Optimization of advanced treatment plants for the reuse of wastewater

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1 Introduction

In the context of treated wastewater reuse, membrane systems are excellent candidates as treatment processes because they allow treated water to be sanitized while exhibiting very good treatment performances as well as great flexibility, for example to conserve nutrients when this proves to be interesting in agronomy (cf. Dai et al., 2022). However, these systems are quite energy-intensive and it therefore appears essential to optimize their operation.

Modeling and control of membrane filtration systems to limit membrane fouling have drawn considerable attention because membrane fouling remains the main problem to be faced when working with membrane systems. Depending on the membrane type, the fluid to be treated and the technology used, various methods have been proposed and tested (Yusuf et al., 2014). However, most of the approaches are based on holistic methods rather than model-based methods. Holistic, here, means methods based on data, knowledge or any kind of procedures that, precisely, do not use mathematical models describing the dynamics of fouling phenomena, as for example (Chen et al., 2003) who used a statistical method to optimally manage physical and chemical membrane cleaning. However, while these methods do not require which is time consuming to design and validate, they do not guarantee the optimality of fouling control strategies. In fact, optimal fouling control consists of using models and above all available action levers (times at which relaxation or regeneration occur, time periods between filtration and the relaxation/backwashing sequence, backwashing pressure or air/gas bubbling flow rates, etc…) to minimize a given optimization objective (e.g. minimizing the time to reach a given target or the filtration/backwashing energy, maximizing the volume of water treated over a given period of time under performance constraints, see for example (Kalboussi et al., 2017)).

One of the main advantages of having a model describing fouling dynamics is that in the presence of disturbances it is usually possible to assess how close (or far) from optimum the actual operation is. Model-based methods have been particularly proposed in areas where the treatment does not allow the production or recovery of high-value products, such as wastewater treatment. In this area, microfiltration (MF) and ultrafiltration (UF) are now commonly used.

This study is specifically focused on membrane systems where fouling is controlled using relaxation or backwashing action levers. As real plants are subject to disturbances typically due to continuous variation of the quality of the influent, it is important to continuously adapt the fouling control strategy and in particular the duration and frequency of the relaxation/backwashing periods. This paper presents the evaluation of a new optimal control strategy (Adaptive Optimal Control). We also present preliminary results obtained in simulation and demonstrate the interest of the proposed approach to deal with a wide class of uncertainties and disturbances (in particular variations in the influent quality) to optimize membrane systems and enable safe and robust reuse of treated wastewater.

2 Optimal control

Optimization and control of membrane filtration systems involves finding control strategies that achieve the desired performance while minimizing energy and maintenance costs, and/or maximizing productivity.

The goal of optimal control is to bring the system from a given initial state to a certain final state, possibly respecting certain criteria. Indeed, an optimal control problem is essentially defined by three elements (Bryson, AE, & Ho, YC (1975)): i) Objective function (or optimization criterion): It mathematically expresses the cost to be minimized or the benefit to be maximized, ii) Constraints: They define a set of authorized values for the system or the control state and iii) Process model: It defines the inputs, outputs and states that make it possible to describe the real system.

Numerical and practical applications have been performed and detailed in several works, to illustrate the strategy of the optimal control. Cogan et al. (2014, 2016) studied the optimization of filtration and cleaning cycles in membrane filtration systems, applying the Pontryagin Maximum Principle (PMP). Their objective was to determine the optimal times to switch between filtration and physical cleaning phases in order to maximize the net water production over a given period. Based on a dynamic filtration model, taken from the literature and applicable to ultrafiltration and microfiltration systems, they showed that the application of the PMP allowed a better understanding of how to manage the filtration in order to obtain a more efficient water production. The results obtained allowed to improve the management of membrane filtration systems by optimizing the duration and frequency of backwashing cycles, a crucial aspect to minimize operating costs and extend the membrane lifetime. In the study by Kalboussi et al. (2019), specifically focusing on the optimization of net water production per membrane area over a defined operating period, the control variable was related to the flow directions, in particular the membrane filtration and backwashing cycles. The authors considered that the main factor contributing to clogging was the deposition of particles on the membrane surface, while pore blockage, often taken into account in other models, was neglected. To model the system behavior, they relied on a simplified and generic model proposed by Benyahia et al. (2013). On the one hand, by applying the PMP to this model, Kalboussi et al. (2019) were able to propose optimal strategies to maximize water production while minimizing the impact of clogging. On the other hand, Aichouche et al. (2020) focused their research on the optimization of production and regeneration systems in membrane filtration processes. The objective of their study was to find an optimal synthesis method to minimize the total energy consumed during the filtration and cleaning phases, while maintaining a fixed production level. By integrating a "hidden variable" into their model, they were able to better describe the dynamics of the filtration system as a function of the production and regeneration cycles (Backwashing/Relaxation). Using the PMP, they identified strategies that minimize not only the energy consumed but also membrane wear, which helps reduce long-term operating costs. Thus, the mathematical model proposed makes it possible to better capture the transient behaviors of the system, taking into account the operating modes alternating between filtration and regeneration.

However, all these optimal control strategies lack adaptability to changes in operational conditions or unexpected disturbances. This limitation can hamper the effectiveness of the control system, especially in environments where conditions can change rapidly. Therefore, an adaptive approach that tracks the actual system state, with a coupled model to simulate data, is considered.

3 Adaptive optimal control

The adaptive approach developed by Chaaben et al. (2024), which incorporates disturbances and uncertainties, is based on the adaptative application of the PMP to minimize the energy consumption per unit of water produced over a free time interval. In other terms, the PMP is applied iteratively on a model which is adapted over the time.

The initialization of the control is the same as in the study of (Aichouche et al., 2020): a first identification is carried out using the data available during one (or more) filtration/backwashing sequence(s). This allows to compute a first optimal strategy which consists in the computation of the optimal ratio between the filtration and the backwash (or relaxation) time periods. Applying this strategy for a number of periods allows the system to indeed converge towards this optimum. However, as underlined in the previous section, environmental conditions may vary with time and the actual strategy may not be optimal anymore for these new conditions. Then, at a given time selected by the user, using the last available data, the dynamics of the model is reidentified in order to be computed and applied for the new optimal strategy. Then, this procedure is repeated again and again until a given quantity of water is produced. The fact to regularly re-identify the dynamics and re-compute the optimal control makes this strategy to be called an adaptive optimal control approach.

4 Simulations

To test the effectiveness of the Adaptive Optimal Control (AOC) approach, the control algorithm was linked to a simulator of an aerobic membrane bioreactor (Fig. 1, adaptive optimal control). This simulator was based on Activated Sludge Model n°1 (ASM1) coupled with a filtration model (Bouabdallah A. (2024) and Boudalia, R. (2024)). The effectiveness tests are based on comparing the adaptive control with two other strategies: i) a Temporised Mode (TM) and an ii) Open-Loop Optimal Control (OLOC) (Fig.1). The three control strategies are detailed in the work of Chaaben et al. (2024). Furthermore, the purpose of this study is to assess the adaptability of the adaptive optimal control to sudden changes in system inputs (Suspended matter in inlet water) which was supposed to pass from 2g/L to 4g/L. For this reason, we simulated the same system twice: i) Case 1: with constant input concentrations and (ii) Case 2: with variable input concentrations.

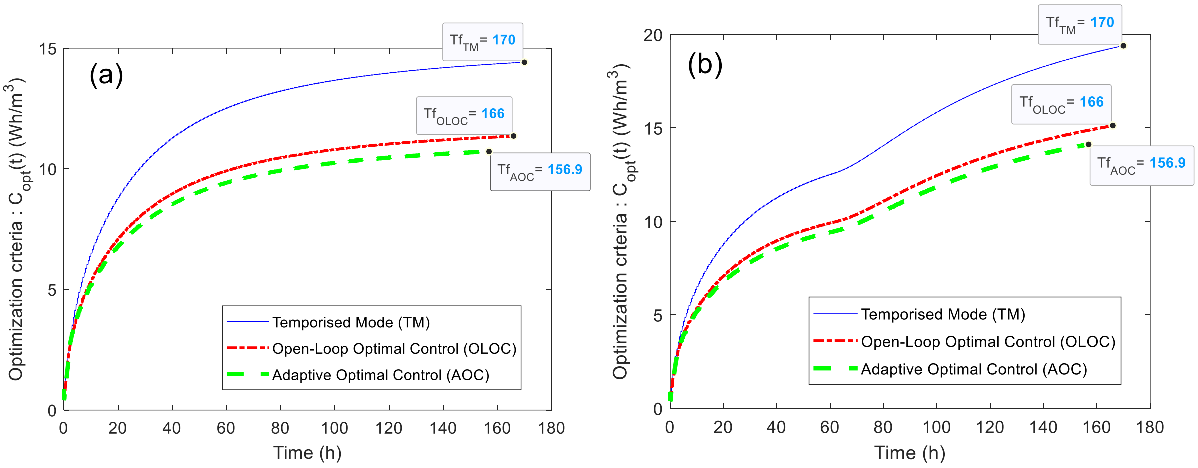

Figure 1 : Variation of energy consumption per unit volume over time: (a) Case 1, (b) Case 2

For both case studies, the strategies were implemented using a data-generating simulator, with MATLAB as the programming environment. Simulations were carried out until the stopping time (Tf), determined by the final produced volume V_T=300L.

Figure 1 shows that the AOC strategy proves to be the best among the three evaluated strategies, not only in terms of energy savings but also in operation time (the required quantity of treated water is produced faster than with other strategies). The application of the adaptive strategy (AOC) resulted in significant energy savings: 25% for case 1 and 27% for case 2, compared to the MT strategy. In comparison to the OLOC strategy, the energy gains were 5.5% for case 1 and 6.5% for case 2. Additionally, AOC reduced system operating time by 7.6% compared to the MT strategy and 5.4% compared to OLOC. Furthermore, when membrane fouling was prioritized during operation by increasing concentrations at the inlet (case 2), the energy savings were more pronounced when applying the AOC strategy.

5 Conclusion

In conclusion, the adaptive optimal control (AOC) strategy has proven to be the most effective control method for both cases studied in this research, as well as those examined by Chaaben et al. (2024). While Chaaben et al.'s preliminary results were based on simulations of an anaerobic membrane bioreactor (AnMBR) using the AM2b model, this study extends the application of AOC to an aerobic membrane bioreactor (MBR) simulator using ASM1 model. Moreover, while membrane filtration is typically considered an expensive process, integrating optimized MBR systems within a REUSE chain can still produce high-quality water at a reasonable cost, making it a practical option for water reclamation and sustainable management.

The system was successfully optimized, although the adaptive optimal control considered only one type of fouling (cake layer deposition). Moving forward, the adaptive optimal control algorithm is planned to be enhanced by incorporating additional states variables in order to extend its applicability field by taking into account another types of fouling (Residual fouling): this would further improve the robustness and efficiency of the system.

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