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Removing violations of the effluent pollution in a wastewater treatment process

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HIGHLIGHTS

- Performance improvement of wastewater treatment plants applying control strategies.
- Effluent quality improvement and costs reduction with a hierarchical control.
- Effluent violations removal for dry, rain and storm weather conditions.
- Simultaneously removal of total nitrogen and ammonia violations.

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ABSTRACT

This paper presents different control strategies for biological wastewater treatment plants, with the goal of avoiding violations of effluent pollution limits while, at the same time, improving effluent quality and decreasing operational costs. The control strategies are based on Model Predictive Control (MPC) and functions that relate the input and manipulated variables. The Benchmark Simulation Model No.1 (BSM1) is used for evaluation. A hierarchical structure regulates the dissolved oxygen (DO) of the three aerated tanks based on the ammonium and ammonia nitrogen concentration (NH) in the fifth tank (NH5). An MPC with feedforward compensation is proposed for the lower level and an affine function is selected for the higher level. A tuning region is determined modifying the tuning parameters of the higher level, in which the effluent quality and operational costs are simultaneously improved in comparison with the default control strategy of BSM1. To eliminate violations of total nitrogen in the effluent ($N_{tot,e}$), an affine function, implemented with a sliding window, adds external carbon flow rate in the first tank based on nitrate nitrogen in the fifth tank (NO5) plus NH5. To avoid violations of NH in the effluent (NH_e), a combination of a linear function and an exponential function that manipulates the internal recirculation flow rate based on NH5 and NH in the influent is proposed. As a result, $N_{tot,e}$ violations and NH_e violations are avoided for dry, rain and storm weather conditions. In addition, an improvement of effluent quality and a reduction of operational costs are achieved at the same time, except in the cases of rain and storm weathers for NH_e violations removal, in which the costs increase.

1. Introduction

The control of biological wastewater treatment plants (WWTPs) is not an easy task due to the complexity of the biological and biochemical processes that take place inside them, the diversity of time constants involved, the large disturbances in concentration and flow rate of the influent and the legal requirements for the effluent (see for instance the European Directive 91/271 "Urban wastewater" established by European Union).

In this work the evaluation and comparison of the different control strategies is based on Benchmark Simulation Model No.1 (BSM1), developed by the International Association on Water Pollution Research and Control [1–3]. This benchmark includes a plant layout, influent loads, test procedures and evaluation criteria.

The BSM1 provides a default control strategy that includes two Proportional-Integral (PI) control loops: control of the dissolved oxygen concentration (DO) in the fifth tank (DO5) at a set point value of 2 g/m^3 by manipulating the oxygen transfer coefficient (K_La) in the fifth tank (K_La5), and control of the nitrate nitrogen concentration (NO) in the second anoxic reactor (NO2) at a set point value of

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1 g/m^3 by manipulating the internal recycle flow rate (Q_{rin}). A complete review of results for PI control can be found in [4].

There are previous works that propose different methods for controlling WWTPs. Some of them apply a direct control of the effluent variables, mainly ammonium and ammonia nitrogen (NH) and total nitrogen (N_{tot}) [5–7]. The difficulty in this method is that the fixed values for the effluent variables are constraints and not set points. Other studies deal with the basic control strategy (DO of the aerated tanks and NO of the last anoxic tank), but testing with different controllers such as Model Predictive Controller (MPC) and fuzzy controller [8–11]. These methods provide an acceptable balance between quality and costs. Finally other investigations propose a hierarchical control that regulates the DO set points, depending on some states of the plant, usually NH and NO values in any tank or in the influent [12–17] or DO in other tanks [18].

Unlike the referred articles, the present work deals with the avoidance of N_{tot} in the effluent ($N_{tot,e}$) and NH in the effluent (NH_e) violations for dry, rain and storm weather conditions, taking also into account the effluent quality and operational costs. The proposed control strategies are based on improving the nitrification process by oxidizing the aerated tanks [19] and by manipulating Q_{rin} [20], and on improving the denitrification process by adding external carbon flow rate (q_{EC}) [21]. Other important innovation is the introduction of a sliding window to dosage the minimum q_{EC1} necessary for the $N_{tot,e}$ violations removal in order to minimize operational costs.

First, a hierarchical control structure is implemented to improve simultaneously OCI and EQI. The lower level is composed by three MPC with feedforward compensation of the influent flow rate (MPC + FF) [22], to control NO2, DO in the third tank (DO3), DO in the fourth tank (DO4) and DO5. The higher level adjusts the DO set points according with NH in the fifth tank (NH5), and an affine function is proposed for this level. A trade-off analysis is made, which determines a tuning region that improves simultaneously the results of effluent quality and operational cost in comparison with default control strategy of BSM1. Next, two controls are added in order to eliminate effluent violations. NH_e and $N_{tot,e}$ are the pollutants that present more difficulties for being kept under the established limits. For reducing peaks of $N_{tot,e}$, q_{EC} in the first tank (q_{EC1}) is added based on NO in the fifth tank (NO5) plus NH5. An affine function is proposed for this control, with a sliding window for its implementation. And for reducing peaks of NH_e, Q_{rin} is manipulated based on NH5, and the control of NO2 is removed. A combination of linear function and exponential function is proposed for this control.

2. Working scenario: BSM1

This section provides a description of the working scenario provided by the BSM1. This is a simulation environment defining a plant layout, a simulation model, influent loads, test procedures and evaluation criteria.

2.1. Plant layout

The schematic representation of the WWTP is presented in Fig. 1. The plant consists in five biological reactor tanks connected in series, followed by a secondary settler. The first two tanks have a volume of 1000 m^3 each and are anoxic and perfectly mixed. The rest three tanks have a volume of 1333 m^3 each and are aerated. The settler has a total volume of 6000 m^3 and is modeled in ten layers, being the 6th layer, counting from bottom to top, the feed layer. Two recycle flows, the first from the last tank and the second from the underflow of the settler, complete the system. The plant is designed for an average influent dry-weather flow rate of 18,446 m^3/d and an average biodegradable chemical oxygen demand (COD) in the influent of 300 g/m^3. Its hydraulic retention time, based on the average dry weather flow rate and the total tank and settler volume (12,000 m^3), is 14.4 h. The default wastage flow rate (Q_w) is fixed to 385 m^3/d that determines, based on the total amount of biomass present in the system, a biomass sludge age of about 9 days. The nitrogen removal is achieved using a denitrification step performed in the anoxic tanks and a nitrification step carried out in the aerated tanks. The internal recycle is used to supply the denitrification step with NO.

2.2. Models

The biological phenomena of the reactors are simulated by the Activated Sludge Model Nº 1 (ASM1) [23] that considers eight different biological processes. The vertical transfers between layers in the settler are simulated by the double-exponential settling velocity model [24]. None biological reaction is considered in the settler. The two models are internationally accepted and include thirteen state variables. The proposed control strategies in this work are based on the conversion rates of NH (r_{NH}) and NO (r_{NO}). They are shown following:

$$r_{NH} = -0.08\rho_1 - 0.08\rho_2 - \left(0.08 + \frac{1}{0.24}\right)\rho_3 + \rho_6 \tag{1}$$

$$r_{NO} = -0.1722\rho_2 + 4.1667\rho_3 \tag{2}$$

where $\rho_1, \rho_2, \rho_3, \rho_6$ are four of the eight biological processes defined in ASM1. Specifically, ρ_1 is the aerobic growth of heterotrophs, ρ_2 is the anoxic growth of heterotrophs, ρ_3 is the aerobic growth of autotrophs and ρ_6 is the ammonification of soluble organic nitrogen. They are defined below:

$$\rho_1 = 4\left(\frac{S}{10+S}\right)\left(\frac{DO}{0.2+DO}\right)X_{B,H} \tag{3}$$

$$\rho_2 = 4\left(\frac{S}{10+S}\right)\left(\frac{0.2}{0.2+DO}\right)\left(\frac{NO}{0.5+NO}\right)0.8 \cdot X_{B,H} \tag{4}$$

$$\rho_3 = 0.5\left(\frac{NH}{1+NH}\right)\left(\frac{DO}{0.4+DO}\right)X_{B,A} \tag{5}$$

$$\rho_6 = 0.05 \cdot ND \cdot X_{B,H} \tag{6}$$

where S is the readily biodegradable substrate, ND the soluble biodegradable organic nitrogen, $X_{B,H}$ the active heterotrophic biomass and $X_{B,A}$ the active autotrophic biomass. The biological parameter values used in the BSM1 correspond approximately to a temperature of 15 °C.

2.3. Influent loads

BSM1 defines three different influent data [25,26]: dry weather, rain weather and storm weather. Each scenario contains 14 days of influent data with sampling intervals of 15 mins.

2.4. Test procedures

A simulation protocol is established to assure that results are got under the same conditions and can be compared. So first a 150 days period of stabilization in closed-loop using constant influent data has to be completed to drive the system to a steady-state, next a simulation with dry weather is run and finally the desired influent data (dry, rain or storm) is tested. Only the results of the last seven days are considered.