Complete solids retention activated sludge process
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ABSTRACT

In a slaughterhouse’s full-scale extended aeration activated sludge wastewater treatment plant (WWTP), operating under complete solids retention time, the evolution of mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids (MLVSS) concentration, food to micro-organisms ratio (F/M) and substrate utilization rate (SUR) were studied for over a year. Biomass growth phases in correlation to sludge biological and morphological characteristics were studied. Three distinguished growth phases were observed during the 425 days of monitoring. The imposed operational conditions led the process to extended biomass starvation conditions, minimum F/M, minimum SUR and predator species growth. MLSS and MLVSS reached a stabilization phase (plateau phase) where almost zero sludge accumulation was observed. The concept of degradation of the considered non-biodegradable particulate compounds in influent and in biomass (cell debris) was also studied. Comparison of evolution of observed sludge yields (Y_{obs}) in the WWTP with Y_{obs} predictions by activated sludge models verified the degradation concept for the considered non-biodegradable compounds. Control of the sedimentation process was achieved, by predicting the solids loading rate critical point using state point analysis and stirred/unstirred settling velocity tests and by applying a high return activated sludge rate. The nitrogen gas related sedimentation problems were taken into consideration.

Key words | activated sludge, complete solids retention, non-biodegradable fractions degradation, sedimentation efficiency, zero net biomass production

INTRODUCTION

The activated sludge (AS) process has been widely used for the treatment of municipal and industrial wastewaters. Due to the nature of the AS process, a large amount of excess sludge is generated daily, depending on influent substrate load, biodegradability of organic pollutants, degradation rate of microbial cells (by endogenous respiration or by cellular lysis) and existence of predator bacteria (Rocher et al. 1999). Recently, many investigations have been oriented to reduce the sludge production in AS wastewater treatment plants (WWTPs), because management and treatment of sludge account for more than 50% of the construction and operating cost (Liu & Tay 2004; Foladori et al. 2010).

According to many researchers, following the endogenous decay, a portion of cell mass (10–15%, cell walls), considered as non-biodegradable particulate organic matter (‘non-biodegradable’ particulate matter, cell debris, X_e), is not dissolved and is accumulated in the system, likewise the influent ‘non-biodegradable’ volatile suspended solids (X_{vs}). These ‘non-biodegradable’ particulate fractions of organics, which are considered biologically inert, become enmeshed in the AS and can be removed through sludge wastage, while the considered non-biodegradable soluble fractions pass through an AS system unchanged in form (Henze et al. 2000; Fenu et al. 2010). This suggests that volatile suspended solids (VSS) accumulation would eventually cause a sludge overload with a negative impact on WWTP’s treatment efficiency.

One approach to minimize the observed sludge yields (Y_{obs}) can be brought about by amplifying microbial cell lysis and generating biomass growth on the lysis products, which is defined as the cryptic growth (Rocher et al. 1999; Liu & Tay 2004). Starvation conditions that occur in high solids retention time (SRT) processes enhance cryptic growth, due to the high biomass concentration and the low food to micro-organisms ratios (F/M). Additionally, sludge minimization through bacterial ecosystem manipulation can be achieved, beside the high SRT, at different operating regimes (extended aeration, cyclic alteration between anaerobic anoxic and oxic conditions, etc.) that
promote metabolic changes and predating bacteria growth (Loosdrecht & Henze 1999; Foladori et al. 2010; Amanatidou et al. 2015b).

According to Amanatidou et al. (2015b) at full-scale AS WWTPs, complete solids retention (no waste sludge), extended aeration, high dissolved oxygen (DO) and high mixed liquor volatile suspended solids (MLVSS), lead to extended starvation conditions and predator species growth. When no sludge is discharged from an AS system, the resulting biomass age is almost equal to WWTP operation days (Henze et al. 2008). In such a process where no sludge is discharged, referred to as complete SRT AS process, new cell production rate becomes equal to the decay rate and the predation phenomena, and sludge observed yields are minimal and tending to zero values (Loosdrecht & Henze 1999; Foladori et al. 2010, Amanatidou et al. 2015b). Additionally, studies conducted on membrane bioreactors operating at high SRT up to complete retention of solids indicated that biomass production was equilibrated by biomass loss (endogenous metabolism, death, lysis and predation) or that influent substrate was completely oxidized for cell maintenance (Henze et al. 2000; Sperandio et al. 2013).

The most commonly encountered problem in high SRT AS WWTPs, especially in membraneless AS processes, is the low sedimentation efficiency (turbid effluent) that is observed due to the increased mixed liquor suspended solids (MLSS) concentration, the alterations of floc morphology and the possible growth of unwanted bacterial species, such as filamentous bacteria (Orhon & Artan 1994; Amanatidou et al. 2015a). Control of clarification efficiency in a secondary clarifier and of biomass morphological and biological characteristics is essential in order to apply complete SRT membraneless AS processes.

Solids accumulation in an AS process, expressed as $Y_{\text{obs}}$, can be predicted by activated sludge models (ASMs). Discrepancies in the $Y_{\text{obs}}$ predictions between the ASM frameworks and the $Y_{\text{obs}}$ measured in high SRT AS processes result in overestimation of solids accumulation in a WWTP. ASM-based evaluation of sludge production in high SRT AS processes can verify the suggested biodegradability of the considered non-biodegradable organic particulate compounds (Hay et al. 2006; Lubello et al. 2009; Fenu et al. 2010; Sperandio et al. 2013).

It is well known that WWTP operating conditions are linked to the biological and morphological characteristics of AS and to microbial manipulation, which influence the sedimentation process, treatment efficiency and net sludge production (Wei et al. 2005; Amanatidou et al. 2015a, 2015b). Generally, operating conditions that affect AS morphological and biological characteristics in biological treatment, selected in such a way that desired bacteria are accumulated, are the MLSS concentration, the F/M, the substrate utilization rate (SUR), the SRT, the hydraulic retention time (HRT), the DO and the return activated sludge (RAS) rate. Additionally, wastewater-dependent parameters such as volumetric and nutrients load can affect AS characteristics such as floc cohesiveness and microbial species diversity (Liu & Tay 2004).

This study presents a successful implementation of a complete solids retention process in a slaughterhouse’s full-scale extended aeration AS WWTP, operating at high MLSS concentration, low F/M, high HRT and high RAS, where almost zero net biomass growth was achieved. The aim of this work is to study the biomass growth phases in correlation to the WWTP’s operational conditions, wastewater characteristics and biomass biological and morphological characteristics. The concept of ‘non-biodegradable’ particulate organic fraction degradation by two ASMs is also discussed. The investigation offers new aspects on AS processes and contributes to cost minimization and efficient treatment and control of complete SRT AS WWTPs, towards zero net sludge production.

**MATERIALS AND METHODS**

A slaughterhouse’s full-scale AS WWTP, operating under complete solids retention, was studied for 425 days. The evolution of MLSS and MLVSS, F/M, SUR and $Y_{\text{obs}}$ was monitored in order to study the biomass growth phases in correlation to sludge biological and morphological characteristics. $Y_{\text{obs}}$ evolution was compared to the classic and modified ASM predictions. Sedimentation efficiency was evaluated in order to control the settling process and ensure good effluent quality. State point analysis based on stirred/unstirred settling velocity tests was performed in order to predict the solids loading rate (SLR) critical point, while taking into consideration the influence of chemical oxygen demand (COD) to nitrogen ratio in nitrogen gas related sedimentation problems.

The WWTP is installed in the Prosotsani municipality of Drama Prefecture, Northern Greece, and consists of two subsystems (Figure 1): (a) a preliminary simultaneous nitrification/denitrification system (SNdN) and (b) a pre-anoxic, complete mix, complete SRT, extended aeration system (PCMAS). The preliminary system has a sedimentation tank with internal recycle of solids. The effluent and the waste sludge is transferred (inflow) in the PCMAS system. Before the SNdN system, primary treatment (automated
bar screen, decanter, aerated flow and load equalization tank) is performed.

A total of 20 samples were taken and analyzed by applying standard methods (Table 1) at an accredited by ISO 17025:2005 laboratory. Furthermore, microscopic analysis for the AS morphological and microbiological characteristics was performed using a Leica DM 1000 phase contrast microscope at ×40 to ×1,000 magnification, within 4 h of sample collection.

The concept of degradation of the considered non-biodegradable compounds was tested through ASM simulations and by comparing the predicted Yobs yields to those measured. Two ASM-based Yobs prediction models were used, one that takes into account the endogenous respiration concept (classic ASM) and another (modified ASM) that adds an additional degradation concept concerning the degradation of endogenous particulate residue (X_E) and particulate ‘non-biodegradable’ organics in influent (X_U), as a first order kinetic reaction (Sperandio et al. 2015).

**RESULTS AND DISCUSSION**

The preliminary SNDN was operated at a relatively constant MLSS concentration of 5 g L⁻¹ and at relatively low DO levels (0.2–0.8 mg L⁻¹), high SRT (approximately 29 days) and high HRT (1.125 days). The pre-anoxic denitrification, complete mix, extended aeration AS system was operated under complete solids retention, highly aerobic conditions in aeration basin (DO > 4 mg L⁻¹) and under high HRT (1.25 and 2.25 days in pre-anoxic and aerobic tanks, respectively). The total oxygen consumption was approximately 410 kgO₂ d⁻¹ and the actual amount of oxygen was approximately 940 kgO₂ d⁻¹, for the DO operating level of 4 mg L⁻¹. These amounts are only 32% higher than of a town with the same equivalent population operating at DO levels of 2 mg L⁻¹ (Metcalf & Eddy 2005) and the difference in aeration cost is more than compensated for by the waste sludge management and treatment negligible cost.

The RAS rate of the PCMAS system was regulated depending on the MLSS concentration from 600 to 1,000%, causing forced sedimentation of sludge and resulting low condensation of sludge in the settler (suspended solids concentration in the recycle flow, X_U, = 1 to 1.5 MLSS).

The SNDN system achieved average COD and total nitrogen (TN) reduction of approximately 32%. Under the imposed low DO concentration conditions, low COD removal and low nitrification rates resulted, as the AS flocs were partially aerobic, while denitrification occurred in the anoxic zones within the floc particles due to oxygen depletion (Holman & Wareham 2005). The PCMAS system obtained average COD and TN removal efficiencies of 95% and 85%, respectively. This high performance was achieved mainly due to highly aerobic conditions in the aeration tank and due to the high

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**Table 1** | Measured influent and effluent quality characteristics in WWTP and methods of analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Standard Methods (APHA 2012)</th>
<th>SNDN influent</th>
<th>PCMAS influent</th>
<th>PCMAS effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD (mg L⁻¹)</td>
<td>5220-COD C</td>
<td>4,150</td>
<td>2,835</td>
<td>36</td>
</tr>
<tr>
<td>BOD₅ (mg L⁻¹)</td>
<td>5210 B 5 Day BOD test</td>
<td>2,380</td>
<td>1,720</td>
<td>20</td>
</tr>
<tr>
<td>BOD₂₀ (mg L⁻¹)</td>
<td>5210 B Ultimate test</td>
<td>3,790</td>
<td>2,650</td>
<td>34</td>
</tr>
<tr>
<td>TKN (mgN L⁻¹)</td>
<td>4500-Norg C</td>
<td>250</td>
<td>165</td>
<td>&lt;2</td>
</tr>
<tr>
<td>Total nitrogen (mgN L⁻¹)</td>
<td>4500-Norg C</td>
<td>450– NO₂ B</td>
<td>272</td>
<td>184</td>
</tr>
<tr>
<td>pH</td>
<td>4500-H⁺ B</td>
<td>7.2</td>
<td>7.6</td>
<td>6.9</td>
</tr>
<tr>
<td>TSS (mg L⁻¹)</td>
<td>2540–D TSS</td>
<td>470</td>
<td>510</td>
<td>&lt;30</td>
</tr>
<tr>
<td>VSS (mg L⁻¹)</td>
<td>2540–E VSS</td>
<td>450</td>
<td>460</td>
<td>&lt;20</td>
</tr>
</tbody>
</table>

*Mean values from 20 measurements.
TSS: total suspended solids.
biomass concentration resulting from complete SRT (Lubbeke et al. 1995; Amanatidou et al. 2009). Furthermore, because of the high SRT and the highly aerated sludge, relatively small flocs were produced (pinpoint) but with good compactness, which assisted in obtaining relatively low sludge volume index values and good sedimentation efficiency. The total Kjeldahl nitrogen (TKN) concentration of less than 2 mg L\(^{-1}\) in effluent indicated almost complete nitrification. The entire WWTP reached overall COD and TN removal efficiencies of 98\% and 90\%, respectively. The mean COD:N:P ratio in influent was 150:9.8:1.8, indicating sufficient nutrient content with a relatively high concentration of nitrogen compounds, while the average BOD\(_{20}/\)COD and BOD\(_u/\)COD (BOD\(_u\): derived from ultimate biochemical oxygen demand (BOD) test) ratios were 0.91 and 0.98, respectively, indicating high influent biodegradability. The low non-biodegradable fractions are attributed to the nature of the wastewater – slaughterhouse wastewaters are considered highly biodegradable (Pozo et al. 2005) – and to the performed primary and preliminary treatment.

The wastewater characteristics in all WWTP stages (SNdN influent, PCMAS influent and effluent) are presented in Table 1.

The PCMAS system showed an increase of MLSS and MLVSS concentration until the 180th day (Figure 2). The imposed operational conditions in the WWTP resulted in extended biomass starvation conditions, growth of predator species, and MLSS and MLVSS reaching a plateau phase (stabilization phase), where low F/M ratios, low SUR values and almost zero sludge accumulation were observed (Figure 2). Three distinguished growth phases were observed that can be described as: (a) startup and high growth phase (1st – 90th day), where micro-organisms indicative of young AS were observed (free-swimming bacteriovorous ciliates, and small heterotrophic flagellates), (b) low growth phase (90th – 180th day), with mature biomass species (free-swimming ciliates, crawling ciliates, stalk ciliates and rotifers – metazoans) and good floc aggregation, and (c) stabilization phase (180th – 425th day), with almost zero observed biomass production, where old biomass microbial species (free-swimming ciliates, crawling ciliates, stalk ciliates and rotifers-metazoan) and pinpoint flocs were observed. The duration of each phase significantly varies between different WWTPs and depends on various parameters, such as organic load, SRT and wastewater type. It must be noted that ciliates are very sensitive to environmental variations, including even low levels of toxicity (Guizani et al. 2014; Guizani & Funamizu 2014), and are recognized as indicators of the operation conditions of the plant (Nicolau et al. 2001).

In the PCMAS system, the F/M ratio decreased proportionally to the MLVSS evolution and on the 90th day reached a value of 0.105 kgBOD\(_5\) kgMLVSS\(^{-1}\) d\(^{-1}\) were obtained corresponding to the extended aeration maximum value, while after the

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**Figure 2 | MLSS, MLVSS, Y\(_{obs}\), SUR, and F/M evolution in the slaughterhouse’s complete solids retention AS WWTP and ASM Y\(_{obs}\) predictions.**
180th day values of 0.06–0.055 kgBOD₅ kgMLVSS⁻¹ d⁻¹ were obtained, corresponding to the extended aeration minimum value. During the period of biomass growth (excess of substrate), growth dominated against the endogenous processes. In the plateau phase low growth rates resulted and the MLVSS/MLSS ratio maintained relatively constant (approximately 0.8), while MLSS and MLVSS concentrations were 16,500–18,500 mg L⁻¹ and 13,200–14,000 mg L⁻¹ respectively. Extended microbial starvation conditions and limited microbial growth (endogenous phase and cryptic growth phenomena) characterized the plateau phase. The high wastewater biodegradability, the high treatment efficiency, the relatively constant solids concentration and MLVSS/MLSS ratio after the 180th day indicate that the considered non-biodegradable fractions of influent particulate organic matter and of biomass are biodegradable and that zero net biomass growth can be achieved. This conclusion does not contradict the prevailing view, which considers cell debris as non-biodegradable for typical SRT values. Similar results were reported by Muller et al. (2004) in an aerobic wastewater treatment pilot plant, with cross-flow filtration and complete solids retention, for a period of 300 days.

The degradation concept of the 'non-biodegradable' compounds, in complete solids retention AS processes, was verified by the comparison of the two ASMs' $Y_{obs}$ predictions with the measured $Y_{obs}$ values. The data used in the ASM simulation runs were obtained from the ASM default values presented in Sperandio et al. (2013), from wastewater fractionation, based on the Park et al. (1997) study and the assumption that the BOD₅ test describes the biodegradable COD. The graphical presentation of the decrease in measured $Y_{obs}$ with increasing SRT fits well the modified ASM curve, while the classic ASM curve remains almost steady regardless of SRT (Figure 2). The modified ASM better predicted the observed sludge yields due to the incorporated degradation process of $X_U$ and $X_E$ fractions. When compared to the modified ASM, the classic ASM reveals its weakness in predicting solids accumulation at high SRT up to complete solids retention, as it overestimates $Y_{obs}$ (Hay et al. 2003). At steady state operating conditions, the PCMAS obtained a mean $Y_{obs}$ value of 0.012 kgVSS kgCOD⁻¹. Consequently, the annual total solids accumulation is 1.6 tons, of which 1.37 tons are non-volatile suspended solids.

The modified ASM predictions that better describe the observed solids accumulation strengthen the hypothesis that under complete SRT and specific operational conditions all particulate organics are degraded.

The complete retention of solids in the PCMAS system resulted in increase of MLSS up to a point where the high solids concentration blocked sedimentation due to gravity, because of the decrease in settling velocity. In this case, the downward movement of the solids is only due to recyling flow (forced sedimentation), which can be determined and set, and that is why it is preferred for the whole process control (Amanatidou et al. 2015a).

Additionally, the high RAS rate is important in order to reduce sludge retention in the settling tank and to prevent accidental denitrification that may cause floating sludge phenomena. Previous study and comparison of solids flux curves between two identical systems treating slaughterhouse wastewaters with different COD:N ratios revealed that, when nitrogen content is high (COD:N:P ratio about 100:12:1), large quantities of denitrification gases are trapped in sludge flocs (Amanatidou et al. 2015a). The trapped nitrogen gas affects sludge settling velocity and
gravity solids flux. This is obvious in Figure 3 where the plotted stirred and unstirred gravity solids flux curves differ in curve height, indicating significant gas entrapment in sludge flocs, that narrows the WWTP operating range.

The underflow line in Figure 3 (RAS 1,000%), at the corresponding state point of 15 kg m\(^{-3}\), is tangent to the gravity flux curve and represents the limiting solids flux, whatever the stirring conditions. This point represents the limit over which a further increase of MLSS concentration will lead to sedimentation problems (Figure 3, RAS rate 1,500%), as the underflow line will cross the lower limb of the gravity flux curve, and elevation of the clarifier blanket to the effluent weir will occur. In order to avoid such problems, a RAS rate of 600% was selected. This value ensures good settling efficiency, while maintaining low HRT in the clarifier, which prevents accidental denitrification. The underflow line then falls well below the lower limb of the gravity flux curve, ensuring good effluent quality even at MLSS concentration higher than 15 kg m\(^{-3}\). The solids flux analysis indicates the SLR and RAS critical values, where efficient sedimentation occurs. When the critical point of SLR is reached, regulation of RAS rate to an optimum value is necessary (Amanatidou et al. 2015a).

It is noteworthy that filamentous and nematode species where not observed during the 425 days of operation. Nematodes are crawling species that are usually encountered in high SRT and high DO wastewater treatment processes. High DO in the extended aeration tank, sufficient nutrient content and an SNdN system, described as an anoxic/aerobic selector that reduces readily biodegradable substrate (rbCOD), prevented the growth of filamentous micro-organisms (Henze et al. 2008). In the WWTP studied they are present in relatively small numbers because the pinpoint flocs of AS at the stabilization phase are not suitable for crawling, which these species prefer over the free-swimming mode.

The overall WWTP energy consumption is 0.93 kWh kgBOD\(_{\text{removed}}\)^{\text{1}} (nitrogen removal included). This value is among the lowest energy consumptions given in the literature (Yang et al. 2010; Bodík & Kubášek 2015).

CONCLUSIONS

Complete solids retention and specific operating conditions applied in an AS WWTP treating high strength, biodegradable wastewaters results in: (a) increase of biomass concentration until a stabilization (plateau) phase; (b) negligible sludge yields; (c) degradation of the considered non-biodegradable particulate compounds in influent and in biomass, an assumption that was verified by AS models for Y_{obs} prediction. AS growth is characterized by three discrete phases with different biomass morphological and microbiological characteristics. The duration of each phase significantly varies between different WWTPs and depends on various parameters, such as wastewater type, organic load and SRT. Sedimentation control is achieved by high sludge recycle rates.

REFERENCES


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