Oxygen requirements in relation to sludge age in wastewater treatment plants

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Abstract. Sustainability of activated sludge (AS) wastewater treatment processes is inexplicably linked to minimization of secondary wastes, such as waste sludge, as well as energy requirements for achieving effluent quality standards. Oxygen requirements and waste sludge management accounts for most of energy consumption in aerobic AS wastewater treatment plants (WWTPs). In this study, a novel, highly aerobic AS process, entitled complete solids retention AS process (CRAS), is being evaluated in terms of waste sludge production and biomass oxygen utilization rate. Aim of this work is to study the effect of solids retention time (SRT) on observed sludge yields and on oxygen requirements for respiration in order to evaluate CRAS process as a sustainable alternative to typical activated sludge processes.

1. Introduction

Design and operation of AS wastewater treatment plants (WWTPs) have been improved to meet more stringent effluent quality standards and additional environmental goals such as improved energy savings and reliability, reduced carbon footprint, low biosolids production and effluent concentrations of emerging contaminants [1]. For these targets the modification of design and operational parameters such as observed sludge yields ($Y_{\text{max}}, Y_{\text{obs}}$), biomass concentration ($MLVSS$), solids retention time (SRT), oxygen demand (OD), sludge recycle rate etc. is necessary. The SRT is the key parameter which influences the operational conditions, the bioreactors volume and the investment cost [2, 3]. According to literature, high SRT is linked to increasing oxygen demands for aeration and high biomass concentration in the aerobic bioreactor [4]. In high SRT small amount of sludge is rejected, microbial manipulation and low growth rate ($Y_{\text{max}}, Y_{\text{obs}}$) is achieved [5]. Respectively, in low SRT large amount of sludge is rejected, in which further treatment is required.

The OD is linked to oxygen uptake rate (OUR) and specific oxygen uptake rate (SOUR). The oxygen uptake rate (OUR) or oxygen consumption rate is one of the most important variables for estimating biological activity in AS processes, quantifying the AS metabolism rate and expresses the oxygen consumption per time unit. OUR is proportional to the microorganism concentration, depends on the quality of the incoming wastewater and is suitable for monitoring and control of the AS processes. SOUR, also known as the oxygen consumption or respiration rate, is defined as the milligram of oxygen consumed per gram of volatile suspended solids (VSS) per hour and calculating by dividing the OUR by the MLVSS concentration [6, 7]. SOUR is a relative measure of the rate of biological activity [19]. The bioactivity decreased as SRT increases [20]. As microorganisms become
more active, the SOUR increases and vice versa. If SOUR increases it is an indication of an increase in the MLSS respiration rate and may require additional oxygen to stabilize [19].

Highly aerobic AS processes have been criticized regarding energy requirements as energy used for aeration contributes to the majority of the energy consumption of a treatment plant [8]. Moreover, sludge treatment and management have high energy requirements and is associated with at least 50% of WWT operational cost [9]. Reducing energy consumption and operational cost, as well as improving energy recovery are essential for improving wastewater treatment sustainability [10]. Such an approach is well described by Complete solids Retention AS (CRAS) process.

CRAS is an aerobic process that achieves the longer possible SRT (up to complete retention), the maintenance of highly aerobic conditions in the aerobic bioreactor (DO>4mg/L), the successful microbial manipulation and the efficient solids/liquid separation [5]. By this approach, efficient wastewater treatment, minimization of sludge accumulation in the WWTP and significant reduction of excess sludge is achieved, with relatively low specific energy consumption [11].

Aim of this work is to study the effect of sludge age on oxygen requirements for respiration and oxidation of organics and nitrogenous compounds in high SRT and high biomass concentration conditions, in order to evaluate CRAS process as a sustainable alternative to typical activated sludge processes. The novelty of this work is the assessment of SRT impact on microorganisms’ respiration by monitoring OUR and SOUR in relation to BOD and nitrogen oxidation. In several works SOUR reduction was studied but the reason for this reduction is not explained [6, 18].

2. Material and methods
In order to evaluate the impact of SRT on respiration of microorganisms, a laboratory-scale WWTP with denitrification (Behr, Model KLD4) was monitored for a two-month period. KLD4 was fed continuously with synthetic wastewater prepared according to APHA 5210-BOD standard solution. This synthetic wastewater consists of glucose, glutamic acid and trace elements that are necessary for the microorganisms growth. Indicative physicochemical characteristics of the synthetic wastewater are presented in Table 1.

Table 1. Synthetic wastewater characteristics.

| Parameter | Value |
|-----------|-------|
| COD       | 1500mg/L |
| TKN       | 50mg/L |
| TP        | 10mg/L |
| pH        | 7 |

The KLD4 is a pre-nitrification system and consists of three tanks, one stirred denitrification tank (5L), one aeration tank (5L) and one final sedimentation tank (2,5L). The wastewater inflows to the denitrification tank at a rate Q_d=3,3 m$^3$/d. The denitrification effluent flows to the aeration tank where air is supplied via a diaphragm pump. Aeration was supplied continuously to maintain a dissolved oxygen concentration of approximately 6–7 mg O$_2$/dm$^3$. Nitrates recirculate from the aeration tank to the denitrification tank at a rate Q$_{RN}$=20L/h. The activated sludge is recycled to the denitrification tank at a rate Q$_R$=10L/h.

During the experiment, the operational parameters of dissolved oxygen (DO), pH, temperature, mixed liquor suspended solids (MLSS) and MLVSS in each bioreactor were monitored three times a week. The influent and effluent COD, ammonia, nitrate and total phosphorus were measured three times a week in order to evaluate system’s performance in terms of organic compounds and ammonium nitrogen oxidation, as well as nitrates removal. Additionally, biological characteristics of sludge were studied twice a week using a Leica DM1000 phase contrast microscope. Measurements of DO were conducted using a Hach HQ30D Portable Dissolved Oxygen Meter with Field Luminescent DO Sensor. All samples were analyzed at the accredited according to ISO 17025 Environmental
Chemistry & Water and Wastewater Treatment Laboratory of Western Macedonia University, Greece, by applying standard methods [12] and using calibrated equipment. COD removal efficiency and biomass growth rate were studied. Oxygen consumption rate, specific oxygen consumption rate and observed growth yields ($Y_{obs}$) were calculated. Oxygen requirements for organic compounds oxidation and oxidation of ammonia nitrogen were determined in different sludge ages. The obtained results were compared with literature data of oxygen consumption in different AS processes. Sludge age is the SRT and was calculated according to the following equation:

$$SRT = \frac{V_r X_r}{\Delta X_v}$$

Where: $V_r$, is aeration tank volume; $X_r$, is aeration tank concentration; and $\Delta X_v$, is waste sludge quantity in the aeration tank.

The oxygen consumption rate data were calculated by the measurement of the decrease in DO concentration in the reactor. The dissolved oxygen concentrations (DO) were measured at 30 minutes until they reached a value close to full depletion. The respiration rate was calculated from the slope, according to the following equation [13, 14]:

$$OUR = \frac{DO_1 - DO_2}{t_2 - t_1}$$

Where: $DO_1$ and $DO_2$ are initial and final dissolved oxygen concentration, respectively; and $t_2 - t_1$, is the time interval between the first and last DO measurement.

Specific oxygen consumption rate ($SOUR$) was calculated in order to estimate the total oxygen requirements per unit of biomass according to the following equation:

$$SOUR = \frac{OUR}{MLVSS} \left( \frac{mg DO}{mg VSS \cdot min} \right)$$

Total oxygen demand ($TOD$) expresses the oxygen for BOD oxidation, for respiration, for nitrification and oxygen released during denitrification. $TOD$ was calculated according to the following equation:

$$TOD = a(S_F - S_e)Q_F + bX_{r,a}V_R + 4.57 \{Q_F * [TKN]_F - Q_F * [TKN]_e\} - 0.12 * (\Delta X_{r,a} + \Delta X_{r,N}) - 2.86 * N-Denitr$$

Where: $a$, is oxygen demand coefficient; $b$, is endogenous respiration coefficient; $S_F$ and $S_e$, are the substrate concentrations in the influent and effluent, respectively; $Q_F$, is feeding flow; $V_R$, is aeration tank volume; $X_{r,a}$ is aeration tank concentration; $TKN_F$ and $TKN_e$, are ammonia nitrogen concentrations inlet and outlet, respectively; $\Delta X_{r,a}$ is waste sludge quantity in the aeration tank which comes from the BOD oxidation; $\Delta X_{r,N}$ is autotrophic biomass daily quantity; and $N-Denitr$, is nitrogen denitrified.

$Y_{obs}$ was calculated according to the following equation:

$$Y_{obs} = \frac{BIOMASS_{produced}}{SUBSTRATE_{utilized}} \cdot \frac{VSS_{produced}}{COD_{removed}}$$

3. Results and discussion

In this study, removal efficiencies of organic and nitrogen compounds, microscopic characteristics of activated sludge, biomass growth rate and oxygen consumption rates in terms of $OUR$ and $SOUR$ were monitored after a biomass acclimatization period of 5 days in order to evaluate CRAS process as a sustainable alternative to typical activated sludge processes.

Removal efficiencies of laboratory-scale WWTP
Organic compounds removal efficiency was measured by COD reduction and ranged from 93% up to 99%. Nitrification efficiency ranged from 91% up to 95% while denitrification efficiency from 95% up to 99%. The relatively stable processes’ efficiencies (figure 1) indicate that the process is under steady state conditions.

Figure 1. Organic compounds removal (COD), nitrification and denitrification efficiencies (%) of laboratory-scale WWTP.

Microscopic characteristics of activated sludge
Throughout the monitoring period activated sludge maintained characteristics of a highly aerated biomass with significant presence of protozoan and metazoan microbial species, mainly ciliates and rotifers (figure 2). Filamentous bacteria and nematodes were not detected. Worth mentioning is that in SRT>100 days the presence of rotifers was more evident.

Figure 2. Left: microscopic depiction of activated sludge with the presence of protozoan and metazoan (magnification: x100); right: microscopic depiction of activated sludge with the presence of rotifers (magnification: x400).

Biomass growth rate
As evident in figure 3, MLSS concentration increased in relation to SRT, maintaining a relatively constant MLVSS/MLSS ratio (\( \lambda \)). The relatively constant \( \lambda \) ratio indicates that there is a limited
accumulation of unbiodegradable particulate matter, such as cell debris, in the bioreactors. Cell debris is biodegradable under CRAS process [10]. The high linear correlation between MLVSS and SRT (95%) indicates that the AS process is in its exponential growth phase [15]. Nevertheless, after an SRT of approximately 175 days, the slope of MLVSS/SRT gradually decreases indicating that AS process approaches the stationary phase i.e., a plateau phase with negligible biomass growth (decreased rate of biological activity). This conclusion is also confirmed by $Y_{obs}$ calculation which decreased with increasing SRT reaching values of approximately 0.03 kgVSS/kgCOD$_{removed}$. These results are in accordance with recent studies [10]. $Y_{obs}$ usually ranges between 0.12 and 0.45 kgMLVSS/kgCOD$_{removed}$ in conventional aerobic AS processes. Recent studies demonstrated that at high SRT and high DO concentration processes $Y_{obs}$ is significantly lower (up to two orders of magnitude) [5, 16].

**Figure 3.** Biomass growth (MLSS, MLVSS) and observed yields ($Y_{obs}$) variation in relation to SRT.

**Oxygen consumption rate**

With increasing SRT, OUR increased (figure 4). This was expected according to literature, where is stated that increasing SRT leads to higher oxygen consumption [17]. Thus, high SRT processes, such as CRAS, require highly aerated bioreactors in order to achieve greater oxygen diffusion. OUR fluctuations that were observed, as CRAS process approaches the stationary phase, could be attributed to the increased biomass decay and lysis and the subsequent oxidation and/or utilization of released intracellular organic matter. There is a critical dissolved oxygen concentration where the rate of oxygen consumption starts to decrease gradually, resulting in a subsequent decrease in the slope of the OUR following the stationary phase of MLVSS. At SRT>175 days OUR values ranged from 12 to 15 mgO$_2$/L h. Accurate estimation of this critical value for CRAS process constitutes a subject of ongoing research.

With increasing SRT and decreasing $Y_{obs}$, SOUR decrease is observed which means reduced biological activity (figure 4). SOUR reduction may be attributed to oxygen depletion inside the biomass floc as biomass concentration increases [13]. Oxygen consumption mainly occurs within the sludge flocs, so there is a tendency for the dissolved oxygen concentration to decrease from the periphery of the floc towards the floc center. A zone without oxygen (anoxic or anaerobic) may
develop in the central region of the flocs. As no oxygen is consumed in this region the overall SOUR will decrease [13].

Figure 4. Oxygen consumption rate (OUR) and specific oxygen consumption rate (SOUR) in comparison with biomass growth (MLVSS) in relation to SRT.

4. Conclusions
Under steady state operational conditions, CRAS process operates with high removal efficiency having a biomass without nematodes and filamentous bacteria, but with the presence of protozoan and metazoan such as ciliates and rotifers. There is a limited accumulation of unbiodegradable particulate matter as the λ ratio is relatively constant. As process approaches the stationary phase as the slope of MLVSS/SRT gradually decreases at SRT>175 days. Yobs reduction observed in CRAS process leads to sludge minimization and low specific oxygen consumption. With increasing SRT, OUR increased and higher oxygen consumption was achieved. Fluctuations that were observed in OUR curve could be attributed to the increased biomass decay and lysis. There is a critical dissolved oxygen concentration where the rate of oxygen consumption starts to decrease gradually, resulting in a subsequent decrease in the slope of the OUR following the stationary phase of MLVSS. With increasing SRT and decreasing Yobs, SOUR decrease was observed which means reduced biological activity. SOUR reduction may be attributed to oxygen depletion inside the biomass floc as biomass concentration increases.

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