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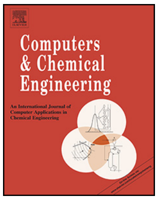

Development of novel control strategies for single-stage autotrophic nitrogen removal: A process oriented approach

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ABSTRACT

The autotrophic nitrogen removing granular sludge process is a novel and intensified process. However, its stable operation and control remain a challenging issue. In this contribution, a process oriented approach was used to develop, evaluate and benchmark novel control strategies to ensure stable operation and rejection of disturbances. Three novel control strategies were developed, evaluated, and benchmarked against each other: a feedforward control (control structure 1 – CS#1), a rule-based feedback control (CS#2), and a feedforward–feedback controller, in which the feedback loop updates the set point of the feedforward loop (CS#3). The CS#1 gave the best performance against disturbances in the ammonium concentration, whereas the CS#2 provided the best performance against disturbances in the organic carbon concentration and dynamic influent conditions. The CS#3 rejected both disturbances satisfactorily. Thus, the appropriate design will depend on the specific disturbances in the influent generated in the upstream units of the wastewater treatment plant.

1. Introduction

There is a general interest in process intensification to reduce costs and improve efficiency. For wastewaters containing high concentrations of nitrogen and low organic carbon to nitrogen ratios, complete autotrophic nitrogen removal (CANR) is a suitable, novel process that can increase the treatment capacity approximately five times. This process, originally designed as a two-stage SHARON-Anammox process (van der Star et al., 2007), is convenient for treating anaerobic digester liquor, landfill leachate, or special industrial wastewaters, because costs related to the need of aeration and carbon addition are lowered by 60% and 100%, respectively, compared to conventional nitrification–denitrification treatment. The complete conversion of ammonium to nitrogen gas consists of a combination of two processes, which are catalyzed by two different microbial groups (aerobic and anaerobic ammonium oxidizing bacteria (AOB and AnAOB)) that grow under different oxic conditions. AOB oxidize ammonium to nitrite with under oxic conditions, while AnAOB oxidize the remaining ammonium with the AOB-produced nitrite as electron acceptor. These microbial groups can coexist in a granular sludge reactor, where the AOB grow in the exterior oxygen receiving parts and AnAOB thrive in the interior anoxic parts (Fig. 1). In addition, there is competition by other microbial groups, such as nitrite oxidizing bacteria (NOB) and heterotrophic bacteria (HB), resulting in a complex set of relationships among the microbial groups. Energy and capital costs can further be reduced by intensifying the process and performing it in a single biofilm reactor, where all processes take place simultaneously, e.g. in a granular sludge reactor.

The automatic control of bioreactors utilizing mixed cultures, such as single-stage CANR, is challenging given their highly nonlinear behavior, interactive dynamics, and variations in the influent (flow rate, composition, temperature, etc.). Furthermore, since only a few actuators are available to influence the process variables, it becomes difficult to reject disturbances entering the system and thereby maintain a stable operation. On top of this, the substrate competing microbial groups do not make the optimal operation and control trivial. In this context, advanced control can improve the process performance: i.e. nonlinear controllers, such as gain scheduling, are suitable to address the nonlinear behavior of the bioreactor or model predictive control (MPC) can tackle the relationships between the multiple microbial groups. However, the development of such advanced control strategies in bioreactors is usually hindered by the low accuracy of models describing the microbial metabolism, the long simulation times required to solve such models, and by the complexity of such controllers (Olsson, 2011). In this respect, the simplicity of a controller is an important characteristic in a bioreactor, since it is likely that

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Nomenclature

AOB	ammonium oxidizing bacteria
AnAOB	anaerobic ammonium oxidizing bacteria (anammox bacteria)
BSM	benchmark simulation model
CANR	complete autotrophic nitrogen removal
COD	chemical oxygen demand
CS	control strategy
CV	controlled variable
DO	dissolved oxygen
$e(t)$	offset in total nitrogen removal efficiency
HB	heterotrophic bacteria
HRT	hydraulic retention time
IAE	integral absolute error
IMC	internal model control
K_C	proportional controller gain
k_La	volumetric mass transfer coefficient
L_{NH_4}	volumetric oxygen loading rate
L_{O_2}	volumetric ammonium loading rate
MPC	model predictive control
MV	manipulated variable
$NH_{4,in}{}^+$	ammonium concentration in the influent
$NH_{4,out}{}^+$	ammonium concentration in the effluent
$NO_{2,in}{}^-$	nitrite concentration in the influent
$NO_{2,out}{}^-$	nitrite concentration in the effluent
$NO_{3,in}{}^-$	nitrate concentration in the influent
$NO_{3,out}{}^-$	nitrate concentration in the effluent
NOB	nitrite oxidizing bacteria
P	proportional
PDE	partial differential equation
PI	proportional–integral
R_{AmmTot}	ammonium removed over total nitrogen removed
$R_{AmmTot,sp}$	set point of ammonium removed over total nitrogen removed
RO	volumetric oxygen loading rate over ammonium loading rate
RO_{sp}	set point of volumetric oxygen loading rate over ammonium loading rate
RT	total nitrogen removal efficiency
RT_{sp}	set point of total nitrogen removal efficiency
SHARON	single reactor system for high activity ammonium removal over nitrite
$S_{O_2,sat}$	oxygen saturation concentration
TN	total nitrogen
TN_{in}	total nitrogen concentration in the influent
TV	total variation
τ_C	closed loop time constant
τ_I	integral time

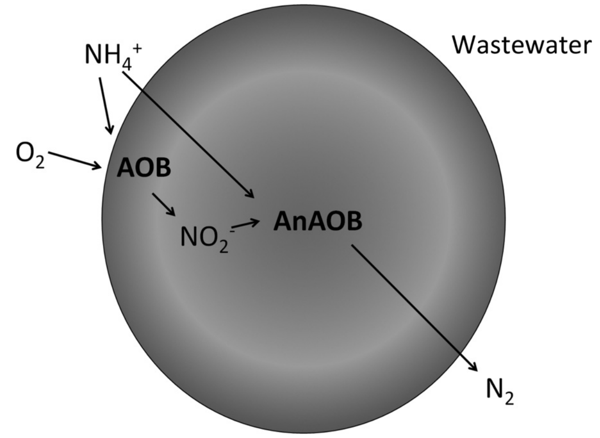

Fig. 1. Schematic illustration of idealized spatial location of the microbial groups in the CANR system.

frequent maintenance will be needed as a result of variations in the feed, seasonal variations, and even because of microbial evolution. Hence, a tradeoff must be achieved between efficient control and monitoring tools on the one hand and simplicity on the other hand, in order to ensure the success of the control strategy.

Previously, several control strategies for the two-stage CANR process have been developed and tested (i.e. Volcke, van Loosdrecht, & Vanrolleghem, 2007). However, results cannot be directly transferred to the intensified single-stage system, since fewer actuators are available and the process dynamics are more complex. This is a common issue faced in intensified systems (Nikacevic, Huesman, van den Hof, & Stankiewicz, 2012). For single-stage treatment, pH (Wett, 2007) and ammonium and nitrate measurements (Christensson, Ekström, Andersson Chan, Le Vaillant, & Lemaire, 2013) have been used as sensors generating the necessary measurements that allow to control the dissolved oxygen (DO) concentration. Yet, these strategies only tackle the regulation of the process, not the performance. As a result, no strategies have so far aimed at directly controlling the nitrogen removal efficiency, i.e. the key performance criterion.

In a previous modeling study, the oxygen to ammonium loading ratio (RO), as opposed to the concentration ratio or solely the DO concentration, was identified as a key factor for securing a high removal efficiency and conversion rate, while avoiding growth of undesired microbial groups (Vangsgaard, Mauricio-Iglesias, Gernaey, Smets, & Sin, 2012). Additionally, ranges of ratios of nitrogen species consumed or produced in the process that indicate a suitable operation, have been formulated based on reaction stoichiometry and process knowledge (Mutlu et al., 2013). Among these, a ratio between the ammonium removal and the total nitrogen removal (R_{AmmTot}) has been formulated as a measure of the relative activity of microbial groups present in the system.

The aim of this work is therefore to design a control system through a systematic process oriented approach, for a single-stage treatment, by utilizing process insights obtained from previous model and experimental studies. This will be illustrated through numerical simulations of a continuously operated reactor system, utilizing an experimentally calibrated and validated model (Vangsgaard, Mutlu, Gernaey, Smets, & Sin, 2013). The objective of the controller was to keep the intensified process at a stable and efficient performance during disturbances in influent composition and set point changes.

The paper is based on a contribution to the ESCAPE23 conference (Vangsgaard, Mauricio-Iglesias, Gernaey, Smets, & Sin, 2013), which has been significantly expanded and thoroughly revised: (i) the mechanistic model used for simulations is presented and explained; (ii) the derivation of transfer functions for the strategies and their IMC based tuning are presented; and (iii) a more comprehensive performance evaluation and benchmarking of the control strategies is now included considering measurement noise, disturbance rejection and set point tracking for step change as well as dynamic influent disturbances. Overall, the contribution provides a deeper understanding and demonstrates the reliability of the tested control strategies, and thus brings them a step closer to full scale evaluation in lab-scale bioreactors which is the focus of on-going work.

2. A process oriented approach to controller design

The controllers were developed by following a step-wise procedure consisting of the following steps: The first step is the definition