Water Research xxx (2015) 1–7

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

High-rate activated sludge system for carbon management – Evaluation of crucial process mechanisms and design parameters

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ARTICLE INFO

Article history:
Received 3 February 2015
Received in revised form
19 June 2015
Accepted 19 July 2015
Available online 21 July 2015

Keywords:
Activated sludge
A-stage
Biosorption
Bioflocculation
Energy
High-rate treatment

ABSTRACT

The high-rate activated sludge (HRAS) process is a technology suitable for the removal and redirection of organics from wastewater to energy generating processes in an efficient manner. A HRAS pilot plant was operated under controlled conditions resulting in concentrating the influent particulate, colloidal, and soluble COD to a waste solids stream with minimal energy input by maximizing sludge production, bacterial storage, and bioflocculation. The impact of important process parameters such as solids retention time (SRT), hydraulic residence time (HRT) and dissolved oxygen (DO) levels on the performance of a HRAS system was demonstrated in a pilot study. The results showed that maximum removal efficiencies of soluble COD were reached at a DO > 0.3 mg O_2/L, SRT > 0.5 days and HRT > 15 min which indicates that minimizing the oxidation of the soluble COD in the high-rate activated sludge process is difficult. The study of DO, SRT and HRT exhibited high degree of impact on the colloidal and particulate COD removal. Thus, more attention should be focused on controlling the removal of these COD fractions. Colloidal COD removal plateaued at a DO > 0.7 mg O_2/L, SRT > 1.5 days and HRT > 30 min, similar to particulate COD removal. Concurrent increase in extracellular polymers (EPS) production in the reactor and the association of particulate and colloidal material into sludge flocs (bioflocculation) indicated carbon capture by biomass. The SRT impacted the overall mass and energy balance of the high-rate process indicating that at low SRT conditions, lower COD mineralization or loss of COD content occurred. In addition, the lower SRT conditions resulted in higher sludge yields and higher COD content in the WAS.

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1. Introduction

In the quest to achieve energy self-sufficiency and sustainable operation, water resource recovery facilities (WRRFs) typically employ some type of energy recovery process, such as anaerobic digestion, to produce biogas for onsite heat and energy generation. It is not typically possible in WRRFs to obtain energy neutral operation without concurrently minimizing energy usage and maximizing energy (organic carbon) recovery. The organic carbon in municipal wastewater typically represents a chemical energy content of approximately 1.9 kWh per m^3 (Heidrich et al., 2011; McCarty et al., 2011; Bowen et al., 2014). Generally, municipal wastewater is treated using activated sludge process. This aerobic biological process not only consumes a considerable amount of energy for aeration (0.3–0.7 kWh per m^3 of wastewater according to Metcalf and Eddy, 2003; Shizas and Bagley, 2004), but also mineralizes or oxidizes a significant fraction of the influent organic carbon, which results in a loss of the energy recovery potential. Additionally, organic carbon is required for biological nutrient removal (BNR) in most cases. Therefore, carbon redirection for energy recovery must be balanced so a WRRF still reliably meets effluent quality criteria, particularly nitrogen and phosphorus limits.

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http://dx.doi.org/10.1016/j.watres.2015.07.032
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Please cite this article in press as: Jimenez, J., et al., High-rate activated sludge system for carbon management – Evaluation of crucial process mechanisms and design parameters, Water Research (2015), http://dx.doi.org/10.1016/j.watres.2015.07.032

There are several processes that are capable of redirecting organic carbon for possible energy generation; however, they are generally limited to the removal of settleable particulate matter (e.g., physical processes such as primary sedimentation or dissolved air floatation), require external chemical addition (e.g., chemically enhanced primary treatment), or mineralize a large fraction of the influent carbon (e.g., activated sludge process) (Verstraete and Vlaeminck, 2011). One process that has been successfully used for carbon redirection is the high-rate activated sludge (HRAS) process (Chase and Eddy, 1944; Jimenez, 2013).

The HRAS process, developed by Buswell and Long (1923), uses high food-to-microorganism ratios and low solids retention times (SRT) with relatively short hydraulic retention times (HRT) to remove chemical oxygen demand (COD) from wastewater (Grady et al., 2011). The HRAS process typically uses SRT between 1 and 4 days, depending on temperature and HRT between 2 and 4 h (Tchobanoglous et al., 2003). By taking advantage of the high-rate of bacterial consumption, HRAS became a relatively affordable method of removing particulate and soluble carbon constituents from wastewater (Jimenez et al., 2007). The HRAS systems can be designed and operated to meet secondary effluent standards (e.g., 30 mg/L BOD_5 and 30 mg/L TSS limits) or as carbon adsorption processes when used as the first step in a two-stage process (e.g., Adsorption/Bio-oxidation, A/B process).

When a HRAS system is the first step in a two-stage process, it can be operated notably differently (Winkler and Widmann, 1994; Böhnke et al., 1997). The high-rate operation of the A-stage (e.g., <1 day SRT, ~30 min HRT, <1 mgO_2/L DO) results in concentrating the influent particulate, colloidal, and soluble COD to a waste solids stream with minimal energy input in a small footprint. Consequently, mechanism of such performance is related to promotion of sludge production (i.e., yield), bacterial storage, and bioflocculation. The concentrated waste stream of an A-stage can be redirected to an energy recovery process such as anaerobic digestion or incineration. By redirecting carbon to anaerobic digestion, the A-stage at the Rotterdam WRRF (Netherlands) is able to produce 0.5 kg methane/kg COD removed (Jetten et al., 1997). Maximizing biomass yield in the A-stage also increases nitrogen and phosphorus removal by assimilation (Jetten et al., 1997). The sludge produced by an A-stage has better digestion characteristics compared to normal secondary sludge, which results in a lower overall sludge production when compared to a single-sludge nutrient removal process preceded by primary sedimentation (van Loosdrecht et al., 1997).

The current application of the HRAS process recognizes that there are three forms of substrate in wastewater – particulate, colloidal, and soluble. Particulate and colloidal substrates are removed effectively from solution by biological flocculation (adsorption into the biological floc) and subsequent solids-liquid separation (Jimenez et al., 2005). The soluble fraction can be removed by intracellular storage, biosynthesis or biological oxidation (EPA, 1975).

To date, HRAS systems, other than that deployed as the A-stage in relatively few A/B plants, are operated at a constant and 'safe' SRT to allow for a year-around effluent quality that conforms with BOD and TSS permit limits. However, the latter does not allow for a specific control of all resource inputs (energy, chemicals) and outputs (effluent quality and sludge production). The distinction between soluble, particulate and colloidal COD and the focus on energy production from organic carbon completely changes the energy arguments, which have been made before and which have overlooked this distinction and thereby the higher energy potential in the organic carbon fraction. Furthermore, EPS produced by bacteria could be an essential buffer against carbon redox cycling that captures colloids and particulates which can be later on separated from the liquid by settling. Bioflocculation is therefore the key element for maximum energy recovery. Beside biological bioflocculation also chemicals (such as iron) can be dosed to increase bioflocculation potential and minimize oxidation of organics (Wett et al., 2015). However, to balance maximum bioflocculation with desired effluent quality, a better understanding of the metabolic fluxes within the complex system is needed. This will allow for direct carbon management instead of the indirect carbon management which is the common practice at this moment. Despite the applicability of HRAS processes, there has been little effort to understand how operation and performance of the HRAS process can be improved to minimize energy consumption while increasing the energy generation potential through minimization of COD oxidation for diversion to anaerobic digestion. In this study, the impact of SRT, HRT and DO on the HRAS performance treating municipal wastewater at psychrophilic temperatures was evaluated.

2. Materials and methods

2.1. Pilot plant description

The activated sludge high-rate pilot plant comprised a rotary screen system (5-mm) to remove large solids from the system followed by an aerobic biological tank with a short hydraulic detention time (ranging from 5 to 60 min), and a sedimentation tank for final solids-liquid separation. The HRAS pilot plant was fed screened and degritted municipal wastewater. The influent feed temperature was maintained between 20 and 25 °C. The biological reactor consisted of a 260 L single complete-mixed reactor equipped with fine bubble aeration, a mechanical mixer and a blower to supply air to the biological reactor. Aeration was controlled using a Hach LDO sensor (Hach Company, Loveland, Colorado) and a motorized valve with PID (proportional, integral, derivative) control. The SRT in the pilot plant was varied between 0.1 days to over 2 days by continuously wasting settled mixed liquor from the return activated sludge (RAS) line. For the purpose of this study, the SRT was based on the biomass inventory in the aerobic reactors only, neglecting the biomass in the sedimentation tank. The sedimentation tank consisted of a 280 L polyethylene conical tank. Mixed liquor from the biological reactor flowed by gravity to the sedimentation tank. A scrapper system, located at the bottom and moved by a gear motor rotating at 1 rpm, was used to reduce sludge accumulation in the sedimentation tank. The sedimentation tank was operated with minimal sludge blanket by controlling the RAS rate and by checking the blanket depth several times per day. Effluent was collected in an effluent storage tank where effluent samples were collected.

2.2. Sampling and analysis

Samples were collected from the influent to the pilot plant, the biological reactor (both the mixed liquor and the supernatant after 30 min of settling), the RAS line and the secondary effluent. Sampling and analysis followed the recommendations and procedures published in Standard Methods (APHA, 1999). The total and filtered (1.5 micron and 0.45 micron) COD analyses were conducted using the Hach Test-in-Tube (TNT) kits (Hach Company, Loveland, Colorado); total suspended solids (TSS) and volatile suspended solids (VSS) were determined by Standard Methods 2540D and 2540E; flocculated and filtered COD (ffCOD) was measured by using the method developed by Mamais et al. (1993). Grab samples were also routinely collected from the biological reactor and RAS line and analyzed for TSS, VSS and COD. Once per week, effluent samples were also analyzed for nitrogen and phosphorus species using Hach TNT kits. Dissolved oxygen, pH, and temperature values were

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