kept at 8 m in this example; therefore, the reactor volume would need to be doubled to meet the hydraulic constraint Eq. 11.5, since the maximum upflow velocity is twice as high as allowed. Alternatively, a buffer tank could be installed. Both these solutions would entail a significant cost increase.

An alternative would be to change the reactor operation instead of the design. During periods of intense rainfall, two reactors could be fed at the same time (lowering Q^{PWWF} in Eq. 11.28 and thus v_{upflow}). Feeding two reactors at the same time would imply shorter reaction times (to ensure that the four AGS reactors in this example remain sufficient to keep a continuous feeding, see Eq. 11.19), which is possible during PWWF conditions because of the lower concentrations.

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

g) Consequences of increased flow rates

The average daily flow rate has increased from Q^{DWF} = 1,875 m^3/h to 2,200 m^3/h, while the peak wet weather flow rate has increased from Q^{PWWF} = 5,625 m^3/h to 8,800 m^3/h. Given the absence of additional data, we assume that the daily peak flow factor remains at S_F^{PDWF} = 1.5, so the daily peak flow has become Q^{PDWF} = 1.5 · 2,200 m^3/h = 3,300 m^3/h. The consequences of these increased flow rates are investigated by checking the hydraulic and biological constraints for this changed situation. The volume exchange ratio under daily peak flow conditions becomes:

$$VER^{PDWF} = \frac{Q \cdot t_{feed}}{V_{reactor}} \cdot 100\ \% = \frac{3{,}300\ m^3/h \cdot 1\ h}{4{,}500\ m^3} \cdot 100\ \% = 73\ \% \tag{11.29}$$

which exceeds the imposed maximum of 65 %.

However, the upflow velocity in the reactor at peak wet weather flow conditions was already too high for the initial situation (Eq. 11.28) and now becomes even higher:

$$v_{upflow}^{PWWF} = \frac{Q_{PWWF}}{\frac{V_{reactor}}{H}} = \frac{8{,}800\ m^3/h}{\frac{4{,}500\ m^3}{8\ m}} = 15.6\ m/h \tag{11.30}$$

This exceeds the maximum of 5 m/h imposed by the hydraulic constraint Eq. 11.5 by a factor of over 3. Even in peak dry weather flow conditions, the upflow velocity in the reactor is too high:

$$v_{upflow}^{PDWF} = \frac{Q_{PDWF}}{\frac{V_{reactor}}{H}} = \frac{3{,}300\ m^3/h}{\frac{4{,}500\ m^3}{8\ m}} = 5.9\ m/h \tag{11.31}$$

In addition, the corresponding SLR at peak dry weather conditions is calculated as:

$$SLR^{PDWF} = \frac{3{,}300\ m^3/h\ \cdot\ 24\ h/d\ \cdot\ 500\ gCOD/m^3}{\frac{15\ h/d}{24\ h/d} \cdot 8{,}000\ gTSS/m^3 \cdot 4{,}500\ m^3 \cdot 4} = 0.46\ kgCOD/kgTSS.d \tag{11.32}$$

which is too high to ensure good nitrification performance in moderate temperatures.

Overall, it is clear that this situation violates both the hydraulic constraints as well as the biological constraint. Even though it would still be possible to feed two AGS reactors at the same time during PWWF conditions, while shortening the reaction phase length, this is not likely to be sufficient to meet all the constraints. Indeed, a shorter reaction phase length makes the relative time spent on feeding longer, which in its turn leads to an increased volume exchange ratio, which was already too high.

Alternatively, a buffer tank or an extra AGS reactor could be added to the plant to overcome all the constraints during PDWF conditions. The installation of a buffer tank, which ensures a good effluent quality at all times, is the preferred option during short intense rainfall when equalisation of the flow rate is required.

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

Example 11.3.2

Design of an AGS system – influence of a buffer tank

An AGS system is constructed to treat wastewater characterised by a dry weather flow rate of 3,250 m^3/h, a daily peak factor S_F^{PDWF} =1.8, and a peak wet weather flow of 12,000 m^3/h. The design needs to fulfil the following two requirements in average dry weather conditions: (*i*) a maximum volume exchange (VER) ratio of 35 % and (*ii*) the maximum volumetric loading rate needs to be 1.2 $m^3/m^3.d$. The time schedule during dry weather flow is t_{feed} = 60 min, t_{react} = 300 min and t_{settle} = 20 min.

The task is to perform the following:

a) Determine the minimal volume for each reactor and the total number of AGS reactors (without a buffer tank) based on the given requirements (*i*) and (*ii*). Indicate the relation with the previously defined hydraulic and biological constraints (Eq. 11.3 and Eq. 11.7, respectively).
b) Calculate the resulting VER of the reactor during dry weather flow, daily peak flow and peak wet weather flow conditions. Determine the maximum flow rate to maintain the same cycle time with a maximum VER of 65 %. Also calculate the volumetric loading rate for each case. How do you expect the sludge loading rates to vary?
c) In order to maintain a sufficient quality of the effluent, the VER needs to be kept below 65 % and the volumetric loading rate below 3.5 $m^3/m^3.d$ during wet weather peak flow conditions, while keeping the reactor volume and the number of reactors. Therefore, the batch schedule must be changed. Recalculate the cycle time (t), feeding time (t_{feed}) and reaction time (t_{react}) to meet these PWWF conditions.
d) To use the reactor volume more efficiently, the number of AGS reactors is reduced to four and a buffer tank is built instead. Calculate the required buffer tank volume to be able to deal with PWWF conditions, keeping the batch schedule determined under c).

Solution

a) <u>Reactor volume and number of reactors</u>

Based on the hydraulic constraint of VER = 35 % during DWF conditions, the reactor volume is determined (by substituting Eq. 11.3 in Eq. 11.1, after rearrangement) as:

$$V_{reactor} = \frac{V_{batch}^{DWF}}{VER_{max}} = \frac{Q^{DWF} \cdot t_{feed}}{100\ \%\ /\ 65\ \%} = \frac{3,250}{0.35} = 9,286\ m^3 \tag{11.33}$$

The corresponding VER under daily peak flow conditions amounts to:

$$\begin{aligned} VER &= \frac{V_{batch}^{PDWF}}{V_{reactor}} \cdot 100\ \% = \frac{Q^{PDWF} \cdot t_{feed}}{V_{reactor}} \cdot 100\ \% \\ &= \frac{S_F^{PDWF} \cdot Q^{DWF} \cdot t_{feed}}{V_{reactor}} \cdot 100\ \% = 1.8 \cdot 0.35 \cdot 100\ \% = 63\ \% \approx 65\ \% \end{aligned} \tag{11.34}$$

So the given requirement of a minimal volume exchange ratio of 35 % under average dry weather conditions will ensure a minimum volume exchange ratio of 65 % under daily peak flow conditions, given S_F^{PDWF} = 1.8. Thus in this case, the hydraulic constraint Eq. 11.33 for DWF conditions is equivalent to the hydraulic constraint Eq. 11.3 for PDWF conditions.

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

The volumetric loading rate (VLR, in $m^3/m^3.d$) is determined by Eq. 11.35:,

$$VLR = \frac{Q}{\frac{t_{react,day}}{24} \cdot V_{reactor} \cdot n_{reactor}} \tag{11.35}$$

and should adhere to:

$$VLR \leq 1.2 \text{ m}^3/\text{m}^3.\text{d} \tag{11.36}$$

The minimum reactor volume resulting from Eq. 11.35 and Eq. 11.36 is determined by Eq. 11.37:

$$V_{reactor} = \frac{Q}{\frac{t_{react,day}}{24} \cdot VLR \cdot n_{reactor}} \tag{11.37}$$

The total reaction time per day is calculated from Eq. 11.22, which requires the knowledge of the number of cycles per day and per reactor (Eq. 11.23). In this example,

$$n_{cycles} = \frac{24 \text{ h/d}}{(600 + 300 + 20)\,\text{min}} \cdot 60 \text{ min/h} = 3.8 \text{ cycles/d} \tag{11.38}$$

$$t_{react,day} = \frac{3{,}8 \text{ cycles/d} \cdot 300 \text{ min/cycle}}{60 \text{ min/h}} = 19 \text{ h/d} \tag{11.39}$$

The number of reactors is calculated from Eq. 11.19 as:

$$n_{reactors} = \frac{(600 + 300 + 20)\,\text{min}}{60\,\text{min}} = 6.3 \tag{11.40}$$

At least 7 reactors are required to maintain a continuous feeding.

The volume of each reactor is calculated from Eq. 11.36 as:

$$V_{reactor} = \frac{3{,}250 \text{ m}^3/\text{h} \cdot 24 \text{ h/d}}{\frac{19 \text{ h}}{24 \text{ h/d}} \cdot 1.2 \text{ 1/d} \cdot 7} = 11{,}729 \text{ m}^3 \approx 12{,}000 \text{ m}^3 \tag{11.41}$$

The obtained volume based on the VER_{max} (Eq. 11.41) is larger than the one based on the maximum allowed VLR (Eq. 11.33) which means that in this example, the biological constraint is more limiting than the hydraulic constraint of the applied VER during DWF.

The final layout comprises 7 AGS reactors which each have a minimum volume of 12,000 m^3.

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

Note that the volumetric loading rate (Eq. 11.35) combines the sludge loading rate (SLR, in kgCOD/kgTSS.d, Eq. 11.6) with the reactor MLSS concentration (X_{TSS}, in kgTSS/m^3) and the influent COD concentration (kgCOD/m^3), according to Eq. 11.42:

$$VLR = SLR \cdot \frac{X_{TSS}}{COD} \tag{11.42}$$

Given the influent COD concentration of 500 g/m^3 and assuming a typical MLSS concentration of X_{TSS} = 8 kgTSS/m^3 for an AGS reactor, the requirement to maintain the VLR below 1.2 m^3/m^3.d (Eq. 11.36) is equivalent to:

$$VLR = SLR \cdot \frac{COD}{X_{TSS}} \leq 1.2\ 1/d \cdot \frac{500\ gCOD/m^3}{8{,}000\ gTSS/m^3} = 0.075\ gCOD/gTSS.d \tag{11.43}$$

which is more stringent than Eq.11.7. However, the requirement VLR ≤ 1.2 m^3/m^3.d was imposed for average dry weather conditions. The corresponding SLR for peak flow conditions, given S_F^{PDWF} =1.8, amounts to:

$$SLR = VLR \cdot \frac{COD}{X_{TSS}} \leq 1.2\ 1/d \cdot 1.8 \cdot \frac{500\ gCOD/m^3}{8{,}000\ gTSS/m^3} = 0.14\ gCOD/gTSS.d \tag{11.44}$$

which is still more stringent than Eq. 11.7. So in this example, the biological constraint Eq. 11.36 for DWF conditions is more stringent than the biological constraint Eq. 11.3 for PDWF conditions.

b) Volume exchange ratios and volumetric loading rates

The volume exchange ratio is calculated from Eq. 11.1 and Eq. 11.2 as:

$$VER = \frac{V_{batch}}{V_{reactor}} \cdot 100\ \% = \frac{Q \cdot t_{feed}}{V_{reactor}} \cdot 100\ \% \tag{11.45}$$

The results for PWF, PDWF and PWWF conditions are summarized in Table 11.1. It is clear that the VER for DWF and PDWF conditions fulfils the hydraulic constraint Eq. 11.3, while the VER under PWWF is too high, which implies that the feeding time will need to be reduced to maintain the VER below the maximum value VER_{max} = 65 %. The maximum flow rate for which Eq. 11.3 holds is obtained by rearranging Eq. 11.45, as:

$$Q = \frac{VER_{max}}{100\ \%} \cdot \frac{V_{reactor}}{t_{feed}} \tag{11.46}$$

which is calculated for this example as 7,800 m^3/h and indicated in Table 11.1 as part of the maximum wet weather flow conditions (WWF_{max}).

The corresponding volumetric loading rates are calculated from Eq. 11.35; their values are summarized in Table 11.1. The VLR ranges from 1.2 to 4.3 m^3/m^3.d (DWF and PWWF conditions, respectively). The sludge loading rate is not expected to present equally large variations, since the influent will likely be diluted under

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

rainy weather conditions, implying a lower COD concentration, which compensates for the increasing flow rate, resulting in a relatively lower SLR (Eq. 11.6).

Table 11.1 Summary of calculations and results for Example 11.3.2. The values in black are given, and calculated values are denoted in blue. The calculations are provided in the spreadsheet 'Chapter 11 Design example 2.xlsx'.

	DWF	PDWF	PWWF	WWF_{max}	Unit
S_F	1	1.8	3.7		-
Q	3,250	5,850	12,025	7,800	m^3/h
VER	27	49	100	65	%
VLR	1.2	2.1	4.3	2.8	$m^3/m^3.d$

c) <u>Alternative constraints for VER and SLR</u>
Alternatively, it is required that the VER is maximum 65% under PWWF conditions:

$$VER^{PWWF} = \frac{V_{batch}^{PWWF}}{V_{reactor}} \cdot 100\ \% = \frac{Q^{PWWF} \cdot t_{feed}}{V_{reactor}} \cdot 100\ \% = 65\ \% \tag{11.47}$$

From Eq. 11.47, the feeding time is calculated as:

$$t_{feed} = \frac{VER_{max} \cdot V_{reactor}}{100\ \% \cdot Q^{PWWF}} = 0.65 \cdot \frac{12{,}000\ m^3}{12{,}025\ m^3/h} \cdot 60\ min/h = 39\ min \tag{11.48}$$

At the same time, the volumetric loading rate needs to be kept below 3.5 $m^3/m^3.d$ during PWWF conditions:

$$VLR^{PWWF} \leq 3.5\ m^3/m^3.d \tag{11.49}$$

The VLR is expressed by Eq. 11.35. However, it can also be alternatively expressed by Eq. 11.37:

$$VLR = \frac{VER_{max}}{100\% \cdot t_{reactor}} \tag{11.50}$$

The equivalence between Eq. 11.35 and Eq. 11.50 can be seen by substitution of Eq. 11.22 in Eq. 11.35:

$$VLR = \frac{Q}{n_{cycles} \cdot \frac{t_{reactor}}{24} \cdot V_{reactor} \cdot t_{reactor}} \tag{11.51}$$

followed by substitution of Eq. 11.23:

$$VLR = \frac{Q \cdot t}{t_{react} \cdot V_{reactor} \cdot n_{reactor}} \tag{11.52}$$

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

which is equivalent to:

$$VLR = \frac{Q \cdot t_{feed}}{t_{react} \cdot V_{reactor}} \tag{11.53}$$

and thus to Eq. 11.50.

From Eq. 11.50, the reaction time during PWWF for a maximum volumetric loading rate of 3.5 $m^3/m^3.d$ is determined by:

$$t_{react} = \frac{VER^{PWWF}}{100\% \cdot VLR^{PWWF}} \tag{11.54}$$

which is calculated for this example as:

$$t_{react} = \frac{65\ \%}{100\ \% \cdot 3.5\ 1/d} \cdot 24\ h/d \cdot 60\,min = 267\,min \tag{11.54}$$

The total cycle duration is calculated from Eq. 11.18 as:

$$t = 39\ min + 267\ min + 20\ min = 326\ min \tag{11.55}$$

d) <u>Buffer tank</u>

The buffer volume is calculated based on Eq. 11.8 from Chen *et al.* (2020), which in this example is applied for PWWF conditions, since the latter correspond to the highest flow that needs to be buffered:

$$V_{buffer} = \frac{Q^{PWWF}}{n_{reactor} \cdot n_{cycles}} - Q^{PWWF} \cdot \frac{t_{feed}}{24} \tag{11.56}$$

The number of AGS reactors was given as four and the number of cycles during PWWF is calculated from Eq. 11.23 and Eq. 11.55 as:

$$n_{cycles} = \frac{24}{t} = \frac{24\ h/d}{326\ min} \cdot 60\ min/h = 4.4\ per\ day \tag{11.57}$$

The required buffer volume thus becomes:

$$V_{buffer} = \frac{12{,}025\ m^3/h \cdot 24\ h/d}{4 \cdot 4.4\ m^3/m^3.d} - 12{,}025\ m^3/h \cdot \frac{39\ min}{60\ min/h} = 8{,}582\ m^3 \tag{11.58}$$

Example 11.3.3

Buffer tank operation

Consider an AGS plant consisting of 2 reactors of 6,000 m^3 each, with a height of 8 m. The total cycle time in dry weather conditions is 240 minutes, consisting of 60 minutes feeding (t_{feed}), 150 min reaction (t_{react}) and 30

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

minutes settling (t_{settle}). Each day one of the cycles starts at 08:00 hours. There is also a buffer tank installed to store the influent wastewater while it cannot be fed to one of the two reactors. Table 11.2 summarizes the daily flow variation reaching the AGS plant during the specified 1-hour time intervals.

Table 11.2 Specific flow rates reaching the aerobic granular sludge plant during dry weather (Q^{DWF}) and peak wet weather (Q^{PWWF}) conditions for a time interval of one hour over one day.

Start time	End time	Q^{DWF} (m^3/h)	Q^{PWWF} (m^3/h)
08:00	09:00	1,022	1,022
09:00	10:00	1,181	1,181
10:00	11:00	1,224	1,224
11:00	12:00	1,238	1,238
12:00	13:00	1,224	1,224
13:00	14:00	1,166	1,166
14:00	15:00	1,109	1,931
15:00	16:00	1,008	3,278
16:00	17:00	936	4,421
17:00	18:00	936	4,498
18:00	19:00	950	3,212
19:00	20:00	1,051	1,256
20:00	21:00	1,152	1,152
21:00	22:00	1,152	1,152
22:00	23:00	1,094	1,094
23:00	24:00	994	994
00:00	01:00	792	792
01:00	02:00	634	3,049
02:00	03:00	475	2,874
03:00	04:00	374	1,198
04:00	05:00	302	765
05:00	06:00	288	288
06:00	07:00	346	346
07:00	08:00	590	590

The following tasks should be carried out:

a) Visualize a logical batch schedule for the two reactors under dry weather conditions. Indicate when the flow needs to be stored.
b) What is the volume of the buffer tank that is used, based on the peak flow during dry weather?
c) The wastewater stored in the buffer tank is emptied each time in the subsequent cycle, adding to the influent flow rate. Calculate the feed flow rate in the 1-hour time interval following the largest buffered wastewater volume, as well as the upflow velocity and VER for the corresponding batch. Are they within the hydraulic limits, *i.e.,* do they fulfil the hydraulic constraints?
d) What is the effect of emptying the storage tank on the SLR? Assess in detail for the 1-hour time interval following the largest buffered wastewater volume.

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

The operator reported a summer thunderstorm event as described in the last column of Table 11.2.

e) Calculate the wastewater volumes fed and stored during the thunderstorm period (1 day), assuming that the wastewater stored in the buffer tank is emptied each time in the subsequent cycle, adding to the influent flow rate. Do the upflow velocity and VER during the thunderstorm event remain within the hydraulic boundaries?
f) How could the system operation be changed in order to meet the hydraulic constraints during these heavy thunderstorms while maintaining the batch schedule from under DWF conditions? How large should the corresponding buffer volume be? Depict the full 24 hours of batch scheduling.
g) Alternatively, could the hydraulic constraints be met by changing the batch schedule? What would be the impact on the required buffer volume? Do you see any other limitations?

Solution

a) <u>Batch schedule under dry weather conditions</u>

A logical batch schedule for the two reactors under dry weather conditions is provided in Figure 11.1 (see the spreadsheet 'Chapter 11 Design example 3.xlsx' on the sheet 'Schedule DWF'). The influent wastewater needs to be stored when one or both reactors are in the reaction or settling phase. Note that the two cycles of the two AGS reactors have been aligned so that the feeding phase of the second AGS reactors starts in the middle of the cycle of the first AGS reactor, *i.e.,* after 120 minutes.

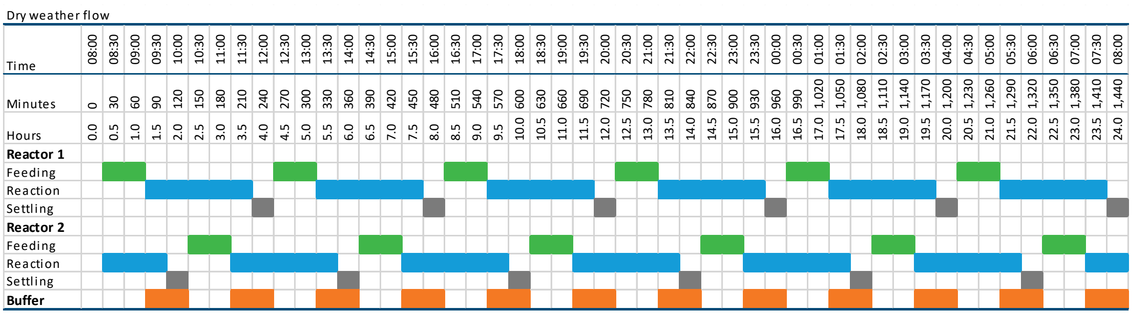

Figure 11.1 Batch schedule for the two AGS reactors under dry weather conditions - Example 11.3.3.

b) <u>Used volume of the buffer tank</u>

The buffered wastewater volume is calculated based on Eq. 11.56 (*i.e*., Eq. 11.8 from Chen *et al.*, 2020) for the highest flow rate during dry weather conditions. The highest flow rate is identified from Table 11.2 as $Q^{PDWF} = 1{,}238\ m^3/h$ and takes place between 11:00 and 12:00. The buffered volume becomes:

$$V_{buffer} = \frac{Q^{PWWF}}{n_{reactor} \cdot n_{cycles}} - Q^{PWWF} \cdot \frac{t_{feed}}{24} \qquad (11.59)$$

The number of cycles during dry weather conditions is calculated from Eq. 11.23 as:

$$n_{cycles} = \frac{24}{t} = \frac{24\ h/d}{240\,min} \cdot 60\ min/h = 6\ per\ day \qquad (11.60)$$

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

With this information, the buffered wastewater volume is calculated from Eq. 11.59 as:

$$V_{buffer} = \frac{1{,}238\ m^3/h \cdot 24\ h/d}{2 \cdot 6\ m^3/m^3.d} - 1{,}238\ m^3/h \cdot \frac{60\,min}{60\ min/h} = 1{,}238\ m^3 \tag{11.61}$$

c) <u>Maximum VER and upflow velocity</u>
An overview of the buffer tank operation under DWF conditions, together with the calculation of the VER and v_{upflow} at every feeding phase, is provided in the spreadsheet 'Chapter 11 Design example 3.xlsx' on the sheet 'Buffer operation DWF'. The volume fed in the 1-hour time interval following the largest stored buffer volume (1,238 m^3, from 11:00 until 12:00) amounts to 2,462 m^3 and is fed between 12:00 and 13:00.

The corresponding VER is calculated as:

$$VER = \frac{V_{batch}}{V_{reactor}} \cdot 100\ \% = \frac{Q^{PDWF} \cdot t_{feed}}{V_{reactor}} \cdot 100\ \% = \frac{2{,}462\ m^3/h \cdot 1\ h}{6{,}000\ m^3} \cdot 100\ \% = 41\ \% \tag{11.62}$$

which fulfils requirement Eq. 11.3.

The upflow velocity in the reactor becomes:

$$v_{upflow} = \frac{2{,}462\ m^3/h}{\frac{6{,}000\ m^3}{8\ m}} = 3.3 m/h \tag{11.63}$$

which adheres to Eq. 11.5. This implies that the hydraulic limits are not exceeded when emptying the buffer tank after the largest volume has been stored.

d) <u>Corresponding sludge loading rate</u>
The SLR is proportional to the flow rate (Eq. 11.6). Emptying the buffer tank during each feeding phase implies an increased feed flow rate compared to only feeding the incoming wastewater flow rate. As a result, the SLR also increases. In this example, no particular information is given on the incoming COD concentration, so it can be assumed that the incoming COD concentration is fairly constant. If the COD concentration is constant, the SLR increases linearly with the feed flow rate (Eq. 11.6).

As for the 1-hour time interval following the largest buffered wastewater volume, the feed flow rate amounts to 2,462 m^3/h, of which the influent flow rate amounts to 1,224 m^3/h. As a result, the SLR increases by a factor:

$$\frac{SLR_{influent+buffer}}{SLR_{influent}} = \frac{2{,}462\ m^3/h}{1{,}224\ m^3/h} = 2 \tag{11.63}$$

i.e., it doubles compared to the case where no stored wastewater is fed. This highlights the impact of processing buffered wastewater on the AGS reactor design.

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

e) Summer thunderstorm – PWWF conditions

An overview of the buffer tank operation under PWWF conditions, together with the calculation of VER and v_{upflow} at every feeding phase is provided in the spreadsheet 'Chapter 11 Design example 3.xlsx' on the sheet 'Buffer operation PWWF_1'. The calculations indicate that for some of the batch cycles, VER and v_{upflow} exceed the hydraulic limitations when emptying the buffer tank each time in the subsequent cycle, adding to the influent flow rate. Moreover, a buffer volume of 1,238 m^3 is no longer sufficient to buffer the flow that needs to be stored when one or both reactors are in the reaction or settling phase.

f) Meeting hydraulic constraints during PWWF conditions

In order to meet the hydraulic constraints, the buffer tank is partially emptied each time in the following cycle, but only to such an extent that the hydraulic constraints are still fulfilled. The spreadsheet 'Chapter 11 Design example 3.xlsx' on the sheet 'Buffer operation WWF_1' shows the 24-hour operation during WWF maintaining the batch schedule in dry weather flow, while taking into account the hydraulic limitations (v_{upflow} limits over the VER). The minimal buffer volume required is 9,165 m^3. It is important to note that Eq. 11.56 (Eq. 11.8 from Chen *et al*., 2020) is no longer valid in this case because the hydraulic limits are not fulfilled for every cycle, which means that the buffer cannot be emptied during feeding.

g) Buffer volume

The reaction time and thus total cycle time during PWWF conditions could be shortened because the influent concentrations (not detailed in this example) are also expected to be lower. A possible alternative batch schedule for PWWF conditions is proposed in the spreadsheet 'Chapter 11 Design example 3.xlsx' on the sheet 'Buffer operation PWWF_2'. The total cycle time is decreased for some batches to 3 hours (60 min fill/draw, 90 min reaction phase and 30 minutes settling and sludge discharge) and in extreme cases to 2 hours (60 min fill/draw, 30 min reaction phase and 30 minutes settling and sludge discharge). In this example, it is opted to shorten the cycles when the buffer tank is not emptied during the feeding phase. This new schedule lowers the required buffer volume to 4,697 m^3. However, this alternative batch schedule runs the risk of not meeting the effluent quality. If this was often the case, a larger buffer or extra reaction tank would be required.

Example 11.3.4

Comparison of AGS systems with and without a buffer

Consider a plant with three AGS reactors (without a buffer tank) and a plant with two AGS reactors and one buffer tank. Design both plants based on a Q_{DWF} of 4,800 m^3/d, a COD influent concentration of 600 g/m^3, an MLSS concentration of 8 kgTSS/m^3 and an SLR of 0.3 kgCOD/kgTSS.d. The settling time (t_{settle}) is set at 30 minutes. For the AGS plant with the buffer, consider a constant t_{feed} of 60 minutes.

Tasks in this exercise are to:

a) Calculate and plot for both designs the influence of t_{react} on the total plant volume. Take a range from 60 to 600 minutes for t_{react}. This plot will result in Figure 11.15 (A) from Chen *et al.* (2020).
b) Calculate and plot for both designs the influence of t_{reac} on the efficiency of the AGS reactors, expressed as t_{reac}/t. Take a range from 60 to 600 minutes for t_{reac}. This plot will result in Figure 11.15 (B) from Chen *et al.* (2020).
c) Check if the calculated buffer volume for a t_{reac} of 2.5 hours complies with the hydraulic limits during one day at Q_{DWF}. What is the limiting hydraulic constraint?
d) The buffer volume is always emptied during feeding. Derive the flow rate during feeding (Q_{feed}) based on Eq. 11.8 from Chen *et al*. (2020).

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

e) Explain how the PDWF and PWWF will influence the total plant volume, efficiency of the AGS reactor and the batch scheduling for both plants.

Solution

a,b) Reactor volumes and buffer volume

The calculations and plots are provided in the spreadsheet 'Chapter 11 Design example 4.xlsx'. The sheet 'Without buffer' provides the calculations and plots related to the plant with three AGS reactors. The sheet 'With buffer' provides the calculations and plots related to the plant with two AGS reactors and one buffer tank. The sheet 'Comparison' shows the plots given in Figure 11.15 from Chen *et al*. (2020).

c) Hydraulic constraints

The hydraulic constraints of the design with a buffer tank were always within the hydraulic limits as can be seen in the sheet 'Buffer check'. The upflow velocity is the limiting hydraulic constraint.

d) Feed flow rate

As the hydraulic constraints are fulfilled for one day at Q_{DWF}, the buffer volume is always emptied during feeding. In this case, Q_{feed} can be derived by rearranging Eq. 11.8 from Chen *et al.* (2020) to Eq. 11.41.

During the feeding phase at a Q_{DWF} of 4,800 m^3/d, $V_{buffer} = 0$ m^3 or:

$$V_{buffer} = 0 = \frac{Q_{DWF}}{n_{reactor} \cdot n_{cycles}} - Q_{feed} \cdot \frac{t_{feed}}{24} \tag{11.64}$$

In this case, for which specific data can be found in the sheet 'Buffer check':

$$Q_{feed} = \frac{Q_{DWF}}{n_{reactor} \cdot n_{cycles}} \cdot \frac{24}{t_{feed}} = 400 \text{ m}^3/\text{h} \tag{11.65}$$

e) Influence of PDWF and PWWF.

Both plants could be designed for PDWF conditions assuming a certain S_F^{PDWF}. S_F^{PDWF} will increase the total plant volume proportionally. The efficiency remains constant. PWWF conditions will comply with the design for PDWF if the reactor scheduling is changed (*e.g.,* shorter feeding and/or reaction time). The buffer tank will not be emptied during feeding as the hydraulic constraints cannot be fulfilled at all times.

11.4 EXERCISES

Process characteristics (exercises 11.4.1-11.4.4)

Exercise 11.4.1

Reactor configuration

1. What are the main differences concerning reactor configuration between an aerobic granular sludge (batch) system and a conventional (continuous) activated sludge system?
2. What are the main differences between traditional sequencing batch processes and aerobic granular sludge (batch) systems?

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

Exercise 11.4.2

Advantages of AGS processes

What are the main advantages of an aerobic granular sludge (batch) system compared to a conventional (continuous) activated sludge system?

Exercise 11.4.3

Unit operations and conversion processes

1. Which four unit operations of an activated sludge plant can be compared to the processes in a single aerobic granular sludge tank?
2. How is it possible that all four processes can be performed in one reactor?

Exercise 11.4.4

Primary settling – suspended solids removal

1. What are the advantages of including a primary settling tank in conventional activated sludge systems and to a lesser extent in AGS systems?
2. How are suspended solids removed when a primary settling tank is not included in the AGS system design?
3. What are the advantages of avoiding the construction of a primary settling tank?

Granulation process (exercises 11.4.5-11.4.12)

Exercise 11.4.5

Drivers for granulation

What are the main drivers for granulation and how are these drivers established?

Exercise 11.4.6

Feast-famine regime

How does the feast-famine regime contribute to stable granulation? What happens during the feast-famine regime? Situate this regime in the SBR cycle.

Exercise 11.4.7

CSTR

Why is a continuous stirred tank reactor (CSTR) not preferable for granule formation?

Exercise 11.4.8

Heterotrophs

Will fast-growing heterotrophic bacteria be able to develop in the aerobic granular sludge reactor?

Exercise 11.4.9

Substrate type

Which substrate is suitable for the formation of compact granules? How does the take-up rate of this substrate influence the anaerobic feeding time of a full-scale and lab-scale plant and how does this differ with industrial wastewater?

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

Exercise 11.4.10

Shear stress

Does aerobic granular sludge coagulate under reduced shear stress? Is shear an important granular selection prerequisite?

Exercise 11.4.11

Sludge selection spill versus excess granular sludge

What is the difference between sludge selection spill and excess granular sludge?

Exercise 11.4.12

Relation between substrate uptake profile, biomass growth and floc/granule structure

The substrate diffusion profile influences the biomass growth pattern and the resulting floc or granule structure. However, the effects are mixed in Figure 11.2. Can you combine the images on the substrate diffusion (A-D) with the corresponding biomass growth pattern (I-IV) and floc or granule structure (1-4)? Which feeding pattern and/or type of influent substrate does this correspond with?

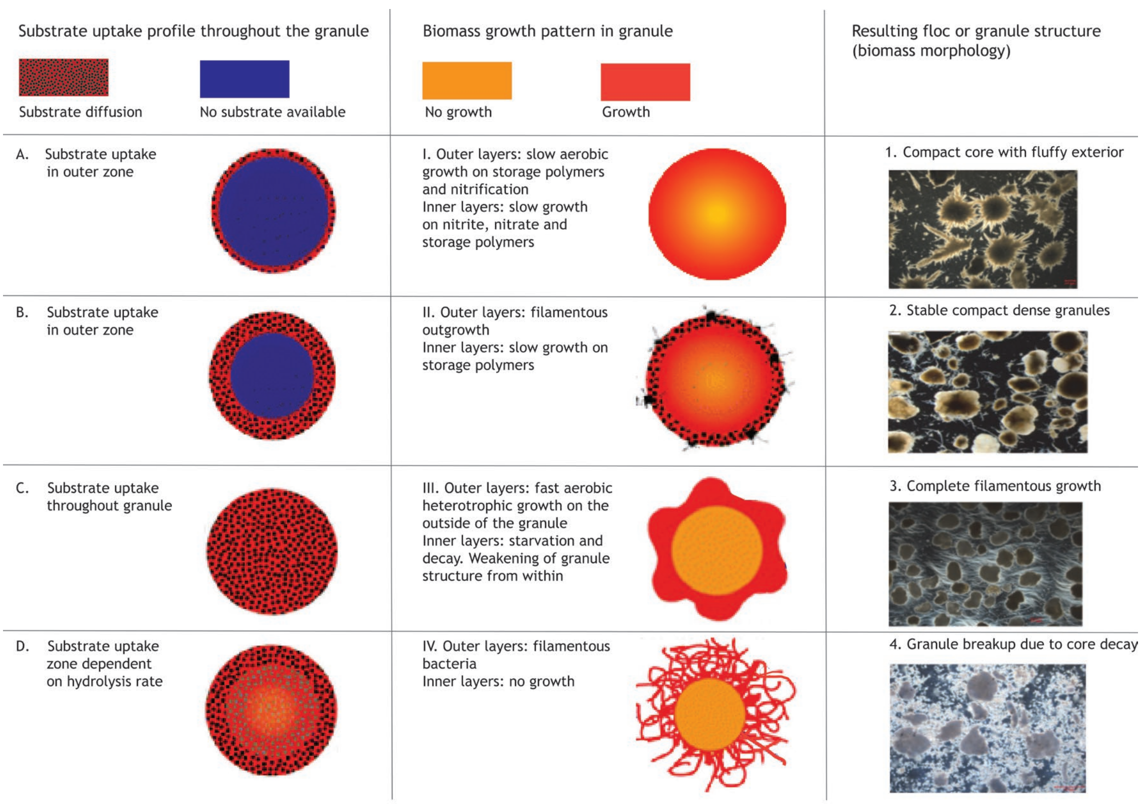

Figure 11.2 Variations in substrate uptake profile, biomass growth pattern and biomass morphology.

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

Kinetics (exercises 11.4.13-11.4.25)

Exercise 11.4.13

Batch cycle dynamics

The (predicted) concentration profile of several substrates during a batch cycle of an AGS reactor is depicted in Figure 11.3. Indicate which substrates are represented by the curves A to D.

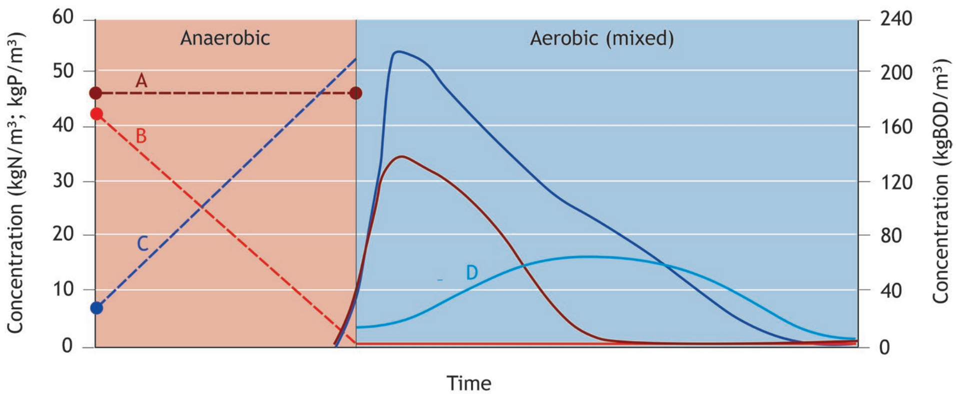

Figure 11.3 Batch cycle dynamics. The solid lines are measured concentrations at the top of the reactor and the dashed lines denote predictions of liquid concentrations during the anaerobic plug-flow regime.

Exercise 11.4.14

Batch cycle dynamics

The AGS process can be divided into two different redox phases: the anaerobic and the aerobic phase, which determine the feast/famine cycle in the reactor. During these phases the granules, composed of different bacteria, complete some reactions of their metabolism, changing the water quality.

Complete the table below, indicating whether the bulk concentration of the specific compound increases or decreases in the specific phase (indicate with 'Increase' or 'Decrease'). If the compound is not involved or remains constant during the specific phase choose —'—'.

	ANAEROBIC PHASE	AEROBIC PHASE
BOD		
PHA		
CO_2		
PO_4^{3-}		
POLY-P		
NH_4^+		
NO_3^-		
N_2		

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

Exercise 11.4.15

Microbial populations - substrates

Characterize the microbial populations according to their respective carbon source and electron donor and acceptor pairs in the aerobic growth period. Complete the table below with these possible answers (multiple answers are possible per table cell):

BOD, CO_2, N_2, H_2O, NO_3^-, PHA, NH_4^+, O_2

	CARBON SOURCE	ELECTRON DONOR	ELECTRON ACCEPTOR	OXIDIZED ELECTRON DONOR	REDUCED ELECTRON ACCEPTOR
PAO					
GAO					
NITRIFIERS					
DENITRIFIERS					

Exercise 11.4.16

Microbial populations - location in the granule

Complete the table choosing from the options given; multiple answers are possible per table cell:

	ORGANISM TYPE (autotroph or heterotroph?)	METABOLISM (aerobic or anoxic?)	LOCATION IN THE GRANULE (inner, middle or outer?)
PAO			
GAO			
NITRIFIERS			
DENITRIFIERS			

Exercise 11.4.17

Effluent concentrations

Why is the COD, N and P concentration in the effluent of an AGS system usually low enough to be discharged without post-treatment?

Exercise 11.4.18

Substrate conversion rates

The substrate conversion rate in an SBR is depicted in Figure 11.4. The red dashed line represents the growth rate for a CSTR, which is constant over time. The theoretical NH_4-N removal efficiency of the SBR is higher than of a CSTR. Which line represents the substrate conversion rate in the SBR?

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

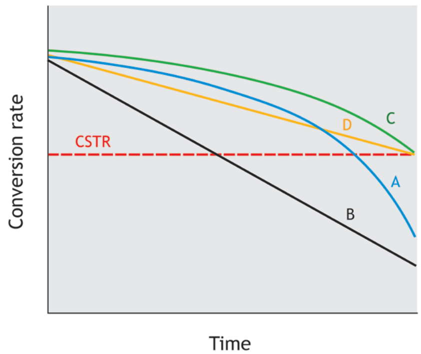

Figure 11.4 Substrate conversion rates in a sequencing batch reactor.

Exercise 11.4.19

Nitrification and denitrification

Is there a need for external dosage of organic carbon during post-denitrification in AGS?

Exercise 11.4.20

Phosphate removal in AGS

One peculiarity of the PAOs is the production of PHA and the capacity of PO_4^{3-} uptake. From literature, it is usually found that PAO can accumulate up to 0.30 gP/gVSS, while in normal organism P uptake is usually around 0.02 gP/gVSS. The growth yield of both ordinary heterotrophs, as well as phosphate accumulating organisms averages 0.4 kgVSS/$kgCOD_{consumed}$.

a) Why is the phosphate uptake higher than the phosphate release?
b) What causes nett P removal in an AGS system?
c) Why is PO_4^{3-} uptake competing with the oxygen consumption of nitrification?
d) Assume an AGS reactor with a biomass concentration of 8 kgVSS/m^3 . This plant receives an influent flow of 2,000 m^3/d, with a VFA concentration of 100 mgCOD/L, a total COD concentration of 400 mg/L and a phosphate concentration of 10 mg PO_4^{3-}-P/ L. Calculate the theoretical P uptake by PAO and the phosphate concentration that can be reached in the effluent. Assume that PAO only use the influent VFA for growth, while the other heterotrophs use the remaining COD for growth.

Exercise 11.4.21

Influence of temperature

The activity of bacteria, and consequently the oxygen uptake rate of micro-organisms is highly dependent on the temperature, which can be expressed by the Arrhenius equation (Eq. 11.66).

$$k(T) = k(20^\circ C) \cdot \theta^{(T-20)} \tag{11.66}$$

k(T) is the maximum growth rate at temperature T (°C) and θ the Arrhenius coefficient (-).

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

a) Complete the missing words to describe the temperature dependency:
   A lower temperature means that nitrifiers will consume ……………. oxygen per time, and thus the thickness of the aerobic layer is ………. .
b) Figure 11.5 displays the ammonium consumption rate as a function of temperature (De Kreuk *et al.*, 2005). Which line indicates the activity in AGS that is due to the temperatures in the system? The red line or the blue one?

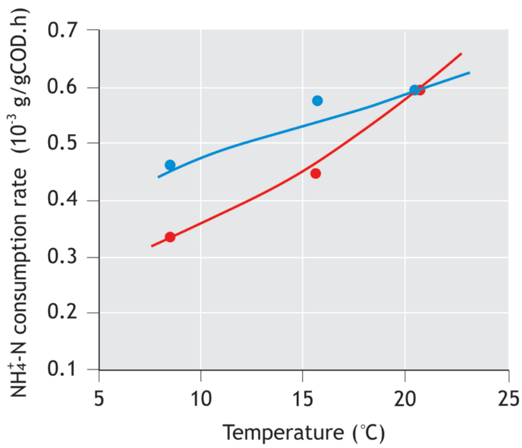

Figure 11.5 Temperature dependency of the ammonium consumption rate.

c) The oxygen uptake rate of nitrifying bacteria is 1.9 gO_2/gVSS.h at 20 °C. What is the conversion rate at 5 °C, given the Arrhenius coefficient of $\theta = 1.06$?
d) Will PAO adapt their activity at varying temperatures in the long term?

Exercise 11.4.22

Influence of dissolved oxygen concentration

What are the two main parameters determining the thickness of the aerobic layer?

Exercise 11.4.23

Influence of dissolved oxygen concentration

Which conversion process will be affected and what is the effect on the effluent in the case of

a) an increasing DO?

b) a decreasing DO?

Exercise 11.4.24

Influence of granule size

How does the size of the granules influence the ratio of aerobic/anoxic volume of the granules? Complete the following sentence.

At the same DO, smaller granules have a relatively …… aerobic volume and …… anoxic volume than larger granules.

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

Exercise 11.4.25

Oxygen consumption rate, oxygen penetration depth and anoxic volume fraction

Assume an aerobic granular sludge reactor filled with granules of a diameter of 3 mm. The oxygen concentration during the nitrification phase in the bulk liquid is kept at 3 mgO_2/L. The nitrification process is the highest oxygen consumer, accounting for 80 % of the oxygen uptake rate. The ammonium conversion rate is 0.4 gNH_4-N/gVSS.h at 20 °C. Recall that the stoichiometric oxygen use is 2 moles O_2 per mol NH_4-N.

a) What is the oxygen consumption rate q_s^{max} in gO_2/gVSS.h in this system during aeration?

b) Calculate the oxygen penetration depth in the granules with Eq. 11.67. Take the following assumptions into account: the boundary layer approaches 0 mm ($C_{si}= C_b$); the diffusion coefficient $D_{O2} = 1.4 \cdot 10^{-9}$ m^2/s; the biomass concentration in the granule (C_x) is 80 $kgVSS/m^3$.

$$3 \cdot \partial - \frac{2 \cdot \partial^3}{R} = \frac{6 \cdot D_{O2} \cdot C_{si}}{q_s^{max} \cdot C_x} \qquad (11.67)$$

With ∂, the penetration depth (m), R, the granule radius (m), D_{O2}, the diffusion coefficient of oxygen in the granule (m^2/s), C_{si}, the concentration at the granule surface (gO_2/m^3), q_s^{max}, the maximum uptake rate (gO_2/gVSS.h) and C_x, biomass concentration in the granule ($kgVSS/m^3$).

c) What is the fraction (%) of anoxic biomass in the granule, assuming that the nitrate diffuses to the core of the granule?

Process monitoring and control (exercises 11.4.26-11.4.33)

Exercise 11.4.26

Monitoring

1. Why are the measured concentrations low during reactor feeding?
2. Indicate which measurements are usually automated and which ones are manual?

Exercise 11.4.27

Process operation

1. What are the different phases in the operation of an aerobic granular sludge lab-scale SBR?
2. What is the difference in phases with a full-scale aerobic granular sludge process and what are the consequences?
3. How is the sludge spilled in a lab-scale reactor compared to a full-scale reactor?

Exercise 11.4.28

Batch operation

What is the critical difference between process control of a continuous versus a batch process?

Exercise 11.4.29

Upflow velocity and volume exchange ratio

Figure 11.6 displays the upflow velocity in the reactor, v_{upflow} (m/h), and the volume exchange ratio, VER (-), as a function of the wastewater flow rate fed to the AGS reactor.

a) How is the upflow velocity calculated?

b) What does VER represent?

c) Find the maximum flow that can be reached without changing the feeding time. What will happen at higher flow rates?

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

d) What is the risk when the maximum upflow velocity is exceeded?
e) To reduce the upflow velocity, which is an important constraint during rainy weather flow, one possible solution is the decrease of the height of the reactor. What are the negative impacts related to lowering the design height?
f) Why is cycle shortening a standard solution for very high rain weather flow conditions?
g) When influent reaches the WWTP via a pressurised sewer, why is it not recommended to switch to the shorter rain weather cycle times immediately? What is usually done?

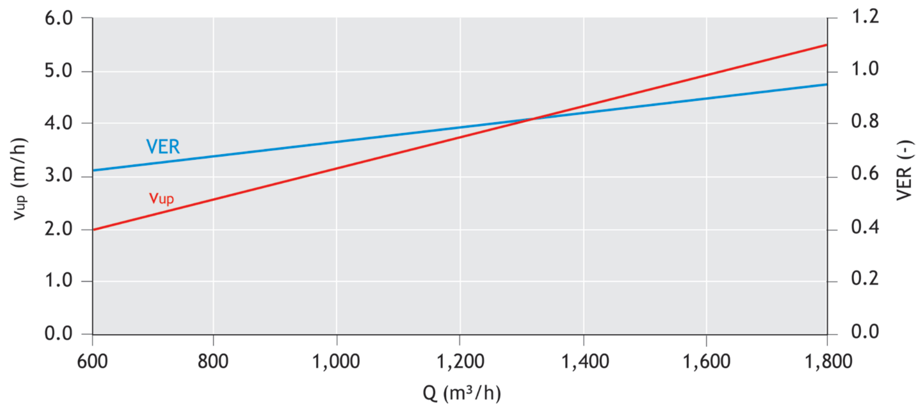

Figure 11.6 Upflow velocity in the reactor v_{up} and volume exchange ratio VER as a function of the wastewater flow rate Q .

Exercise 11.4.30

Variations between cycles

SBR reactors experience fluctuations due to the different influent batches they receive. The following variables may differ between batches: temperature, COD, nitrogen and phosphorus concentration, flow rate and pH. Figure 11.7 shows the concentration profiles of ammonium, nitrate, phosphate and dissolved oxygen over different batch cycles.

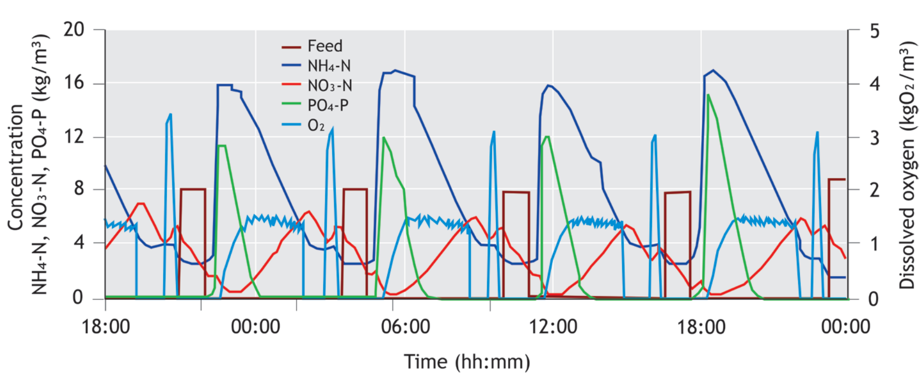

Figure 11.7 Substrate concentration profiles over different batch cycles.

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

a) What are the two main parameters influencing the concentration peaks?
b) Just before the next feeding period, the DO concentration peaks to a high value. It appears that the aeration is started for a short while at high capacity. Why?
c) Identify the moment at which the operator turns off the aeration. Why is this done?
d) In domestic wastewater treatment the concentration of NH_4^+ is normally approximately 4 to 7 times higher than the concentration of PO_4^{-3}. However, in the graph this is not the case. What happened in the AGS reactor?

Exercise 11.4.31

Sludge loading rate and reactor performance

The concentration peaks per batch vary over the day. Accordingly, the sludge load also varies over the day; this similarly occurs in the conventional activated sludge process. However, to make sure that the sludge loading per batch stays optimal, the concentration peaks in the batch cycle are controlled by adapting the feeding time.

a) When the influent is transported to the WWTP via a combined sewer, the COD concentration in the influent will decrease significantly during a rain event (assume that the COD of rain is equal to zero). How does the sludge loading rate change?
b) Which possible risks occur for the AGS reactor at non-optimal sludge loading rates?

Exercise 11.4.32

Simultaneous nitrification-denitrification

The graph below shows the ammonium and nitrate profile during a cycle. Which arrow represents the N conversion via simultaneous nitrification-denitrification?

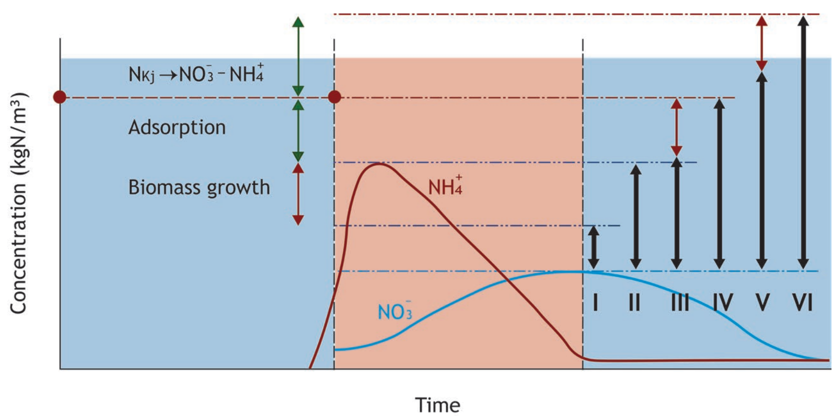

Figure 11.8 Concentration profiles of nitrogen compounds and their relation to conversion processes.

Exercise 11.4.33

Suspended solids

a) Which are the two factors that could hinder the settling of suspended solids and contribute to their presence in the effluent?
b) Which three measures can be taken to marginalise the presence of suspended solids in the effluent?

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

Process configuration (exercises 11.4.34-11.4.37)

Exercise 11.4.34

System setup

Which three setups ensure processing of a continuous flow of wastewater in an aerobic granular sludge wastewater treatment plant?

Exercise 11.4.35

Influence of a buffer tank

Why can the AGS reactor be designed smaller when a buffer tank is applied?

Exercise 11.4.36

Reactor volume – influencing factors

Indicate in the following table whether the variables will lead to a smaller or larger reactor volume per reactor.

Variable	Does the variable make the volume (per reactor) smaller or larger?
Influent flow increases (m^3/d)	
PWWF/DWF ratio increases (-)	
COD concentration increases (g/m^3)	
Total reaction time per day increases	
Sludge concentration increases (g/m^3)	
Sludge loading rate increases (kgCOD/kg TSS.d)	
Volumetric loading rate increases ($m^3/m^3.d$)	
Number of reactors increases (-)	

Exercise 11.4.37

Hydraulic constraints

What are the parameters influencing the hydraulic restrains to design the reactor volumes, assuming a fixed Q^{DWF}?

Resource recovery (exercises 11.4.38-11.4.39)

Exercise 11.4.38

Sludge application

How can excess granular sludge be applied today and/or in the (near) future?

Exercise 11.4.39

Methane production potential of sludge

Which sludge type has the highest methane potential (in $m^3CH_4/gVSS$)? Put the following in order from high to low: primary sludge, activated sludge, aerobic granules, selection spill.

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

ANNEX 1: SOLUTIONS TO EXERCISES

Process characteristics (solutions 11.4.1-11.4.4)

Solution 11.4.1

Reactor configuration

1. Main differences concerning reactor configuration between an aerobic granular sludge (batch) system and a conventional (continuous) activated sludge system:
    - In contrast to conventional activated sludge systems, AGS systems are either built as minimum three AGS reactors in parallel, or as one or more AGS reactors (usually two) and a buffer tank. Indeed, the batch-wise operation implies that a single reactor cannot receive influent all the time, since influent cannot be fed during the reaction or settling phase. A minimum of three AGS reactors in parallel is required for continuous operation. Alternatively, it is possible to opt to build a buffer tank and as such reduce the number of AGS reactors. The latter may be more economical for smaller plants (requiring a low reaction volume) as well as for larger plants that would require more than three reactors (and where a buffer tank enables a shorter feeding phase with higher flows, and thus a relatively longer reaction time). Note that for large facilities, activated sludge processes are also designed with parallel reactors.
    - Another main difference is that an AGS reactor is always fed in plug-flow mode. The plug-flow regime allows simultaneous feeding and discharge.
2. Main differences between traditional sequencing batch processes and aerobic granular sludge (batch) systems:
    - The feeding in AGS is from the bottom in a plug flow through the reactor. Therefore, the reactor has a constant volume and there is no need for a mechanical decanter for effluent extraction, nor for decanting time within the cycle length. The plug-flow feeding also eliminates the need for a mixer during the anaerobic phase, since the influent is in contact with the granules from the moment it enters the reactor.
    - Due to the fast settling, there is virtually no cycle time required for sludge settling; only a short time to eliminate turbulence after the aeration phase is required.

Solution 11.4.2

Advantages of AGS processes

An aerobic granular sludge batch reactor compared to a continuous activated sludge plant:

- Has a smaller footprint: no need for settling tanks and the AGS reactor is designed to be more compact, because of high biomass concentrations allowing a high volumetric loading rate (Pronk *et al.*, 2015a).
- Needs fewer construction materials, for the same reasons.
- Needs less mechanical equipment, such as recycle pumps, return sludge pumps, clarifier bridges, mixers. This saves on investment, maintenance requirements and energy usage (Pronk *et al.*, 2015a).
- Reaches a high effluent quality more easily: batch-wise operation ensures a relatively high substrate concentration compared to completely mixed reactors, thus minimizing diffusion limitation and therefore allowing higher conversion rates. Also, the reactor content is not continuously fed with wastewater, resulting in a faster drop in concentration in the liquid phase of the reactor. Lastly, the N removal is not dependent on an internal recycle flow from the aeration tank to the pre-denitrification tank[1], but can be controlled by the oxygen set-point and length of the post-denitrification phase.

[1] In activated sludge plants, the internal recycle from the nitrification tank to the pre-denitrification tank determines the nitrate concentration in the effluent assuming all ammonium is nitrified and all nitrate returned is denitrified. For example: with a recycle flow of 4 times the influent flow, approximately 20 % of the incoming ammonium will still leave the activated sludge plant in the form of nitrate.

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

Solution 11.4.3

Unit operations and conversion processes

1. The anaerobic, aerobic, anoxic, and settling tank.
2. The large size of granules compared to activated sludge flocs enables different redox zones (from outside to core: aerobic, anoxic, and (with large granules) anaerobic) in each granule, favouring bacterial communities with different functions (organic carbon removal, phosphorus removal, nitrification, and denitrification). The anaerobic plug-flow feeding through the settled bed followed by the aeration and post-denitrification phase enables biological phosphate removal. The high settling velocity of the granules enables the integration of the settling in the reactor. Moreover, batch scheduling makes it possible to adapt the phases within the cycles as well as the cycle length to reach the desired effluent quality (*e.g.,* by applying a separate denitrification phase to complement simultaneous nitrification-denitrification).

Solution 11.4.4

Primary settling – suspended solids removal

1. A primary settling tank for conventional activated sludge is advantageous to decrease the load on the biological reactor and the associated oxygen consumption by removing suspended solids. Moreover, primary sludge has a very good biogas production potential and is therefore advantageous in view of energy recovery. In an AGS system, suspended solids are removed via the sludge selection spill during settling so there is not a real need for a primary settler for suspended solids removal. Also, the total AGS excess sludge (consisting of the floc fraction with suspended solids on the one hand and granules on the other hand) has a similar biogas production potential as the combined primary and secondary sludge for activated sludge tanks.
2. The suspended solids will be mainly either removed by uptake by protozoa, metazoa or end up in the flocculated sludge fraction. This is removed as excess sludge during the sludge selection spill during settling in the batch cycle. Colloidal material that will also partly be removed as primary sludge could potentially also be hydrolysed in the anaerobic feeding phase and result in substrate for EBPR. The flocculent fraction has a short solid retention time (SRT) in the process (Ali *et al.*, 2019) and particulates are therefore marginally mineralised in the AGS reactor.
3. The advantages of avoiding the construction of a primary settling tank are: a smaller area required for the treatment plant (even though the biological reactor may need to be slightly larger), less odour emission and easier operation.

Granulation process (solutions 11.4.5-11.4.12)

Solution 11.4.5

Drivers for granulation

The formation of compact granules is stimulated by:

- having high substrate concentrations during feeding and making sure that diffusion is not limiting which is established by plug-flow feeding under anaerobic conditions.
- selecting slow-growing organisms which is established by an anaerobic feeding phase in which bacteria take up readily biodegradable substrate and convert it into cell internally stored polymers. These bacteria therefore do not compete on growth rate and do not have a high growth rate.
- selective pressure due to the difference in settling velocity. This makes it possible to selectively remove the flocculent biomass and selectively feed the faster settling (larger) granules.

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

Solution 11.4.6

Feast-famine regime

The feast-famine regime ensures periods with high substrate concentrations in the reactor alternate with periods without substrate supply. This favours slow-growing organisms. During the feast phase, *i.e.*, the anaerobic feeding phase, there is readily biodegradable BOD (RBCOD) uptake by PAO and GAO and conversion to storage polymers. However, during the famine phase, *i.e.,* the aeration phase, there is consumption of storage polymers by PAO and GAO, since they do not compete on growth rate; they do so at a relatively low specific growth rate.

Solution 11.4.7

CSTR

Substrate concentrations in CSTRs are typically very low, leading to low substrate penetration in immobilised biomass such as granular sludge. This induces flocculent biomass growth since this will have less influence from diffusion limitation.

Solution 11.4.8

Heterotrophs

No, because the RBCOD concentration in the aerobic phase is almost zero and if they grow, they are removed within 0.5-5.0 d via the sludge selection (or excess sludge) spill.

Solution 11.4.9

Substrate type

A suitable substrate for the formation of compact granules is RBCOD. Municipal wastewater does not usually contain a lot of RBCOD (≤ 100 g/m^3, depending on the type of sewer system). An anaerobic feeding phase of 1 hour (determined in general more by the hydraulic design than based on biokinetic parameters) is more than sufficient to take up all the RBCOD by the granular sludge. A part of the slowly biodegradable COD can also be anaerobically hydrolysed, fermented and stored during the 1-hour feeding phase. However, in lab-scale reactors and/or industrial treatment plants, the anaerobic feeding time could differ according to the anaerobic PHA storage. In these reactors the hydraulic considerations are less dominant and the anaerobic time might be designed according to the anaerobic substrate uptake kinetics.

Solution 11.4.10

Shear stress

No, the granule has a stable structure and does not coagulate under reduced hydrodynamic shear. With the selection for PAO and GAO during the anaerobic feed, shear is not an important granular selection prerequisite.

Solution 11.4.11

Sludge selection spill versus excess granular sludge

The sludge selection spill mainly consists of the flocculent fraction and is discharged during settling to establish a hydraulic selection pressure for the sludge that is not settling well (Pronk *et al*., 2015a). The excess granular sludge is granules that are discharged in order to maintain a constant biomass concentration in the reactor and also to remove large granules that consist of a significant inactive volume fraction. Both these discharges differ in concentration, morphology and SRT of the sludge.

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

Solution 11.4.12

Relation between substrate uptake profile, biomass growth and floc/granule structure

			Feeding pattern	Influent substrate type
C	I	2	Anaerobic	Readily biodegradable dissolved substrates
B	III	4	Aerobic mixed (pulse)	Readily biodegradable dissolved substrates
D	II	1	Anaerobic	Polymeric substrates
A	IV	3	Aerobic mixed (slow)	Readily biodegradable dissolved substrates

Kinetics (solutions 11.4.13-11.4.25)

Solution 11.4.13

Batch cycle dynamics

A = NH_4^+

B = BOD (NOTE: BOD could be higher at the start of the aeration time and will follow a decreasing trend during aeration. BOD ending up in the aerobic phase comes from slowly biodegradable COD. It either partly contributes to flocculent sludge growth (removed via the sludge selection spill indirectly) or is incorporated with the more flocculant sludge and then discharged (removed via the sludge selection spill directly).

C = PO_4^{3-}

D = NO^{3-}

Solution 11.4.14

Batch cycle dynamics

	ANAEROBIC PHASE	AEROBIC PHASE
BOD	Decrease	--/ Decrease
PHA	Increase	Decrease
CO_2	Small increase[2]	Increase
PO_4^{3-}	Increase	Decrease
POLY-P	Decrease	Increase
NH_4^+	--	Decrease
NO_3^-	---	Increase[3]
N_2	--	Increase

[2] Some CO_2 is produced by EBPR and some by fermentation processes.

[3] Due to simultaneous nitrification-denitrification, nitrogen is removed during the aeration phase of the AGS process. Depending on the anoxic volume of the granule, not all nitrate will be removed and therefore nitrate will accumulate during the aeration phase. To increase nitrate removal, the process operation can be adapted to stimulate denitrification. This can be done by switching aeration on and off during the reaction phase or by adding a post-denitrification phase after the aeration phase.

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

Solution 11.4.15

Microbial populations – substrates

	CARBON SOURCE	ELECTRON DONOR	ELECTRON ACCEPTOR	OXIDIZED ELECTRON DONOR	REDUCED ELECTRON ACCEPTOR
PAO	PHA	PHA	O_2/NO_3^-	CO_2	H_2O/N_2
GAO	PHA	PHA	O_2/NO_3^-	CO_2	H_2O/N_2
NITRIFIERS	CO_2	NH_4^+	O_2	NO_3^-	H_2O
DENITRIFIERS	BOD	BOD	NO_3^-	CO_2	N_2

Solution 11.4.16

Microbial populations - location in the granule.

	ORGANISM TYPE (autotroph or heterotroph?)	METABOLISM (aerobic or anoxic?)	LOCATION IN THE GRANULE[4] (inner, middle or outer?)
PAO	Heterotroph	Substrate uptake: anaerobic Growth: aerobic/anoxic	Middle
GAO	Heterotroph	Substrate uptake: anaerobic Growth: aerobic/anoxic	Middle
NITRIFIERS	Autotroph	Aerobic	Outer
DENITRIFIERS	Heterotroph	Anoxic	Inner

Solution 11.4.17

Effluent concentrations

In a continuous reactor the concentrations are always low, thus giving conversion close to the K_S value for the substrate, *i.e.*, reaction rates are reduced. In a batch operation the concentrations are initially high resulting in high conversion rats. Moreover, in a continuous reactor there is continuous input of pollutants making it more difficult to reach very low values. In addition, the cycle time and different phase lengths can be adapted to reach the optimal effluent quality.

---

[4]A granule can be described by different zones due to the diffusion limitation of oxygen. There is an aerobic outer layer and an anoxic core. Sometimes an anaerobic core can be present although this is not taken into account in this exercise, as an anaerobic core does not have a function. However, it can exist if the oxygen as well as the nitrate does not penetrate to the inner core of the granule. This happens when granules become large.

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

Solution 11.4.18

Substrate conversion rates

Line A.

Theoretically the rate of conversion is not linear (which eliminates B and D), and also the conversion rate at the end of a AGS reactor cycle is usually lower than for a CSTR reactor. At the end of the batch cycle, the effluent concentrations reached in a batch reactor are generally lower than in a CSTR system.

Solution 11.4.19

Nitrification and denitrification

External carbon dosage is not required because during the anaerobic feeding there is storage of PHA throughout the granule. During aeration, only the PHA in the outer layer is oxidised with O_2. Inside the granule the PHA is already used for denitrification during the aerobic phase. During the post-denitrification phase PHA is used in the entire granule. This is in contrast to activated sludge, where the entire floc is aerobic during aeration and many more storage polymers are oxidised with O_2.

Solution 11.4.20

Phosphate removal in AGS

a) Due to the net biomass growth (which is determined by the biomass yield).
b) Nett P removal is obtained by wasting the excess of biomass accumulating P.
c) PAO will use oxygen as the electron acceptor to oxidize the storage polymer PHA during the aerobic phase. This creates energy for their anabolism and for the uptake of PO_4^{3-}. Since nitrifiers also need oxygen, both populations compete for it.
d) 400 mgCOD/l is consumed, which means that 160 mgVSS/l of heterotrophs are produced (0.4 mgVSS/mgCOD consumed · 400 mgCOD consumed/l). To maintain a biomass concentration of 8 kgVSS/m^3, 160 mgVSS of heterotrophs will be wasted. Roughly, ¼ of the COD (100 mg of the total 400 mgCOD is VFA) is consumed by PAO, the other ¾ is likely consumed by ordinary heterotrophs.

   Net PO_4^{3-} uptake:
   By PAO: (1/4 · 160 mgVSS/L) · 40 mgVSS/L · 0.30 mgP/mgVSS = 12 mgP/L
   By OHO: (3/4 · 160 mgVSS/l) · 120 mgVSS/L · 0.02 mgP/mgVSS = 2.4 mgP/L
   Phosphate concentration reached in the effluent: 0 mgP/L.

Solution 11.4.21

Influence of temperature

a) A lower temperature means that nitrifiers will consume less oxygen per time, and thus the thickness of the aerobic layer is extended.
b) The blue line represents the long temperature effect, as the overall nitrification rate is recovered by granule adaptation to the new situation. The red line represents short temperature effects.
c) $k(5\ °C) = 1.9\ gO_2/gVSS.h \cdot 1.06^{(5-20)} = 0.79\ gO_2/gVSS.h$.
d) The overall denitrification and phosphate removal rate stay lower for decreasing temperature in the short and the long term. PAOs grow with oxygen or nitrate as an electron acceptor. An increased aerobic zone means at the same time a decreased anoxic zone. The granule volume in which PAO can grow stays the same, so there will be no extra space for them to grow to increase their concentration and compensate for the lower conversion rates because of the lower temperature.

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

Solution 11.4.22

Influence of dissolved oxygen concentration

1) Activity of the micro-organisms and dissolved oxygen (DO) concentration.
2) Oxygen is used to oxidize ammonium to nitrate and to oxidise BOD. The aerobic and anoxic layer thickness in the granules will be determined by the amount of oxygen in the bulk and the rate at which it is oxidized at the granule outer layer.

Solution 11.4.23

Influence of dissolved oxygen concentration

a) Increasing DO: denitrification will be affected because the anoxic volume is smaller. NO_3^- will remain in the effluent.
b) Decreasing DO: nitrification will be affected because the aerobic volume is smaller. More NH_4^+ in the effluent.

Solution 11.4.24

Influence of granule size

At the same DO, smaller granules have a relatively higher aerobic volume and lower anoxic volume than larger granules.

Solution 11.4.25

Oxygen consumption rate, oxygen penetration depth and anoxic volume fraction

a) To oxidize 0.4 gNH_4-N/gVSS.h or 0.03 molN/gVSS.h (N = 14 g/mol), 0.06 $molO_2$/gVSS.h or 1.92 gO_2/gVSS.h is consumed. In total 2.4 gO_2/gVSS.h is consumed (1.92/0.8 gO_2/gVSS.h).
b) Wolfram Alpha or Excel Solver can be used to solve this cubic equation. Tutorials of how to solve equations using the Excel solver are readily accessible on YouTube. The oxygen penetration depth in the granules is 443 μm.
c) Anoxic biomass volume fraction = $(1.5 – 0.443)^3$ mm^3 / 1.5^3 mm^3 = 0.35 or 35 %.

Process monitoring and control (solutions 11.4.26-11.4.33)

Solution 11.4.26

Monitoring

1. Due to the plug-flow regime during the feeding phase, the instruments (kept at the top of the reactor) still measure the effluent concentration of the previous batch, thereby measuring low values (Pronk *et al.*, 2015a).
2. Automated: NH_4^+, NO_3^-, ORP, pH. Manual: COD, total N, total P.

Solution 11.4.27

Process operation

1. Fill, react, settle, drain, and idle phase.
2. In the full-scale process the filling and draining phase are combined, which saves cycle time and complex constructions. Smaller reactors can be built. The full-scale plant works at a constant volume.
3. In a lab-scale reactor, withdrawal of liquid at around the mid-column level is used as a selection pressure on fast-settling sludge. In full-scale Nereda© plants however, effluent flows out from the top. The hydraulic selection pressure is established via a separate sludge selection spill from the reactor for the poor settling sludge, which is called the sludge selection spill (Pronk *et al.*, 2015b).

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

Solution 11.4.28

Batch operation

Both operations try to achieve the desired effluent concentrations. In a continuous process the control is often based on a set-point for the concentration equal to the effluent concentration. In a batch process the control is based on the reaction rate (*i.e.*, the change in concentration over time). The batch operation allows a more flexible operation. A flexible operation can better deal with external conditions, maintaining a high quality of the effluent. The batch operation can change the time schedule based on the influent conditions (flow rate, concentrations), therefore *e.g.*, the time schedule can be shortened during a peak hydraulic load. As in the conventional activated sludge system, there is the necessity to both design and operate the reactors based on the hydraulic and biological conditions.

Solution 11.4.29

Upflow velocity and volume exchange ratio

a) The upflow velocity in the reactor represents the influent (feed) flow rate divided by the cross-section area of the reactor (see Eq. 11.4).
b) The volume exchange ratio represents the ratio between the influent wastewater volume fed during a batch cycle and the total reactor volume (see Eq. 11.1).
c) Q_{max} = 800 m^3/h as the maximum VER is 65 %. At higher exchange ratios, breakthrough of influent in the effluent can take place.
d) At an upflow velocity higher than 5 m/h, there is the risk of fluidization of the settled granule bed causing influent and effluent mixing.
e) A larger footprint of the reactors, a larger number of air diffusors and injection points and enhancement of vertical diffusion. Besides, the VER is still 0.65, so the influent volume that can be dosed per batch will not change by changing the height over diameter ratio.
f) Shortening the cycle time, by reducing the reaction time, is a countermeasure to the VER increase when VER is over 0.65.
g) Because of the 'first flush' peak, causing an immediate high BOD loading rate. The first flush can be stored in a rainwater buffer tank and treated during dry weather conditions or it can be divided over the available reactors that are in the feed phase.

Solution 11.4.30

Variations between cycles

a) The influent concentration variations and the VER.
b) This is known as the stripping phase. Denitrification takes place in the settling granule bed, leading to dinitrogen gas formation and lower local NO_3^--N concentrations. The short aeration pulse helps to get rid of the dinitrogen gas that is in solution and would lead to bubble formation during the next feeding phase and by that flotation of the flocculent fraction and suspended solids accompanying the AGS in practice (van Dijk *et al*., 2018). Moreover, it mixes the bulk liquid and gives a final boost for nitrification to reduce ammonium in the final effluent.
c) 4 gNH_4^+-N/m^3. When ammonium is sufficiently lowered, the remaining nitrate should be converted to N_2 by denitrifiers. Therefore, the anoxic sludge fraction is increased by switching off the aeration.
d) PAOs release PO_4^{-3} in the anaerobic phase, leading to a peak concentration at the moment aeration mixes the reactor completely. Furthermore NH_4^+ is absorbed onto the granule during the feeding phase, leading to a lower concentration than expected by the VER and the influent concentration (Bassin *et al.,* 2011).

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

Solution 11.4.31

Sludge loading rate and reactor performance

a) The sludge loading rate remains more or less constant. The sludge loading rate is defined by the COD concentration multiplied by the flow rate, divided by the amount of biomass in the reactor (Eq. 11.6). The loading rate of the system does not change too much with a rain event (the flow increases but the total COD load reaching the plant will probably be the same). It is assumed here that rainwater is relatively clean, although it might contain street run-off or solids from the sewer.

b)
- More readily biodegradable COD than PAOs and GAOs can take up in a cycle, which reduces selection pressure for PAO and GAO and causes the proliferation of fast-growing heterotrophic bacteria in non-granular shape.
- Oxygen demand is higher than oxygenation capacity.
- Peak concentrations of NH_4-N and oxidisable organic N for which the available mass of nitrifiers cannot oxidise within the available aeration time and thus ammonium concentrations exceed effluent demands.
- The presence of specific degradable compounds that may cause substrate inhibition when their concentration is too high (*e.g.*, for industrial wastewater).

NOTE: If there are a couple of cycles with non-optimal sludge loading, this will not damage the system straight away but it should not last for weeks.

Solution 11.4.32

Simultaneous nitrification-denitrification

Arrow V.

The fraction that is simultaneously converted cannot simply be determined by the difference between the ammonium consumed and the nitrate produced. It is also necessary to take into account the ammonia consumption due to biomass growth, since 12 % of the biomass consists of nitrogen. At the same time, ammonia is adsorbed to the biomass during feeding. This ammonia is still available for bioconversions. This fraction of adsorbed ammonia is not measured by the installed online measurements and can be as high as 25 % of the ammonia that is fed to the reactor. Furthermore, note that the online measurement determines ammonia, but not organic nitrogen. The nitrogen Kjeldahl is also available for nitrification, so that adds another 30 % to the nitrogen that needs to be nitrified. To summarize, if you determine the simultaneous denitrification rate by the difference between the ammonium consumption rate and the nitrate production rate, you underestimate the rate due to the ammonium adsorption and organic nitrogen, and you overestimate it due to the nitrogen that is used for growth.

Solution 11.4.33

Suspended solids

a) The presence of suspended solids in the effluent is caused either by rising sludge due to the degasification of nitrogen gas during the feed and decant phase (when the stripping phase has not been applied or was insufficient) and/or by wash-out of particles that intrinsically do not settle (*i.e.*, fats and foams in the influent) (Van Dijk *et al.,* 2018).

b)
- Add an N_2 stripping phase before the feeding phase.
- Install a baffle in front of the effluent discharge gutter that prevents a possible floating layer from entering the effluent discharge.
- When effluent demands are very strict, it is possible to add a post-treatment such as sand filtration or membranes.

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

Process configuration (solutions 11.4.34-11.4.37)

Solution 11.4.34

System setup

- Minimum of three sequencing batch reactors in parallel with always one reactor in feed and draw mode for 1/3 of the total cycle time.
- Buffer tank in front of the sequencing batch reactor (only one batch reactor is sufficient). The influent is stored when the reactor(s) is/are in the aeration or settling phase.
- Combination of a conventional activated sludge system and AGS reactor in parallel where the influent flow is divided over the two systems.

Solution 11.4.35

Influence of a buffer tank

The AGS reactor can always be fed closer to the maximum VER or loading rate. The buffer tank levels the hydraulic peaks (*e.g.*, hydraulic regulation of daily peaks, wet weather flow).

Solution 11.4.36

Reactor volume – influencing factors

Variable	Does the variable make the volume (per reactor) smaller or larger?
Influent flow increases (m^3/d)	Larger
PWWF/DWF ratio increases (-)	Larger
COD concentration increases (g/m^3)	Larger
Total reaction time per day increases	Smaller
Sludge concentration increases (g/m^3)	Smaller
Sludge loading rate increases (kgCOD/kg TSS.d)	Smaller
Volumetric loading rate increases (m^3/m^3.d)	Smaller
Number of reactors increases (-)	Smaller

Solution 11.4.37

Hydraulic constraints

- The peak dry weather flow: this is the largest flow corresponding with the maximum reaction time (because the concentrations will be the highest).
- The length of the feed and draw phase.
- The volume exchange ratio (max. 0.65).
  - These three parameters will influence the hydraulic restraints to design the total reactor volume (m^3).
- The peak dry weather flow.
- The upflow velocity (max. 5m/h)
  - These two parameters will influence the hydraulic restraints to design the reactor area (m^2)

Resource recovery (solutions 11.4.38-11.4.39)

Solution 11.4.38

Sludge application

For agricultural reuse (if legally allowed), energy recovery, inoculation of new treatment plants, resource recovery of Extracellular polysaccharides (EPS) (Kaumera™).

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

Solution 11.4.39

Methane production potential of sludge

Primary sludge > Selection spill > Activated sludge > Aerobic granules (Guo *et al*., 2020).

REFERENCES

Ali M., Wang Z., Salam K.W., Hari A.R., Pronk M., van Loosdrecht M.C.M. and Saikaly P.E. (2019). Importance of Species Sorting and Immigration on the Bacterial Assembly of Different-Sized Aggregates in a Full-Scale Aerobic Granular Sludge Plant. *Environmental Science and Technology,* 53, 8291–8301. https://doi.org/10.1021/ACS.EST.8B07303

Bassin J.P., Pronk M., Kraan, R., Kleerebezem R. and van Loosdrecht M.C.M. (2011). Ammonium adsorption in aerobic granular sludge, activated sludge and anammox granules. *Water Research*, 45, 5257–5265. https://doi.org/10.1016/J.WATRES.2011.07.034

Chen, G. H., van Loosdrecht, M.C.M., Ekama, G. A. and Brdjanovic D. (eds.) (2020). *Biological Wastewater Treatment: Principles, Modelling and Design*. ISBN: 9781789060355. IWA Publishing, London, UK.

De Kreuk M.K., Pronk M. and van Loosdrecht, M.C.M. (2005). Formation of aerobic granules and conversion processes in an aerobic granular sludge reactor at moderate and low temperatures. *Water Research,* https://doi.org/10.1016/j.watres.2005.08.031

Guo H., van Lier J.B. and de Kreuk M. (2020). Digestibility of waste aerobic granular sludge from a full-scale municipal wastewater treatment system. *Water Research*, 173. https://doi.org/10.1016/J.WATRES.2020.115617

Pronk M., de Kreuk M.K., de Bruin B., Kamminga P., Kleerebezem R. and van Loosdrecht M.C.M. (2015a). Full scale performance of the aerobic granular sludge process for sewage treatment. *Water Research*, https://doi.org/10.1016/j.watres.2015.07.011

Pronk M., de Kreuk M.K., de Bruin B., Kamminga P., Kleerebezem R. and van Loosdrecht M.C.M. (2015b). Full scale performance of the aerobic granular sludge process for sewage treatment. *Water Research*, 84, 207–217. https://doi.org/10.1016/j.watres.2015.07.011

van Dijk E.J.H., Pronk M. and van Loosdrecht M.C.M. (2018). Controlling effluent suspended solids in the aerobic granular sludge process. *Water Research,* 147, 50–59. https://doi.org/10.1016/j.watres.2018.09.052

NOMENCLATURE

Symbol	Description	Unit
C_b	Concentration in the boundary layer	gO_2/m^3
C_{si}	Concentration at the granule surface	gO_2/m^3
C_x	Biomass concentration in the granule	$kgVSS/m^3$
COD	Influent COD concentration	$kgCOD/m^3$
D_{O2}	Diffusion coefficient of oxygen in the granule	m^2/s
H	Reactor height	m
X_{TSS}	Mixed liquor suspended solids (sludge) concentration	$kgTSS/m^3$
k(T)	Maximum bacterial growth rate at temperature T	
n_{cycles}	Number of cycles per day per reactor	1/d
$n_{reactor}$	Number of reactors	-
R	Granule radius	m
S_F^{PDWF}	Daily peak flow factor	-
S_F^{PWWF}	Wet weather peak flow factor (= rain weather peak flow factor)	-

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest

SLR	Sludge loading rate	kgCOD/kgTSS.d
T	Temperature	°C
t	Total cycle duration	h
t_{feed}	Feeding phase duration	h
t_{react}	Reaction phase duration	h
$t_{react,day}$	Total reaction time per day	h
t_{settle}	Sludge settling phase duration	h
V_{batch}	Volume fed during a new batch cycle	m^3
V_{buffer}	Total buffer volume	m^3
$V_{reactor}$	Reactor volume (for one reactor)	m^3
v_{upflow}	Upflow velocity	m/h
VER	Volume exchange ratio	%
VER_{max}	Maximum volume exchange ratio	%
VLR	Volumetric loading rate	m^3/m^3.d
Q	Influent flow rate	m^3/h
Q^{DWF}	Dry weather flow rate	m^3/h
Q_{feed}	Flow rate during the feeding phase	m^3/h
Q^{PDWF}	Peak dry weather flow rate (= daily peak flow rate)	m^3/h
Q^{PWWF}	Peak wet weather flow rate	m^3/h
q_s^{max}	Maximum oxygen uptake rate	gO_2/gVSS.h
∂	Oxygen penetration depth	m
θ	Arrhenius coefficient	-

Abbreviation	Description
AGS	Aerobic granular sludge
CSTR	Continuous stirred tank reactor
DO	Dissolved oxygen
DWF	Dry weather flow
EBPR	Enhanced biological phosphorous removal
EPS	Extracellular polysaccharides
GAO	Glycogen accumulating organism
PAO	Phosphate accumulating organism
PDWF	Peak dry weather flow
PE	Population equivalent
PHA	Poly hydroxy-alkanoates
PWWF	Peak wet weather flow
RBCOD	Readily biodegradable COD
SBR	Sequencing batch reactor
SRT	Solid retention time
WWF_{max}	Maximum wet weather flow

Downloaded from http://iwaponline.com/ebooks/book/chapter-pdf/1217649/9781789062304_0357.pdf
by guest