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Experimental validation of a simple dynamic model of a laboratory scale recirculating aquaculture system fitted with a submerged membrane bioreactor

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ABSTRACT

Submerged membrane bioreactors (sMBRs) are a promising technology for nitrogen removal in recirculating aquaculture systems (RASs). However, there are still relatively few reports on the experimental application of this strategy. In this study, a laboratory-scale system, mimicking a RAS fitted with a sMBR, was designed and automated, and a simple dynamic sMBR model including biological and physical phenomena was validated. The system was analyzed based on measurements collected by a data logging structure involving a programmable logic controller (PLC), an industrial network protocol and a LabView application software. This study confirms the suitability of sMBR systems within aquaculture applications. The dynamic model has good predictive capabilities and could be used for the design of advanced control structures, such as model predictive control.

1. Introduction

The growth of the world population and the scarcity of water, land and other natural resources motivate the use of recirculating aquaculture systems and their optimization [1]. For most agro-food processes, profits are computed based on the quantity of consumed resources, production yield by process footprint, and environmental impact. Especially in aquaculture systems, the ratio between fresh incoming water and recirculated water is a determining economic and ecological factor, usually set to a maximum of 10% of the total volume replaced per day [2]. However, if the recirculated water is not properly treated, harmful compounds could accumulate, such as ammonia and nitrate. In order to prevent this accumulation, the use of rotating disk contactors, trickling filters, bead filters or fluidized sand biofilters [3] is a common solution. On the other hand, submerged membrane bioreactors (sMBRs) have been increasingly used in water treatment. They accomplish the combined functions of an aerobic activated sludge system, a secondary clarifier, and a tertiary filter [4], reducing the process footprint and producing high-quality effluent [5–8]. Despite these decisive advantages, only a limited number of applications have been reported in recirculating systems [9]. One of the reasons is the fouling of the membrane, which decreases membrane permeability, such that the membrane requires periodic cleaning [10].

The use of submerged membrane bioreactors (sMBRs) in recirculating aquaculture systems (RASs) is therefore relatively new. The RAS differs from conventional domestic and industrial wastewater treatment in the composition of the inflow and specially in the low total suspended solids (TSS) concentration [11]. These aspects contribute to different rates of fouling and internal recirculation flows, which affect the operating and cleaning cycles of sMBRs as well as the membrane cleaning procedures. Also, [12,13] evidenced a remarkable reduction in wastewater and residue load in RAS treatment when compared to conventional water treatment in aquaculture systems.

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As experimental data from aquaculture systems with sMBR is scarce, it is of interest to develop additional laboratory-scale studies, and the objective of this work is threefold: The first objective is to set-up a laboratory-scale RAS and collect informative experimental data. Indeed, industrial processes should not be disturbed so as to avoid any harmful effect on the fish population, and a laboratory-scale platform with synthetic wastewater is ideal for developing experimental analysis and model validation, with data covering a range of operating conditions. This paper gives a full description of a suitable laboratory-scale process. The second objective is to validate experimentally a dynamic model that was recently proposed and analyzed by the authors in [14]. The model is four-dimensional and possesses ten parameters to be identified. In view of its modest size, this model is a good basis to implement model-based optimization and control. the third objective is to propose a dedicated parameter identification procedure that exploits the characteristics of the dynamic model and the existence of three different time-scales. This procedure allows the identification of the model parameters from data collected at laboratory scale, with satisfactory accuracy and precision, and could be used in practice for setting-up models of full-scale plants.

This paper is organized as follows. Section 2 describes the laboratory-scale process, including sensors and actuators, as well as the data acquisition system. Section 3 briefly presents a simple mathematical model proposed in [14,15], together with a parameter identification strategy. The main experimental results are then presented in Section 4 and discussed in Section 5. Finally, some conclusions are drawn in Section 6.

2. Materials and methods

2.1. Process description

Recirculating aquaculture systems are sustainable fish production facilities in terms of water usage. Water reuse is possible only if efficient nitrification, denitrification and removal of organic matter are achieved. A sMBR can be incorporated into the system in view of its high effluent quality. In this study, we undertake a case study involving the production of tilapia and trout, which are susceptible to high concentrations of ammonia resulting from fish feces and excretion, but are tolerant to nitrate [16]. Future studies could be carried out with other species, where the nitrate concentration plays a critical role in the process.

2.2. Experimental setup

The laboratory-scale RAS-sMBR is designed to remove nitrogen and solid matter (see Fig. 1). The influent is composed of a synthetic wastewater that mimics fish excrement with ammonia mass flow of around 19.8 mg/h. This value is based on the ammonia excretion values reported by [17] and [18], for a total fish basin volume of 0.05 m^3 and a fish density of 24 kg/m^3.

The bioreactors have a total volume of 0.22 m^3 divided into an anaerobic compartment (41% of the total volume), an aerobic compartment (41%), and a compartment with submerged microfiltration membranes (18%). The recirculation between the sMBR and the nitrification tank is 0.7 m^3/d while the recirculation between the nitrification and denitrification tanks is 0.7 m^3/d. The total area of the membrane is 0.35 m^2, working at $t_{permeate}$ = 0.0035 d (i.e., 5 min) filtration and t_{relax} = 6.94 × 10^{-4} d (i.e., 1 min) relaxation. The permeate production is around 18.7 $L/m^2/h$, and membrane aeration is around 20 m^3/d. The suspended solids concentration in the membrane compartment ranges from 0.05 to 0.6 g/L. Online data, including temperature, flows and trans-membrane pressure (*TMP*), are measured every second. Offline measurements of suspended solids concentration, pH, air-flow rates and ammonium concentration are carried out daily. The measurement of ammonia concentration is carried out using HACH kits LCK-304. The confidence interval at 95 % is ±0.012 mg/L. Note that ammonia can be presented in water in two forms, which depends on the pH of the water. When pH is less then 7 the ammonia is mainly presented as its ionized form (NH_4^+), as pH increases above 7 its un-ionized (NH_3) form is also present. The system includes five pumps of three different types. The intermediate circulation pumps (MP1, MP2, MP3) are magnetic couple AC pumps (IWAKI model MD-6-230GS01), which allow flows up to 8 L/min. The global recirculation and backwash pump is a diaphragm 24 Vdc pump (SHURflo model 8000-991-236) with a maximum flow rate of 2 L/min. The last pump is the dosing pump (ISMATEC model Reglo Digital MS-2/6-160), whose flow is adjusted to emulate the effect of fish excretion by injecting a solution containing ammonia into the system.

The AC pump sources are phase-angle dimmers (NS-80 from FG ELEKTRONIK) that allow the PLC to control the pumps through its analog outputs. The diaphragm pump is a DC pump powered by a DC driver, which allows the PLC to change the flow using pulse width modulation (PWM).

To control the pump flow rates, the levels of the tanks and the differential pressure across the membrane, the following sensors are used: level sensors, which consist of a simple float switch that prevents the tank from overflowing; flow-meters, ranging from 0.05 to 10 L/min, which allow a large range of operating conditions, and a pressure sensor that is used for the *TMP* measurement and ranges from −1 to 1.6 bar, producing an output current of 4–20 mA.

Two motorized 3-way valves (V1 and V2) are used to reverse the flow from permeate to backwash on the sMBR module and V3 controls the waste flow. The system uses reinforced flexible tubing of 13 mm in diameter.

For the aeration of the nitrification tank, a Roeflex disc diffuser from Passavant-Geiger Gmbh is used, which permits good diffusion of air at the bottom of the tank. The air source for the nitrification tank is separate from the sMBR air source. For the nitrification tank, an air pump with constant air flow is used while variable flow is applied to the sMBR. Airflow sensors and manual control allow manipulation of the airflow rate in a range from 0 to 300 NL/h (NL are normal liters, referring to 0 °C and 1 atm).

The membrane used is a BIO-CEL Lab from Microdyn-Nadir Gmbh. It has a membrane surface area of 0.35 m^2 and is installed in a PVC frame with integrated cross-flow aeration via a membrane diffuser. Connections for permeate drainage and air supply are already provided. The Nadir membrane (type UP150) has 150 molecular weight cut-off (MWCO) [kDa], and is made of polyethersulfone (PES). The material is hydrophilic with a high chemical resistance (pH from 0 to 14 and max temperature 95 °C). The membrane has been designed for environmental protection, metal processing, textiles, paper, food/dairy, pharma/biotech and chemical processes. The membrane is identical to that of the full-scale BIO-CEL module, making the laboratory-scale device representative of a real-life process [19].

For data acquisition and control, a PLC S7-1200 from Siemens is used, which has all the inputs and outputs needed for the process monitoring and control. To complete the monitoring part, a PC is used as an industrial network using OPC-server ensuring communication between the PLC and LabView. In this configuration, the PLC and the LabView application are the OPC-clients. A LabView interface was also designed for human–machine interface. Moreover, LabView allows the interaction between the PLC and Matlab & Simulink software for simulation tests.

Fig. 2 shows the automation structure of the process. This includes the human–machine interface at the top (LabView), the control part (PLC), sensors, drivers and the actuators at the bottom.