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Practice article

Fuzzy logic for plant-wide control of biological wastewater treatment process including greenhouse gas emissions

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ABSTRACT

The application of control strategies is increasingly used in wastewater treatment plants with the aim of improving effluent quality and reducing operating costs. Due to concerns about the progressive growth of greenhouse gas emissions (GHG), these are also currently being evaluated in wastewater treatment plants. The present article proposes a fuzzy controller for plant-wide control of the biological wastewater treatment process. Its design is based on 14 inputs and 6 outputs in order to reduce GHG emissions, nutrient concentration in the effluent and operational costs. The article explains and shows the effect of each one of the inputs and outputs of the fuzzy controller, as well as the relationship between them. Benchmark Simulation Model no 2 Gas is used for testing the proposed control strategy. The results of simulation results show that the fuzzy controller is able to reduce GHG emissions while improving, at the same time, the common criteria of effluent quality and operational costs.

1. Introduction

Wastewater treatment plants (WWTPs) are used worldwide to ensure the suitable water quality for the receiving environment. Some of the pollutants are reduced to allowed levels by the default WWTP structure without applying any automatic control. However, other pollutants are more difficult to be reduced. For this reason and also to restrict operational costs, the application of control engineering in WWTPs is playing an important role in research in recent years (Vilanova et al. [1,2]).

Another major issue regarding to WWTPs is the greenhouse gas (GHG) emissions generated during the treatment process. Actually, GHG emissions are important in maintaining the proper temperature for life on Earth, since they retain part of the infrared radiations reflected from the surface of the Earth. The problem is that the GHG emissions increase generated by the industrialized world is creating a global climate change, which can cause serious impacts on both the land and socioeconomic systems.

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Among the GHG emitted in the wastewater treatment process, the present paper focus on the nitrous oxide (N_{2O}) emissions during the nitrification process, on the carbon dioxide (CO_2) emissions due to endogenous respiration of biomass, on CO_2 generated from external carbon source production and on CO_2 due to electric consumption.

There are previous works in the literature as Kimochi et al. [3], Kampschreur et al. [4], Foley et al. [5], Law et al. [6], Flores-Alsina et al. [7,8], Aboobakar et al. [9] or Wang et al. [10], which show that N_{2O} is an intermediate in the nitrification of WWTPs and that it has a high impact in the GHG emissions. Incomplete nitrification or denitrification can lead to an accumulation of nitrite concentration (S_{NO_2}) that triggers the production of N_{2O} emissions. The endogenous respiration of the biomass is a process of autoxidation that takes place after the depletion of food reserves. In this process, the microorganisms metabolize their own cellular material until its own destruction generating CO_2 emissions, as explained in Monteith et al. [11]. In the case of the electric consumption, it is related to the fact that the electricity is mostly generated by burning fossil fuels, which generates CO_2 emissions.

In this article, the control strategies applied to cope with effluent quality, costs and GHG emissions have been tested using the Benchmark Simulation Model no 2 Gas (BSM2G), which was introduced by Flores-Alsina et al. [7]. This benchmark has been modified over the last years by the same authors, who added ammonia oxidizing

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List of abbreviations

AE	Aeration Energy (kWh/d)
AOB	Ammonia Oxidizing Bacteria
ASM1	Activated Sludge Model no. 1
BOD_5	5-day Biological Oxygen Demand (mg/l)
BSM1	Benchmark Simulation Model no 1
BSM2	Benchmark Simulation Model no 2
BSM2G	Benchmark Simulation Model no 2 Gas
CO_2	Carbon dioxide (kg/d)
COD	Chemical Oxygen Demand (mg/l)
COD_t	total Chemical Oxygen Demand (mg/l)
DCS	Default COntrol Strategy
EC	External Carbon (kg/d)
EQI	Effluent Quality Index (kg of pollutants/d)
GHG	Greenhouse gases
HE_{net}	Net Heating Energy (kWh/d)
HRT	Hydraulic Retention Time (s)
K_La	Oxygen transfer coefficient (d^{-1})
K_La_i	Oxygen transfer coefficient in tank i (d^{-1})
ME	Mixing Energy (kWh/d)
MET_{prod}	Methane production in the anaerobic digester (kg/d)
N_{2O}	Nitrous oxide (kg equivalent CO_2/d)
N_2	dinitrogen CO_2/d)
OCI	Overall Cost Index
PE	Pumping Energy (kWh/d)
PI	Proportional-Integral
Q	Flow rate (m^3/d)
Q_a	Internal recycle flow rate (m^3/d)
q_{EC}	External carbon flow rate (m^3/d)
Q_{in}	Influent flow rate (m^3/d)
$q_{EC,1}$	External carbon flow rate in the first tank (m^3/d)
Q_w	Wastage flow rate (m^3/d)
Q_{st}	Flow rate from the storage tank (m^3/d)
$S_{N_{tot}}$	Total nitrogen concentration (mg/l)
$S_{N_{tot,e}}$	Total nitrogen concentration in the effluent (mg/l)
S_{NH}	Ammonium and ammonia nitrogen concentration (mg/l)
$S_{NH,in}$	Ammonium and ammonia nitrogen concentration at the input of the primary clarifier (mg/l)
$S_{NH,i}$	Ammonium and ammonia nitrogen concentration in tank i (mg/l)
$S_{NH,e}$	Ammonium and ammonia nitrogen concentration in the effluent (mg/l)
S_{NO}	Nitric Oxide concentration (mg/l)
S_{NO_2}	Nitrite concentration (mg/l)
S_{NO_3}	Nitrate concentration (mg/l)
$S_{NO_3 i}$	Nitrate concentration in tank i (mg/l)
S_{NK_j}	Kjeldahl nitrogen (mg/l)
$S_{N_{2O}}$	Dissolved nitrous oxide concentration (mg/l)
S_O	Dissolved oxygen concentration (mg/l)
$S_{O,i}$	Dissolved oxygen concentration in tank i (mg/l)
SP	Sludge Production (kg/d)
T_{as}	Temperature (°C)
TSS	Total Suspended Solids (mg/l)
WWTP	Wastewater Treatment Plants

bacteria (AOB) denitrification pathway for N_{2O} emissions based on Guo and Vanrolleghem [12]. In addition, BSM2G is the result of the evolution of previous benchmarks. First, the Benchmark Simulation Model no 1 (BSM1) was developed in Copp [13], which includes the biological treatment and a secondary clarifier, using one-week period to evaluate results. Next, the Benchmark Simulation Model no 2 (BSM2) (Gernaey et al. [14]) included the whole cycle of a WWTP, adding the sludge treatment and a primary clarifier, applying a more complete influent with a one-year period for evaluation. BSM2G differs from BSM2 mainly in the inclusion of GHG emissions assessment. It should be noted that the use of models for the evaluation of GHG emissions is currently restricted to the research domain, due to the incomplete knowledge regarding the S_{NO_2} production pathways (Mannina et al. [15], Ni and Yuan [16]).

Although the present work uses Proportional-Integral (PI) controllers, the main contribution is based on a fuzzy controller to cope with the mentioned problems in WWTPs. There are already many works in the literature that have applied fuzzy control strategies in WWTPs. For example, the fuzzy controller was applied for the basic control loop of the dissolved oxygen concentration (S_O) in the fifth reactor ($S_{O,5}$) by using BSM1 in Belchior et al. [17] and Nasr et al. [18] or in a pilot plant in Traore et al. [19]. In the case of Santín et al. [20] and Meyer and Pöpel [21], the fuzzy controller is used for ammonium and ammonia nitrogen concentration (S_{NH}) in the fifth tank ($S_{NH,5}$) cascade control by manipulating the $S_{O,5}$ setpoint, also by using BSM1 as testing plant. The fuzzy inference system is employed in Pai et al. [22] to improve artificial neural network to predict the total suspended solids (*TSS*) and the chemical oxygen demand (*COD*) in the effluent from a hospital WWTP. By using BSM2 as a working scenario, Santín et al. [23] Santín et al. [24] apply fuzzy control to deal with pollutants limits violations. Fuzzy logic has also been applied for evaluation (Kalavrouziotis et al. [25]) or management (Hirsch et al. [26]) of real WWTPs. However, none of the referred papers have taken into account GHG emissions.

Although there is a large number of works that apply control strategies in WWTPs, the evaluation of GHG emissions has emerged in recent years. Some works that analyze GHG emissions in WWTPs by applying control strategies are Flores-Alsina et al. [7,8] and Barbu et al. [27]. They use BSM2G, but with different model versions. Flores-Alsina et al. [7] tests the effect of traditional control strategies in GHG emissions, but without considering those produced by nitrification. Flores-Alsina et al. [8] shows the effect on GHG emissions of the different areas of a WWTP. Barbu et al. [27] presents the effects of other traditional control strategies on water quality, operational costs and, especially, on GHG emissions, by an integral indicator for performance evaluation. However, it was not the goal of these works to implement specific control strategies in order to reduce N_{2O} emission in the nitrification process. On the other hand, Santín et al. [28] reduce N_{2O} emissions combining cascade S_{NO_2} control and cascade $S_{NH,5}$ control. Boiocchi et al. [29] reduce N_{2O} emissions with a fuzzy controller that manipulates the oxygen transfer coefficient (K_La) of the aerobic reactors based on S_{NH} and the nitrate concentration (S_{NO_3}) in the input and in the output of the nitrification process. In addition, Boiocchi et al. [29] take into account the effect that the oxygen aeration can produce on effluent costs and quality. Santín et al. [28] combine two control strategies with PI controllers to also reduce costs and improve the effluent quality, but without attempting to eliminate nutrient violations. Both articles only manipulate K_La of the aerobic reactors and only reduce S_{NO_2} as GHG emissions.

The present article reduces the S_{NO_2} emissions using a different control strategy than the two referred articles, by means of only

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