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Accidental aerobic granules – data evaluation of a full-scale SBR plant

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ABSTRACT

This paper describes and evaluates a large-scale SBR with a design capacity of 35,000 p.e. where the activated sludge exhibits excellent settling properties. The sludge volume index (SVI) of all four SBR is mostly below 50 ml g^{-1} and shows annual fluctuations; the lowest values of 30 ml g^{-1} are measured during summer. The focus of this study was to identify reasons for this excellent settling behavior. Microscopic images of the sludge showed a compact and dense structure with small granules. Particle size distribution indicates that about 74.4% of the particles had a size above 200 µm, which is a characteristic size of aerobic granules. Approx. 50% of the sludge particles were larger than 320 µm. SV_{10}/SV_{30} ratio was calculated with 1.21. Based on the existing knowledge of aerobic granular sludge it can be assumed that the long filling during denitrification leads to anaerobic conditions and promotes the formation of aerobic granules. Legal requirements for the effluent quality were met the entire year. The average COD and TN removal amounted to 94.2 and 83.3%.

Keywords Aerobic granular sludge; Full-scale SBR; Anaerobic feed

1. Introduction

In recent years, a lot of research has been done in the field of aerobic granular sludge (AGS), a biomass that is characterized by a compact and dense structure with excellent settling properties. A common tool to control the thickening and settling behavior of the activated sludge is the sludge volume index (SVI). AGS is characterized by a lower SVI (< 60 ml g^{-1}) compared to flocculent sludge (80–100 ml g^{-1}). Another criterion to differentiate between aerobic granules and flocculent sludge is the use of sludge volume ratios (SV_5/SV_{30} and SV_{10}/SV_{30}). For AGS, the sludge volume after 5 or 10 min of settling is usually already close to the final sludge volume achieved after 30 min. Since the biomass settles significantly faster than flocculent activated sludge, numerous operational advantages are possible. Shorter settling and thus shorter cycle times for SBR plants in combination with a higher biomass concentration make room for higher hydraulic and organic loads. SBR processes with AGS can be applied in order to increase the capacity of existing plants especially when space is limited. Moreover, Giesen and Thompson [1] as well as by Pronk et al. [2] reported a more energy-efficient operation of AGS plants.

SBR systems are especially suitable for aerobic granulation due to the periodic feeding and the formation of feast and famine conditions. Overall, the anaerobic feed was claimed as the most relevant parameter for the formation of AGS in SBR. De Kreuk and van Loosdrecht [3] found out that the anaerobic feeding promotes the enrichment of slow growing organisms, which increase the sludge stability significantly. However, many other parameters, like sludge separation, aeration intensity and organic loading rate (OLR) also affect the sludge structure. In particular, the washout of flocculent biomass due to short settling times is mentioned in many studies to contribute to a fast granulation [4].

Most studies on AGS relate to laboratory work, thus full-scale plant experiences are limited. Pronk et al. [5] published an extensive study of a full-scale AGS plant (WWTP Garmerwolde) with a treatment capacity of 28,600 m^3 d^{-1}. With the Nereda process, the SVI was stable in a range of 35 to 45 ml g^{-1} with a TSS above 8 g L^{-1}. The percentage of gran-

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ules exceeded 80%. The dry weather operation included a 60 min plug-flow feed with an OLR of 0.1 kg COD kg TSS^{-1} d^{-1}. Li et al. [6] investigated a full-scale SBR treating approx. 50,000 m³ d^{-1}. Hereby, the SVI averaged on 47.1 ml g^{-1} with a mean diameter of 0.5 mm. The plant was operated with an A/O (anaerobic/oxic) plug-flow process and an OLR of 0.56 kg COD m³ d^{-1}. The authors report that aerobic granules could not develop, if the settling time was not well controlled, even though a periodic feast-famine regime was present. Świątczak et al. [7] investigated a full-scale WWTP after upgrading towards AGS and reported a SVI$_5$ and SVI$_{10}$ of 64 and 48 ml g^{-1}.

The present paper deals with a conventional SBR plant nearby Vienna, where stable granules were observed over several years. SVI of the activated sludge was mostly between 30 and 50 ml g^{-1}. A detailed analysis of the WWTP was undertaken to identify the reasons for this extraordinary good settling behavior. Operational data of one year were considered. Additional sludge investigations were conducted and supplemented by on line nutrient measurements.

2. Description of the plant

Fig. 1 shows a scheme of the WWTP Wolkersdorf, which includes a buffer tank with 450 m³ and four activated sludge tanks as SBR with a volume of 2,646 m³ each (21 m × 21 m × 6 m). The operation of each SBR is placed in series (e.g. SBR 1 is filled, while SBR 2 is in reaction mode). The SBR are equipped with hyperboloid stirrer, but the stirrers are only operated during feeding and between aeration with a mean daily mixing time of 4.4 h. Exchange ratios depend on the inlet flow and are normally in the range of 11–19%. The plant was designed for 35,000 p.e., while the average load amounts to approx. 15,500 p.e. (COD) with peak loads of approx. 20,000 p.e. during the wine campaign. Sludge is stabilized aerobically in the reactors and is subsequently dewatered via centrifuge. Centrate from the sludge dewatering is pumped into the buffer tank, where $FeCl_3$ is dosed for phosphate removal. The SBR are filled with wastewater from a pipeline from above under mixed conditions.

Table 1 shows the cycle time operation during dry and wet weather conditions. The dry weather operation includes a 500 min cycle with a denitrification time of 170 min. The wet weather cycle lasts 300 min with a feeding time of 60 min. Settling time is 60 min for both operation modes with a subsequent 60 min decant period. The aeration of the SBR is controlled to a set point of 2 mg DO L^{-1} and is stopped to achieve nitrification and denitrification. Moreover, pre-denitrification is achieved during the feeding time.

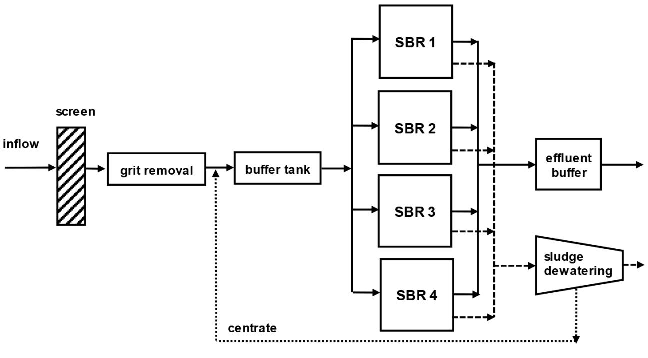

Fig. 1. Scheme of the WWTP Wolkersdorf.

Table 1
Cycle time operation during dry and rain weather conditions [min]

	Dry weather	Wet weather
Denitrification (feeding)	170 (130)	–
Aeration (feeding)	230 (0)	120 (60)
Settling	60	60
Decant	50	50

3. Wastewater characteristic

The WWTP treats municipal sewage and industrial wastewater from food industry and viniculture. About 20% of the COD results from food industry. Average COD/BOD$_5$ (biological oxygen demand) ratios was 1.6, which indicates a higher biological availability of the COD. Moreover, a metalworking company is connected to the sewer system and causes slightly increased nickel and copper concentrations. Table 2 presents the average influent concentrations as well as the 85-percentile. The sewage is characterized by a low N/COD ratio of about 0.06 (P/COD~0.01). Settle able substances in the wastewater were on average 10.7 ml L^{-1}.

4. Sludge structure and settling behavior

As a first step of the investigation, the activated sludge was examined via microscopy (Fig. 2). The images of the biomass showed a mixture of sludge flocs and compact dense granules. Numerous granules comprised sizes in a range of 200–500 µm. These compact sludge particles were colonized by many sessile ciliates, which is often reported for aerobic granules [8,9]. Moreover, the biomass obtained a high abundance of Zoogloea spp., which was also reported by [10,11]. The presence of filaments was low.

Additionally, a Malvern Mastersizer 2000 was used to analyze the particle size distribution of the activated sludge (Fig. 3). The investigated sludge sample had a SVI of 57 ml g^{-1} with a SV$_{10}$/SV$_{30}$ ratio of 1.21. VSS/TSS and COD/VSS ratio were 0.65 and 1.48, respectively. The results were compared with particle size distributions of two reference samples from a conventional activated sludge plant (CAS) in continuous-flow operation and additionally with samples of a lab-scale SBR (AGS). Detailed information on the operation of the lab-scale SBR can be retrieved from Jahn et al. [12]. Fig. 3 indicates that

Table 2
Mean influent concentration, 85-percentile during 2016

Influent	Mean	85-percentile
COD [mg L^{-1}] (*n* = 200)	770	1,034
BOD5 [mg L^{-1}] (*n* = 52)	466	580
TN [mg L^{-1}] (*n* = 202)	43.1	55.6
TP [mg L^{-1}] (*n* = 298)	7.3	9.0

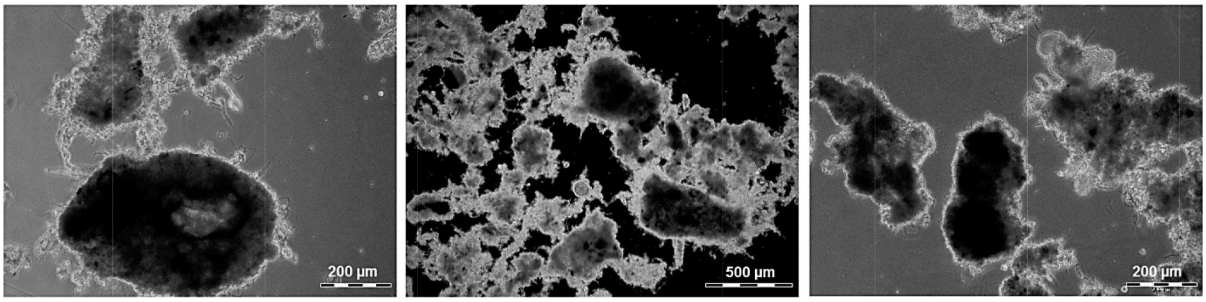

Fig. 2. Microscopic image of the activated sludge (Leica microscope).

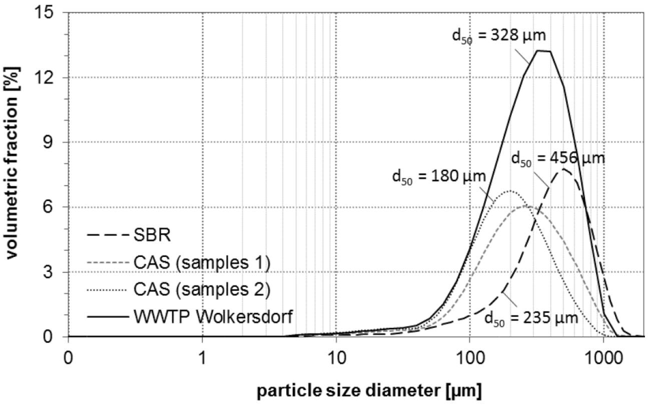

Fig. 3. Particle size distribution and d_{50} values for samples of the WWTP Wolkersdorf, CAS samples and granules from the lab-scale SBR.

the particle size diameters of the full-scale SBR plant (WWTP Wolkersdorf) were between the results of the sludge removed from the CAS and the AGS from the laboratory SBR. Approx. 10% of the particles were smaller than 117 µm, while 50% had a size above 329 µm; in total, 74.4% of the analyzed sludge particles from the WWTP Wolkersdorf reached a particle size above 200 µm, which is characteristic for aerobic granular sludge. Overall, there was a higher fraction of middle ranged particles. In comparison, the curves of the CAS samples and the granules from the SBR are more flat, which is attributed to an overall wider size range.

Fig. 4 presents the SVI of the full-scale SBR for a period of 365 days, whereby the trends are similar for all reactors. Due to refurbishment of the aeration system, SBR 3 was not in operation for 83 days during summer. After the restart of SBR 3, the SVI increased to about 50 ml g^{-1} and was thus slightly above the values measured for SBR 1, 2 and 4. Up to May, the SVI of all SBR were mostly between 40 and 50 ml g^{-1}, whereas during June and July the SVI dropped below 30 ml g^{-1}. All reactors showed a reverse correlation between the temperature and the SVI. The lowest SVI of approx. 30 ml g^{-1} was measured at 22°C, while higher SVI above 50 ml g^{-1} were related to temperatures of 15°C. Comparable, the settling velocity of the total sludge bed (flocs and granules) was 3 m h^{-1} at 15°C and 8 m h^{-1} at 22°C. Up to now, the temperature effect on AGS is only described in a few studies. Winkler et al. [13] investigated the temperature effect on granules and found a two-fold difference in the settling velocity (35–63 m h^{-1}) for the same granule by increasing the temperature from 5°C to 40°C. The authors explained this observation by the fact that the viscosity of water decreases at higher temperatures. Although, the annual difference in temperature was only about 10°C; the viscosity effect could be a reason for the overall lower settling velocities during summer. Moreover, the hydrolysis of particulate matter depends on the temperature too. An increased hydrolysis during the feed could improve the COD uptake and thus the regular growth of the granules. Otherwise, not hydrolyzed polymeric substances can cause the formation of irregular structures with decreased settling properties and higher SVI. The trend of the settling is in line with de Kreuk et al. [14], where the start-up of AGS was tested under different temperatures. A more stable granulation was detected at 20°C; in contrast to the start-up at 8°C, which lead to a more irregular growth of the granules. A further reason for poorer settling properties during winter could be the increase of filamentous bacteria, especially Microthrix parvicella was found to grow under lower temperatures [15].

A further correlation was identified between the SVI and the measured COD and TN influent concentrations (Fig. 5). Slightly increased concentrations and loads were observed by the end of the year (day 260), which correlates with increasing SVI. Average TN and COD load was 96.3 kg d^{-1} and 1,647 kg d^{-1} before day 260 and raised to 121.1 kgTN d^{-1} and 2,450 kgCOD d^{-1} afterwards. This increased load is probably attributed to the beginning of the wine campaign, which normally starts in August/September. The annual data illustrate that the higher concentrations appeared simultaneous to the declining temperatures. Thus, there could be a strengthened impact of both parameters, since changing process conditions can affect the microbial composition of the biomass, which can further affect the settling properties and SVI [16].

5. Treatment performance

Table 3 presents the average effluent concentrations as well as the 85-percentile of the measured data. The effluent concentrations and removal efficiencies complied with the legal requirements throughout the year. Average COD and BOD removal achieved 94.2% and 98.3%. TP removal amounted to 94.3% with an average effluent concentration of 0.4 mg L^{-1} and TN removal was calculated to be 83.3%. OLR was nearly constant over the year with an average value of 0.06 kgCOD kg TSS^{-1} d^{-1}, the volumetric loading was 0.23 kgCOD m^{3} d^{-1}. No settable substances were measured in the effluent, indicating that the biomass was completely retained in the SBR and not washed out during decant.

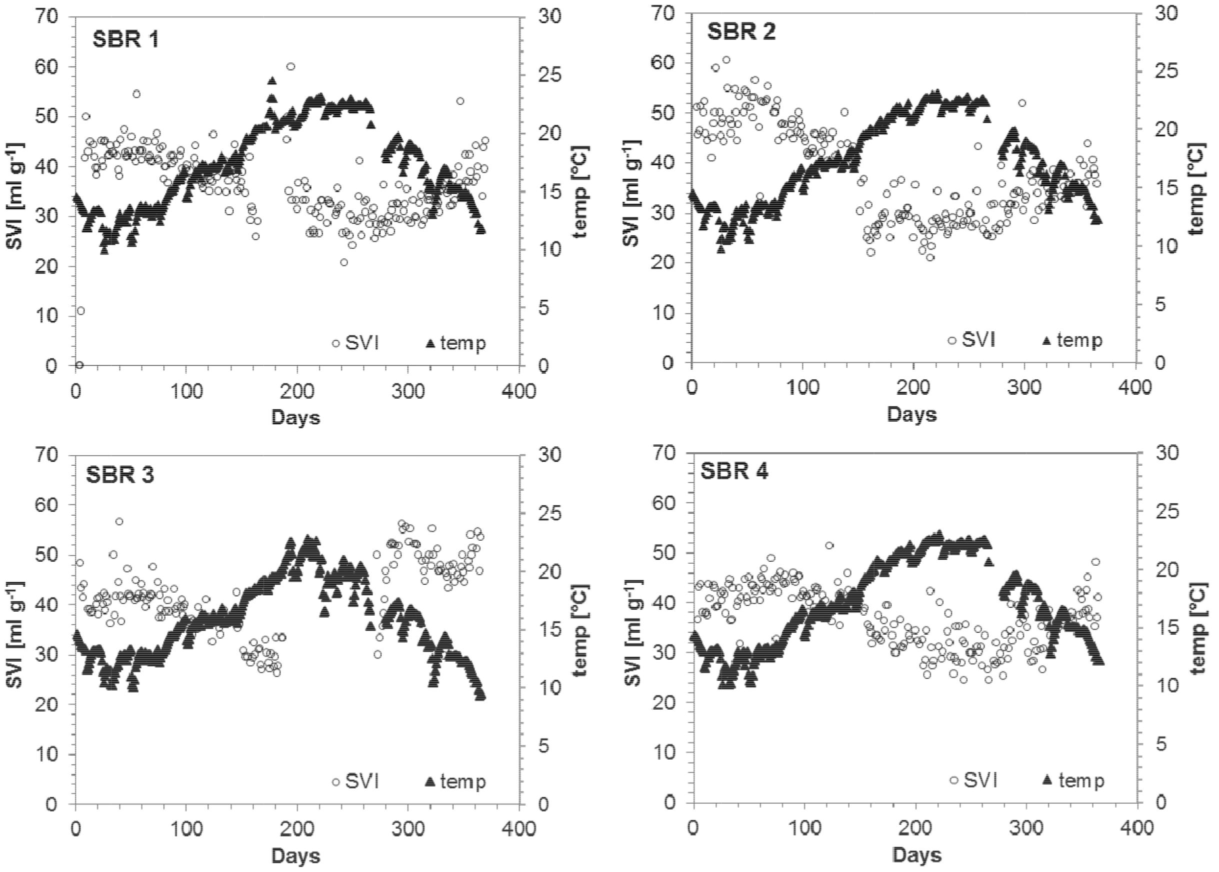

Fig. 4. SVI and temperatures of the SBR over a period of one year, starting in January.

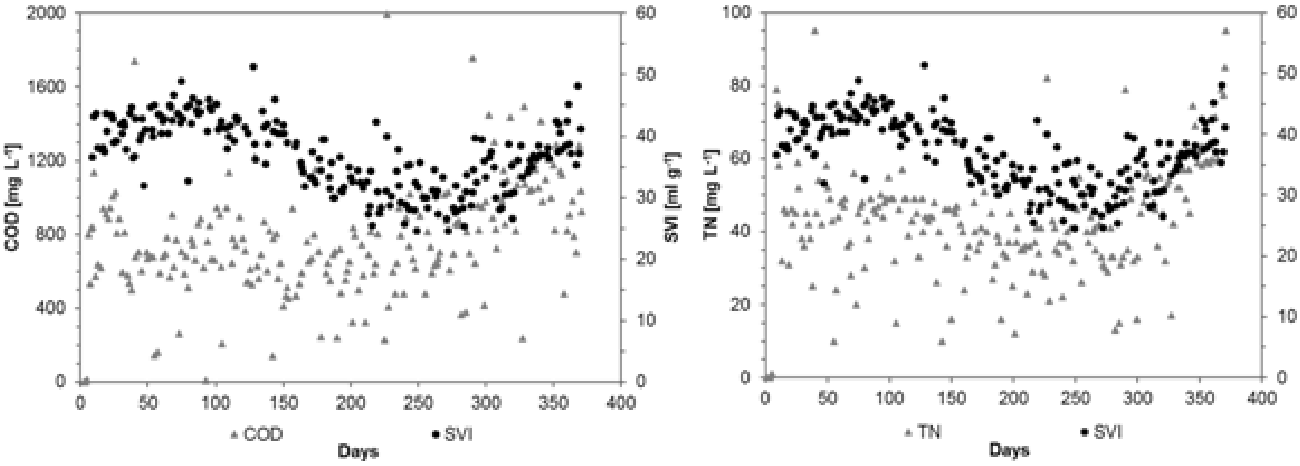

Fig. 5. COD (left) and TN (right) influent concentration and SVI (SBR 4).

Table 3
Mean effluent concentration, 85-percentile during 2016

Effluent	Mean	85-percentile
COD [mg L^{-1}] (*n* = 209)	25.4	30.5
BOD5 [mg L^{-1}] (*n* = 52)	7.3	10.0
TN [mg L^{-1}] (*n* = 202)	6.4	9.0
TP [mg L^{-1}] (*n* = 298)	0.4	0.5

In order to describe the processes in the SBR, the NO_3-N concentrations and the DO were monitored in SBR 3 during a period of 10 d dry weather mode. Fig. 6 shows the course of the measured concentrations during the cycle operation (A-E). Based on the data it can be concluded, that there were no fully anaerobic conditions during feeding (A), since NO_3N effluent concentrations were measured up to 5.0 mg L^{-1}. Anaerobic feeding conditions were established as soon as the NO_3N was depleted (pre-denitrification). Low

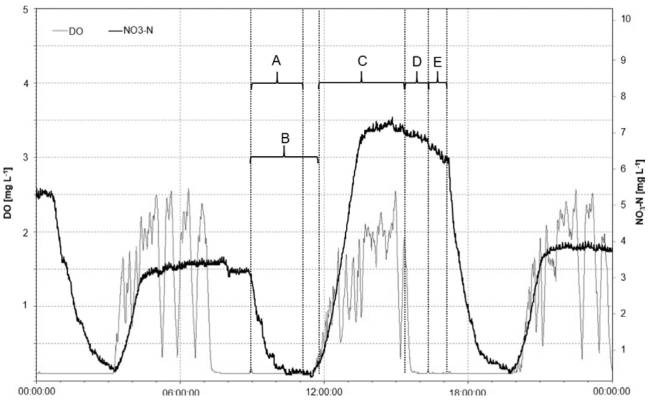

Fig. 6. Exemplary cycle for SBR 3 (A: Feeding, B: Denitrification, C: Aeration, D: Sedimentation, E: Decant), NO_3-N and DO under dry weather operation.

NO_3-N effluent concentrations (Fig. 6, first cycle: $NO_3N < 2$ mg L^{-1}) were found to increase the anaerobic time up to 1 h. Anaerobic conditions during the feed are generally the most important parameter for an aerobic granulation [16]. Thwaites et al. [18] investigated the performance of a split anaerobic-aerobic feed to a complete anaerobic feed and found comparable results for the granulation. This study is similar to the feeding conditions of the WWTP Wolkersdorf, although this operation included first the anaerobic and then aerobic conditions. During settling and decant, NO_3-N was nearly constant since there was no further contact between the settled biomass and the purified wastewater limiting biological reactions.

During the year, TSS in the SBR ranged between 3.4 and 3.7 g L^{-1} with an ash content of 67%. Excess sludge production varied between 0.38 and 0.40 gTSS $gCOD^{-1}$, which is in line with the theoretical excess sludge production calculated according to ATV-DVWK-A 131 (2016). Muda et al. [19] reported an excess sludge production in the range of 0.24 to 0.41 gTSS $gCOD^{-1}$ for AGS, with a decreasing sludge production correlated to an increasing sludge retention time (SRT). Pronk et al. [5] reported a SRT of 20 to 38 d for a large-scale Nereda plant. At the WWTP Wolkersdorf, the SRT amounted to approx. 40 to 50 d, being in the range of plants operated for AGS.

The specific energy consumption of the biological stage was 21.6 kWh (p.e. $a)^{-1}$ with a total energy consumption of approx. 43 kWh (p.e. $a)^{-1}$. These values are in the common range for Austrian WWTP with aerobic stabilization and an average energy consumption of 43 kWh (p.e. $a)^{-1}$ [20].

6. Discussion

The presented data of the SVI, particle size distribution and the microscopic images confirm that the activated sludge of the WWTP Wolkersdorf have great similarities to AGS. In the following part, potential reasons for the aerobic granular sludge formation on this WWTP are discussed considering known parameters for improving the sludge structure and settling behavior.

In order to face an upcoming demographic increase of the region, the WWTP has currently some spare capacity. Although, the sewage is characterized by high COD concentration (mean 770 mg L^{-1}), the average OLR was 0.06 kgCOD $kgTSS^{-1}$ d^{-1} and thus in a range reported by Pronk et al. [5] for a large-scale Nereda plant. De Kreuk and van Loosdrecht [21] state that the COD load is an important process parameter for large-scale operation, especially the availability of carbon during the feed is essential for the granulation. High concentrations of organic substances allow a deep diffusion into the core of the granules; consequently, the substrate is also available to microorganisms in the inner zones. This increased diffusion effect is strengthened by high substrate concentrations and can be seen as a driving force towards larger granules. Furthermore, the availability of the carbon source was found to effect the granules formation too. Adler et al. [22] investigated the AGS structure and nitrogen removal under different substrates and found the largest granules for the reactor fed with volatile fatty acids. An easy available carbon source is almost completely stored during the anaerobic feed, which causes a slow grow rate of the heterotrophs with a compact granules formation. In contrast, more complex substrates and particulate COD were found to promote the growth of irregular structures [9,22,23]. An irregular growth appears, when particulate substrates are not completely hydrolyzed during the anaerobic phase. Thus, the substrate is available in the aerated phase and favors a fast heterotrophic growth that can lead to irregular forms [22]. The sewage to the WWTP Wolkersdorf is dominated by a large portion of industrial wastewater from food industry, which is reflected in the lower COD/BOD_5 ratio. Thus, it is assumed, that in the present study an easily available carbon source contributes to the regular formation of granules since the COD is stored during the anaerobic phase. In the case of an incomplete COD uptake, COD is available in the aerobic phase and can cause an irregular growth [24]. A possibility to improve the anaerobic COD uptake is the enlargement of the anaerobic contact time with an increased hydrolysis of particulate organic matter [23]. A further driver for the granulation is the nutrient to carbon ratio. The average N/COD ratio of the influent to the WWTP Wolkersdorf was 0.06. This low N/COD ratio of the wastewater promotes a high nitrogen removal (denitrification), which in turn ensures enlarged anaerobic conditions during the feed.

Furthermore, it was assumed that the metalworking company and the increased heavy metals are beneficial to the sludge structure by increasing the weight of the activated sludge. Fig. 7 shows the heavy metal concentrations in the sewage sludge of the WWTP Wolkersdorf in comparison to average values from Germany (BMU, 2015) and Austria [25]. The data indicate that the copper, nickel and chrome concentrations were only slightly increased compared to the published average values, while other heavy metals were in the common range for municipal WWTP. Thus, an effect of the heavy metals on the sludge structure due to metal precipitation can be excluded.

Operational data of the WWTP Wolkersdorf indicate that it is possible to develop aerobic granules on a full-scale SBR plant. The operation was contradictory to the known AGS process, since there was no plug-flow feed applied. Generally, the anaerobic plug-flow feed without mixing is considered as the most favorable feeding strategy since they result in high substrate gradients in the sludge bed, which promote the growth of substrate-storing organisms.

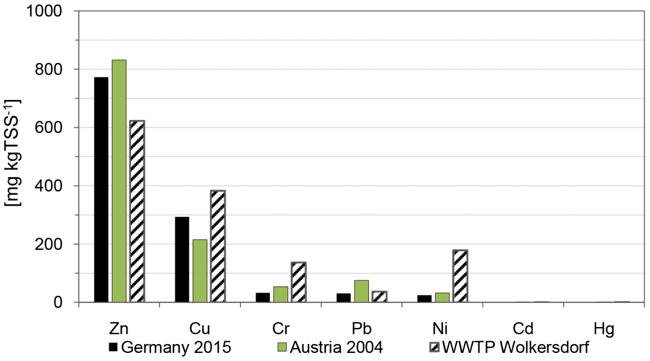

Fig. 7. Heavy metals contents in sewage sludge compared to average values from Germany (average) and Austria (median).

Aerobic granulation is mostly linked to the accumulation of substrate-storing organisms, whereby the operation mode is primarily intended to promote the enrichment of phosphate-accumulating organisms (PAO). PAO are able to create polyphosphate storage and promote the aerobic granulation due to a slow growth rate. Furthermore, P-accumulating granules are characterized by an overall higher density [26]. Lin et al. [27] investigated the effect of different P/COD ratios on the SVI and specific gravity of aerobic granules and found a higher specific gravity and lower SVI with increasing P/COD ratios. This observation was explained by the fact that a higher phosphate availability promotes the accumulation of P-storing organisms. Aerobic granules that were fed with a P/COD ratio of 0.01 in the wastewater had a SVI of approx. 30 ml g^{-1}. These results are similar to the sludge of the WWTP Wolkersdorf where the mean P/COD ratio was 0.01. Based on the operating data, the β-value of the system was calculated. This parameter indicates the molar relationship between the precipitant consumption and the removed phosphorus. A β-value below 1.0 usually indicates an enhanced biological phosphorus removal (EBPR). The annual average of the ß-value of the WWTP Wolkersdorf was above 1.5 and thus in a range for municipal WWTP without EBPR. In addition to PAO, aerobic granulation can also occur by the accumulation of glycogen-storing bacteria (GAO) [3]. These organisms are able to create storage polymer like PHB without an increased P-uptake. Unfortunately, there are no data available for the microbial composition of the sludge. Thus, it is recommended to differentiate the microbial composition by further investigations via DNA sequencing or FISH.

On the WWTP Wolkersdorf, the feeding is applied during denitrification by a pipeline from above, i.e. no plug-flow conditions are possible. However, due to the relatively low NO_3-N concentrations in the effluent, it was proven that anaerobic conditions are achieved within the denitrification and feeding phase. Compared to previous large-scale Nereda systems, the activated sludge of the WWTP Wolkersdorf is stirred during feeding as well as between the aeration intervals. The influence of stirrers on the aerobic granular biomass has not yet been fully described yet; only a few studies investigated the effect of stirrers on the aerobic granular sludge. For example, Nor Anuar et al. [28] found a slightly decreased settling velocity with an increased shear stress. Rocktäschel et al. [29] reported smaller granules as a result of stirring during the anaerobic feed compared to complete plug-flow feeding conditions. However, this observation is probably more related to the lower substrate gradient caused by mixing. SBR tanks of the WWTP Wolkersdorf are equipped with hyperboloid stirrers. This type of stirrer is generally considered to be gentle to the sludge structure since the flow direction of the particles is only switched and the particles are not destroyed by the mixing plates. The overall mixing time is quite short with approx. 4–5 h d^{-1}.

Large-scale plants, which are designed according to the Nereda technology, are characterized by a simultaneous feeding and decant phase [5]. In the case of the WWTP Wolkersdorf, the sedimentation takes place over a period of 60 min with a separate withdrawal of likewise 60 min. A reduction of the settling time is not necessary, as the capacity of the plant is currently not limited. Flocs are kept in the system, which allows the assumption that the washout of slow settable biomass is less important for the granulation than the need for anaerobic feeding conditions.

7. Summary

The operational data of the WWTP Wolkersdorf indicates that aerobic granular sludge with excellent settling properties (SVI: 30 to 50 ml g^{-1}) developed at a full-scale SBR plant treating municipal and industrial wastewater without special design considerations for aerobic granular sludge. The granules formation on this plant can be seen as an interaction of different favorable parameters. Especially, the anaerobic feed was identified as a driving force for aerobic granules. Moreover, the sewage composition with an increased proportion of readily available carbon and a low N/COD ratio is favorable for the formation of granules on this WWTP. The results show that a high selection pressure (short settling time) is not crucial to form aerobic granules. Our conclusion of this study is that the presented SBR operation promotes the formation of granules-like aggregates, since there was a long filling time applied under non-aerated conditions. We assume that changing the SBR operation mode towards this strategy could have a positive effect on the sludge settling of existing SBR plants.

Acknowledgement

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