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Aeration control by monitoring the microbiological activity using fuzzy logic diagnosis and control. Application to a complete autotrophic nitrogen removal reactor

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ABSTRACT

Complete Autotrophic Nitrogen Removal (CANR) is a novel process where ammonia is converted to nitrogen gas by different microbial groups. The performance of the process can be compromised by an unbalanced activity of the biomass caused by disturbances or non-optimal operational conditions. This contribution describes the development of a fuzzy-logic based system for both diagnosis and control of a CANR reactor. Based on a combination of measurements of the nitrogen species concentration in the influent and in the effluent on the one hand, and insights into the activities of three distinctive microbial groups on the other hand, the diagnosis provides information on: nitritation, nitratation, anaerobic ammonium oxidation and overall autotrophic nitrogen removal. These four results give insight into the state of the process and are used as inputs for the controller that manipulates the aeration to the reactor.

The diagnosis tool was first evaluated using 100 days of real process operation data obtained from a lab-scale single-stage autotrophic nitrogen removing reactor. This evaluation revealed that the fuzzy logic diagnosis is able to provide a realistic description of the microbiological state of the reactor with process engineering insight analysis. An evaluation of both the diagnosis tool and the controller was done by simulating a disturbance in the influent concentration. High and steady nitrogen removal efficiency was achieved thanks to the diagnosis and control system. Finally, development of the diagnosis and control as two independent systems provided further insight into the operation performance, gives transparency towards the operator and makes the system flexible for future maintenance or improvements.

1. Introduction

Monitoring microbial activity is essential for achieving high control performances in biological reactors. Advances in molecular tools based on omics technology (genomics, metabolomics, etc.) provide a qualitative assessment of the activated sludge microbial community structure with its diverse functions [1]. These measurements are however off-line, tedious, time-intensive, expensive and not able to fulfil the actual needs of most monitoring and control applications. In addition, due to the presence of interacting microbial groups many challenges arise when trying to estimate the microbial activity in a mixed-culture bioreactor. Hence the information given by the few sensors usually implemented in a bioreactor needs to be expanded with observers or other state-estimation tools in order to infer the state of the microbial groups. When first principle models of the microbial kinetics are not available or mismatch significantly with the reality, expert-knowledge about a process system can represent a useful alternative for the development of control strategies. The so-called "fuzzy-logic inference system" (FIS) is a means to exploit this knowledge for control strategy development [2,3]. Since its control laws are expressed in linguistic rather than mathematical expressions, FISs are intrinsically easy to understand and to adapt in function of control performance requirements. Moreover, FISs have been shown to enable integrating quantitative mechanistic knowledge with qualitative expert knowledge, making it suitable for processes that are still in the development stage. Previous applications of FISs

Abbreviations: AOB, ammonia-oxidizing bacteria; AnAOB, anaerobic ammonia-oxidizing bacteria; CANR, Complete Autotrophic Nitrogen Removal; ER, exchange ratio; FIS, fuzzy inference system; FLC, fuzzy-logic control; FLD, fuzzy-logic diagnosis; HB, heterotrophic bacteria; MF, membership function; MV, manipulated variable; NOB, nitrite-oxidizing bacteria; SBR, sequencing batch reactor; TN, total nitrogen.

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in wastewater treatment (WWT) include the control of activated sludge processes [4,13], digesters [11] or improving disturbance rejection [6].

The so-called Complete Autotrophic Nitrogen Removal (CANR) is a novel process that has shown its usefulness for the side-stream treatment of reject water from anaerobically treated sludge dewatering or landfill leachate [4–6]. The CANR process performs the conversion of ammonium (NH_4^+) to dinitrogen (N_2) through the activity of ammonia-oxidizing bacteria (AOB) and anaerobic ammonia-oxidizing bacteria (AnAOB) [4,5]. AOB partially convert NH_4^+ to nitrite (NO_2^-) with oxygen (O_2) as electron acceptor and AnAOB oxidize the remaining fraction of NH_4^+ by reducing the AOB-produced NO_2^- [4,7–9]. In this process, a minor fraction of nitrate (NO_3^-) is produced. Well-known advantages of the CANR process are: reduction of O_2 supply, no need for organic biodegradable carbon addition and negligible sludge production [5]. CANR can be accomplished in a single reactor, where AOB and AnAOB work simultaneously, or in a two-stage configuration designed to have the aerobic AOB-mediated process, namely nitritation, preceding the AnAOB-mediated process. The performance of a single-stage CANR can be seriously compromised due to disturbances as well as operating conditions leading to unbalanced activity of the biomass. For example, a significant activity of nitrite-oxidizing bacteria (NOB), a class of autotrophic microorganisms converting NO_2^- to nitrate (NO_3^-), reduces the total nitrogen (TN) removal efficiency, since NO_3^- requires a significant amount of readily degradable organic carbon and the presence of heterotrophic bacteria (HB) to be converted to N_2.

Ensuring a balanced microbiological activity during CANR is therefore central in order to achieve a good and steady performance. Since many microbial processes take place simultaneously resulting in dependencies and competition between the microbial groups, linear controllers using constant set point values for dissolved oxygen, O_2 reduction potential, N species or pH alone may not be enough to ensure balanced microbial community activities and therefore performance stability [10–12]. Too high O_2 concentrations inhibit the AnAOB activity and enhance the undesired activity of NOB. On the other hand, too low O_2 supply leads to low aerobic AOB activity [4,8]. Therefore, a diagnosis of the microbiological operation is needed to establish the appropriate control action.

The present work is a comprehensive extension and analysis of the work presented at the CAB/DYCOPS conference in 2013 [13]. The main additions made are: (i) a structured methodology and in-depth description of the work flows underlying the development of a fuzzy-logic diagnosis and fuzzy-logic controller. In addition, the control block diagram indicating the data-flow and information flow hierarchy is presented, (ii) detailed analysis and validation of the diagnosis tool with experimental data and process engineering insights, (iii) control performance evaluation under more challenging disturbances and conditions. The objective of this work is to develop a fuzzy-logic diagnosis (FLD) and a fuzzy-logic control (FLC) with the objective of achieving high and steady TN removal in a single-stage CANR reactor with granular sludge. The FLD will provide information regarding the activity of the biomass as an input to the FLC. Diagnosis and control will be developed independently in order to achieve transparency on the input information given to the controller, and flexibility in case of needed control performance improvement and feasibility for the implementation of the knowledge by the operator.

The paper is organized as follows: first the mathematical model of a lab-scale CANR reactor and the modelling of generic FIS are presented. Afterwards, the development of the FLD and FLC tools is explained. The fuzzy-logic diagnosis performance will first be evaluated on the basis of the consistency of the outputs produced and of their capability of realistically describing the actual situation of the biomass during 100 days of a lab-scale CANR operation. Finally, both the FLD and the FLC are evaluated by simulation of a disturbance in the nitrogen load to the reactor, in the form of a change in the incoming ammonium concentration.

2. Materials and methods

The FLD and FLC system developed were implemented using the fuzzy logic toolbox of MATLAB R2013 (The MathWorks, Natick, MA). The developed FLD and FLC were then coupled to a process model built in Simulink. The process model consists of the description of the physical and biochemical processes occurring in a lab-scale CANR reactor. In this section, first a brief description regarding the mathematical model used and the physical configuration of the reactor are provided. Afterwards an overview of the generic work done by a fuzzy-logic inference system will be shown.

2.1. Mathematical model and physical configuration of the reactor

The mathematical model employed in this work describes a granular based single-stage CANR sequencing batch reactor (SBR) shown in Fig. 1. The model developed and described in detail by Vangsgaard et al. [14] is shortly described here for the sake of completeness. It consists of mass balance equations for each soluble and particulate compound considered in the model. The main assumptions included are: (a) the transfer of soluble compounds within the granule occurs only by diffusion (Eq. (1)) and (b) the transport of particulate compounds occurs only by advection (Eq. (2)). The bulk of the reactor is assumed to be completely mixed, which results in Eq. (3).

$$\frac{\partial S_i}{\partial t} = D_i \cdot \frac{1}{z^2} \cdot \frac{\partial}{\partial z}\left(z^2 \cdot \frac{\partial S_i}{\partial z}\right) + r_i \tag{1}$$

$$\frac{\partial X_i}{\partial t} = \frac{\partial (X_i \cdot u_F)}{\partial z} + r_i \tag{2}$$

$$\frac{dC_i}{dt} = \frac{Q_{in} \cdot C_{i,in} - Q_{out} \cdot C_{i,bulk} - j_{bio,i} \cdot A_{bio}}{V} + r_i \tag{3}$$

In Eqs. (1)–(3) D_i is the diffusivity of compound i, z is the radial direction in spherical coordinates, S_i is the concentration of soluble compound i, r_i is the reaction rate for compound i, X_i is the concentration of particulate compound i, u_F is the biofilm net growth velocity, C_i is the concentration of generic compound i (it applies to both soluble and particulate compounds), Q_{in} and Q_{out} are the in- and outflow, respectively, $j_{bio,i}$ is the flux in and out the biofilm and V is the reactor volume. The reaction rate expression is deduced

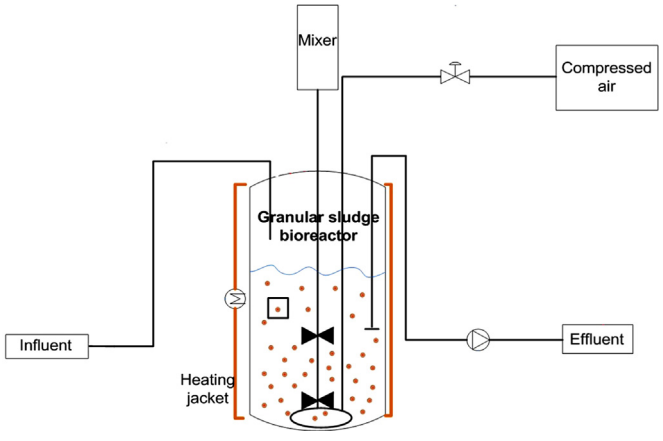

Fig. 1. Reactor configuration [15].