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Operation of an innovative WWTP with environmental objectives. A model-based analysis

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Abstract: Operation of wastewater treatment plants can be subjected to economic, energetic and/or environmental objectives, besides the compliance with effluent limits. As trade-offs between different objectives are frequently unavoidable, model based analysis can assist in decision making and give further insight on the effect of the operating conditions. Furthermore, as new wastewater treatment technologies have appeared in the latest years, model-based analysis is needed to ascertain what the advantages of the new technologies are. We demonstrate here how to assess and operate an innovative WWTP according to different objectives with case-study based on a real innovative pilot plant. The plant features the use of denitrifying anaerobic methane oxidation (DAMO) bacteria to deplete methane from digestate. Furthermore, given the slow growth rate of the system and the tendency to create complex syntrophic environments, the use of a model becomes a keystone to operate these reactors.

***Keywords**:* plantwide operation; wastewater treatment; N-DAMO bacteria; methane release; optimisation

1. INTRODUCTION

The operation of a wastewater treatment plant (WWTP) must deal with a hierarchy of objectives which are often in conflict, leading to trade-off solutions. In general, the first objective that must be fulfilled is the requirements in the effluent which depend on whether the WWTP treats urban or industrial water, which is the receiving water body and, of course, the regulation applying to the area. Effluent limits include almost universally COD and solids, in most cases nowadays nutrients (phosphorous and nitrogen compounds) and in some countries emerging pollutants are now being regulated as well. When effluents limits are fulfilled, a plant manager will seek to reduce the energy expenses as, together with the chemicals, they represent the major part of the operating cost for a WWTP. Only on top of these two layers of objectives, would environmental goals be implemented. The main negative impacts of WWTP identified include sludge disposal, electricity and chemicals consumption for operation and direct greenhouse gas (GHG) emissions. The reduction of GHG emissions has only recently been tackled in the last years due to the difficulty in characterizing, quantifying and modelling those emissions.

In a number of cases, the major environmental impact of a WWTP is related to its energy use; therefore, reducing the energy consumption also leads to a better environmental record provided that the effluent limits are respected. Hence, minimising environmental impact and the energy consumption constitute a non-zero sum game (i.e. win-win). However, in cases where energy use is not the main contributor to the environmental impact, the optimisation of both criteria tends to be a zero-sum game and trade-offs between the two objectives are unavoidable.

Running a WWTP at low GHG emissions is admittedly not an easy task, especially while respecting the effluent limits and keeping the operating costs controlled. This task becomes even more complex given the common structure of incentives and objectives in a WWTP: operators are evaluated for keeping the process running and respecting the effluent limits while, it is the plant manager and/or chief operator who must focus on minimising the operating costs (Rieger and Olsson 2014). In this context, simulation and model based analysis appears as an essential tool for assisting in decision making on how to operate, manage and control the plant.

We address here the issue of operating an innovative plant with different objectives (effluent, energy and environment) by using a model-based analysis of the process. We use as a case-study an innovative process patented at the University of Santiago de Compostela (SIAM, Buntner et al. 2013) To demonstrate the methods and tackle the GHG emission as an environmental impact, we focus on reducing the release of methane by avoiding downstream stripping of digestate, the main contributor to methane release with biogas leaks and sludge disposal.

This paper is organised as follows. First the model of the plant is described, together with indicators of the plant performance. Then the operating window is mapped and the different operating regions are characterised in terms of activity, objectives and microbial diversity. Finally, conclusions about how to operate the plant in different scenarios and proposals to implement a plantwide control are given.

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2. MODEL AND PLANT DESCRIPTION

2.1 *Plant description*

An innovative pilot plant located at the University of Santiago de Compostela (Spain) was chosen as a case study. The plant (fig. 1) is a novel two-stage MBR process referred to as SIAM, (Spanish acronym for *Integrated system of methanogenic anaerobic reactor and membrane bioreactor for COD and nitrogen removal in wastewater)*. The plant and the operating conditions are described in detail elsewhere (Buntner *et al*. 2012) and summarised here for the sake of completeness. The influent is characterised by a high concentration of methane (25 mg CH_4/L), corresponding to the saturation from a psychrophilic UASB reactor at 17 ^oC. Apart from methane, there are 30 mg/L of soluble COD, 30 mg/L of particulate COD, 55 mgN/L of total ammonium and 25 mgN/L of total nitrite.

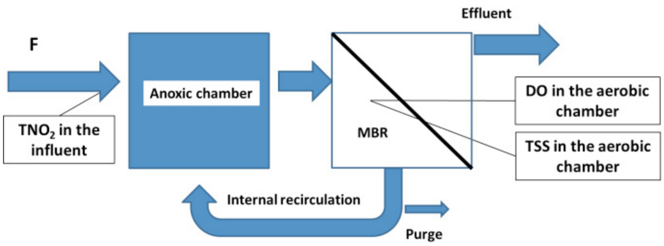

Fig. 1. Section of the SIAM plant studied. The influent is a digestate from an UASB reactor.

The design of the plant enhances the removal of methane from the anaerobic digestate and thereby avoids the stripping to the environment. Methane can be used as a source of electrons by the following microbial groups: denitrifying anaerobic methane oxidation (DAMO) process, by aerobic methane oxidizers (AMO) or by syntrophic consortia such as anaerobic methanogenic archaea (ANME) and sulphate-reducing bacteria (SRB).

2.2 *Plant model*

The process is modelled as two stirred tank reactors in series to represent the anoxic and the aerobic chamber. The aerobic chamber features a membrane which is modelled as having total rejection of particulate compounds and no rejection of soluble compounds. The mass balance of each compound is expressed by:

$$\frac{dC_{ij}}{dt} = D_j\left({C_{ij}}^{IN} - C_{ij}\right) + r_{ij} + j_{ij} \qquad (1)$$

where C_{ij} is the concentration of compound i in tank j, ${C_{ij}}^{IN}$ is the concentration of compound i in the inflow of tank j, r_{ij} is the net generation by reaction and j_{ij} stands for the mass transfer to and from the gas phase. D_j is the dilution rate which is defined as:

$$D_j = \frac{{F_j}^{IN}\,\rho_j}{M_j} \qquad (2)$$

where ${F_j}^{IN}$ is the inflow of tank j, M_j is the mass hold-up of tank j and ρ_j is the density of tank j. As the tank outflow is determined by overflow, the volume of each tank remains constant. Furthermore, approximating the density of the hold-up as close to the density of water, Mj can be assumed as constant.

The model includes 21 states per chamber, namely the total mass and:

- 9 soluble compounds, namely dissolved oxygen, soluble COD, dissolved nitrogen, total ammonium nitrogen, total nitrite nitrogen, nitrate, soluble inerts, total inorganic carbon(TIC) and dissolved methane.
- 10 particulate compounds, namely particulate inerts, particulate COD, heterotrophs (Xh), storage product (Xsto), ammonium oxidizing bacteria (AOB), nitrite oxidizing bacteria (NOB), DAMO archaea (Xda), DAMO bacteria (Xdb), anaerobic ammonium oxidizing bacteria (Xan or anammox), aerobic methane oxidizers (Xamo) and total solids (TSS)

The microbial kinetics are modelled by 25 processes that are briefly summarised here. The heterotrophic metabolism was modelled using the activated sludge model no. 3 (Henze *et al*. 2003) with the modification added by Iacopozzi *et al*. (2007) to include two step nitrification-denitrification as nitrite is the substrate of anammox and DAMO bacteria. The biological reactions of AOB, NOB and anammox were modelled as in Vangsgaard et al. (2012) using the unionized form of ammonium and nitrous acid as true substrates. The model of DAMO archaea and bacteria was taken from Chen *et al.* (2014) but modified in order to include the oxygen inhibition results obtained by Luesken et al. (2012). Finally, the aerobic methane oxidizers were modelled as in Arcangeli and Arvin (1998).

Only O_2, CO_2, CH_4 and NH_3 are considered to be volatile, and therefore can be transferred to and from the aerating flow (transfer with the headspace is considered as negligible). The flow rate of compound, in mass per volume and time, is given by:

$$j_i = k_L a\,(Mw_i\,H_i\,P_i - S_i) \qquad (3)$$

where k_La is the specific mass transfer coefficient, Mw_i is the molecular weight, H_i is Henry's constant, P_i is the partial pressure of i in the gas phase and Si is the concentration of the volatile compound. Note the difference between S_i and C_i, e.g., C_i represents the total ammonium plus ammonia concentration whereas S_i only stands for the concentration of ammonia, which is the only volatile form.

2.4 *Modelling of aeration and energy consumption*

The relation between the air flow rate and the oxygen transfer is modelled as reported by Martin *et al*. (2011)

$$Q_{air} = \frac{j_{O2}\,V_{aer}}{x_{O2}\,\rho_{air}\;\alpha\,\beta\,\gamma\,OTE} \qquad (4)$$

where Q_{air} (in m^3/d) is the air flow rate V_{aer} is the volume of the aerobic chamber, x_{O2} is the volume fraction of oxygen in air, ρ_{air} is the density of air, α is the mass transfer ratio between clean water and wastewater, β and γ are efficiency