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Observer-based output feedback linearizing control strategy for a nitrification–denitrification biofilter

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ABSTRACT

The objective of the present work is to propose an output-feedback control scheme for a wastewater treatment biofilter, in order to regulate the outlet concentrations of nitrate and nitrite below a prescribed level (in accordance with the norms). The nitrification–denitrification biofilter is described by a set of mass balance partial differential equations (PDEs), of hyperbolic or parabolic type, depending on the consideration of diffusion/dispersion phenomena. The design of the output-feedback control strategy follows a late lumping approach, in which the PDE system is considered, and descretized only at a later stage for implementation purposes. This strategy is based on feedback linearization and requires a state estimator, which takes the form of a distributed parameter Luenberger observer. A point of particular attention is the formulation of the model boundary conditions, from the classical Dankwerts conditions to more advanced formulations including dynamic boundary conditions, which has a significant influence on the control performance. The control strategy is tested against model uncertainties and measurement noise in simulation.

1. Introduction

Nitrate is a contaminant in groundwater aquifers and rivers which has been increasing in recent years mainly due to the extensive use of nitrogen fertilizers and improper treatment of wastewater from the industrial sites. Denitrification (reduction of nitrate nitrogen into nitrogen gas) is then an important step in biological wastewater removal systems. It may be classically processed in full nitrification–denitrification activated sludge systems or by biofiltration. Biofiltration is a technology based on a biological reaction using micro-organisms which are immobilized forming biofilms or biolayers, where the bioreactions take place, around solid particles. These immobilized particles are packed in a column known as a biofilter [1]. The development of biofiltration has been promoted by its advantages over other alternative technologies. It is an environmentally friendly and cost-effective method thanks to its compactness, efficiency and low energy consumption. With the advent of more and more stringent norms for water reject, reuse or for drinking water, the need for better understanding and improvement of reactor performance naturally comes to mind and impels the development of efficient controllers to optimize the real-time operation of these processes.

Many mathematical models of biofilters have been proposed to understand and improve the reactor performance [2]. Because the biofilter state variables may be distributed both in time and space, a system of partial differential equations (PDE) is deduced from the mass balance of each component (concentrations, biomass, etc.) to describe its dynamics. In this way, a biofilter is described as a distributed parameter system (DPS).

In order to control a DPS, two strategies are commonly used: the early and late lumping approaches. In the first one, the partial differential equations are discretized to obtain an ordinary differential equation (ODE) system and then, ODE-based control strategies for nonlinear or linear systems may be applied (see for example [3]). On the other hand, in the second approach, controllers are designed based on the PDE model, and discretization occurs at a latter stage only, so as to preserve the distributed nature of the problem as long as possible in the design procedure (see for example [4–6]).

For years, control of distributed parameter bioprocesses has used the early lumping approach. This is because the most important control strategies have been developed to control systems described by either linear or non-linear models represented by ODEs. In this context, several works have been developed, for instance: in [7], the authors applied adaptive control schemes to

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nonlinear distributed parameter bioreactors by using an orthogonal collocation method to reduce the original PDE model to ODE equations. In [8] the authors dealt with the linear boundary control problem in an anaerobic digestion process by using the solution at steady state.

However, in the last two decades, several control strategies using a late lumping approach based on the non-linear control theory have been proposed. In [9], the authors applied variable structure control to fixed bed reactors described by nonlinear hyperbolic PDEs. In [10] a nonlinear multivariable controller is designed for an anaerobic digestion system described by a set of PDEs, which consists of an observer and two nonlinear control laws on the boundary conditions.

In this work, a late lumping approach and a nonlinear control strategy are investigated for a biofilter described by a set of PDEs. The relative degree of the PDE system is analyzed in order to propose a new system of coordinates to synthesize a control law which linearizes the output dynamics, assuring in addition closed-loop asymptotic stability [11–13]. The states needed by the linearizing control law synthesized must be either measured or estimated. A distributed Luenberger observer, as proposed in [14], is considered to estimate the overall set of state variables distributed along the reactor. Even if only those ones needed by the linearizing control law are required, this full observer might be useful for monitoring purposes as well.

In order to synthesize an output feedback linearizing controller the diffusion phenomenon may be either neglected or considered. In the first case, the biofilter is modeled by a hyperbolic PDE system composed of a first-order derivative term (convection term) and a reaction term:

$$\frac{\partial \xi}{\partial t} = -\nu \frac{\partial \xi}{\partial z} + r(\xi)$$

complemented by Dirichlet boundary conditions at the input biofilter. In the second case, the precedent PDE system is completed by a second-order derivative term (diffusion term), resulting in a parabolic PDE system:

$$\frac{\partial \xi}{\partial t} = D_f \frac{\partial^2 \xi}{\partial z^2} - \nu \frac{\partial \xi}{\partial z} + r(\xi)$$

Classical boundary conditions used in reactors modeled by parabolic PDEs were proposed in [15]. They are compounded by Robin boundary conditions at the input reactor and Neumann boundary conditions at the output reactor. However, Neumann boundary conditions are not well suited to linearize the output dynamics of biofilters taking diffusion into account because in such case, the controlled input is not more related to the controlled output. Alternative and more realistic boundary conditions must therefore be investigated.

Depending on the biofilter model and the boundary conditions selected, from a simple to a more complete version of the linearizing control law are synthesized. The main contribution of this work is to demonstrate, through closed-loop simulations, that the diffusion term improves the controller performance, yielding to consider the parabolic model over the hyperbolic one to design a controller for a nitrification–denitrification biofilter. This article is organized as follows: in Section 2 the nitrification–denitrification biofilter and its PDE model are presented. Both cases without (hyperbolic model) and with (parabolic model) diffusion are considered. In addition, different boundary conditions are discussed. In Section 3 the control objective is defined, including the definition of the controlled input, the controlled output, additive disturbances and uncertainties. In Section 4 a feedback linearizing strategy is used to design a controller for regulating the nitrogen concentration at the biofilter output. This controller is complemented by the distributed parameter observer developed in Section 5. In Section 6 the overall observer-based output feedback linearizing control law and its implementation are discussed. In Section 7 numerical results are examined. Finally, in Section 8 conclusions about this work are presented.

2. A nitrification–denitrification biofilter model

Biofiltration has proven to be a promising reaction system for wastewater [16,17] or drinking water treatment [18,19], but also in aquaculture or for control of air pollution. Biofiltration is performed by a biofilter tubular reactor. Such a device is compact, fairly simple to build and operate, and has shown good efficiency for biological treatment associated to low energy consumption. Such biofiltration unit is characterized by spatial distribution of micro-organisms which are fixed on a solid support [20]. They are mathematically described as distributed parameter systems (DPS) and represented by partial differential equations (PDE) to explain their distributed nature [21].

The nitrification–denitrification process under study is a biofilter, shown in Fig. 1, filled with a porous pouzzolane material. Nitrate and nitrite nitrogen issued from some wastewater are considered at the reactor input. An additional ethanol supply source may be used as a control input action or at least to ensure a sufficiently high ratio C/N *(carbon source per nitrate)* such that carboneous component does not become the limiting source for the growth. Denitrification is performed in anoxic conditions, i.e., in absence of O_2 in gaseous form. The biological reaction is a two-stage reaction. The first stage is the denitratation which transforms nitrate (NO_3) into nitrite (NO_2) while the second phase transforms nitrite into gaseous nitrogen (N_2). The same micro-organism population (bacteria) is involved in both stages, with ethanol as co-substrate. This biomass

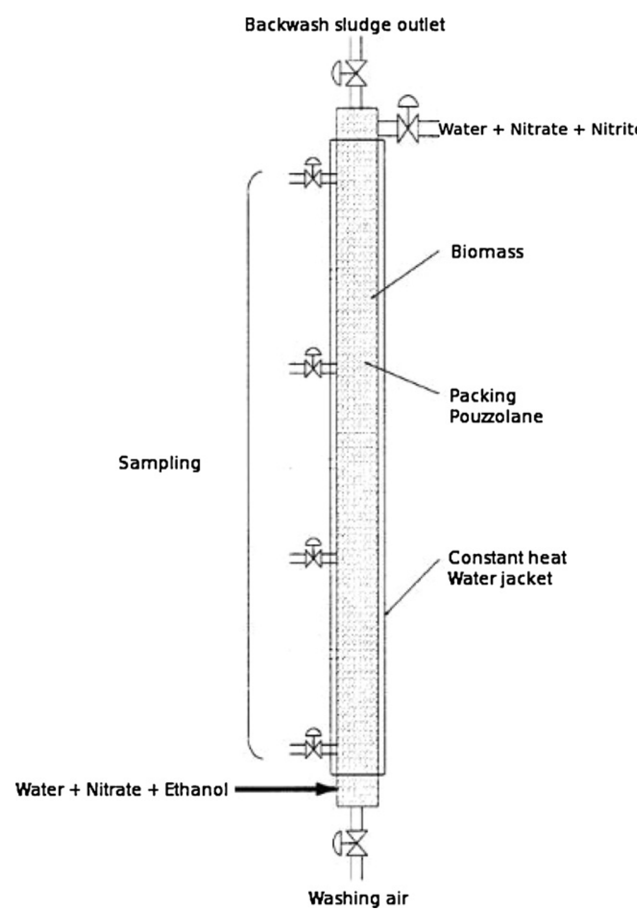

Fig. 1. Denitrification biofilter.