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The fouling phenomenon in membrane bioreactors: Assessment of different strategies for energy saving

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ABSTRACT

Membrane fouling represents one of the major issues for a membrane bioreactor (MBR). Membrane fouling and high aeration requirements (for inducing shear stress to limit fouling) make MBR operation economically demanding due to high energy costs. Although several studies on MBR fouling have been performed, comprehensive knowledge on how to reduce membrane fouling and consequently save energy is still lacking.

An integrated mathematical model for MBR is applied to a University of Cape Town membrane bioreactor with the final aim to reduce the energy costs. In particular, the influence of the aeration intensity, the duration of filtration/backwashing cycles, and the number of membrane cleanings are investigated. Five scenarios are analyzed and compared, each implementing different operating conditions. The features of the analyzed scenarios are quantified by employing Monte Carlo simulations and performance indices partially drawn from literature. The results provide insights about the role played by the main physical/chemical/biological processes in view of a system optimization. As expected, MBR operation at low air flow rate (qa) leads to a substantial reduction of the operational costs (specifically, 20% with respect to the suggested manufacturers ones in terms of qa). Despite such a reduction of qa, a good effluent quality is also obtained as an effect of a high biological cake thickness. Results also show that the values of filtration time (Tf) higher than those suggested by manufacturers (e.g., Tf=9 min) can be used to increase effluent quality. This study demonstrates that both energy savings and effluent quality can be improved by varying the operational variables with respect to those of the suggested manufacture. One of the main insights gained from this study is that the values of the operating variables (i.e., qa, Tb and Tf) suggested by the manufactures can be changed to obtain a system that still respects high effluent quality and is characterized by lower economical cost. The proposed modeling approach can be an useful tool for the optimization of the operating conditions in order to reduce the operational costs for MBR systems.

1. Introduction

A Membrane Bioreactor (MBR) is an emerging technology increasingly used for wastewater treatment [1]. Despite the numerous advantages of MBR over the conventional activated sludge (CAS) process (e.g., high effluent quality, reduced footprint, lower excess sludge, higher organic loading rates applicable), the MBR technology is affected by crucial issues that may hamper widespread application. Membrane fouling is certainly one of the major obstacles [2]. More specifically, fouling causes permeability reduction and/or an increase of transmembrane pressure (TMP) leading to significant operating costs. The required energy due to TMP as well as the high aeration requirements, make MBR an economically demanding technology. Among the operating conditions, aeration represents a crucial element for membrane fouling. In fact, aeration is used both to provide oxygen for maintaining activated sludge in suspension and to reduce fouling by scouring on the membrane surface [3]. A balance between flux, TMP, energy demand and cleaning frequency is crucial [4,5]. To date, many researchers have been working on membrane fouling in order to identify which factors affect this phenomenon and how to reduce the operating costs [6–8].

The required energy to achieve a pressure suitable for flow reversion (backwashing) or for aeration (relaxation combined with aeration) contributes to increase the MBR energy demand and consequently operating costs [9]. The reduction of operating costs is recommended in order to make MBR technology more competitive and widely applicable.

In the past, due to limit operating costs previous experimental studies have demonstrated how modifying factors that affect

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membrane fouling lead to a possible reduction of MBR operating costs [10,11]. Meng et al. [12], by analyzing the behavior of three MBR pilot plant, demonstrated that the increase of aeration rate may also negatively affect membrane fouling. An intense aeration rate may damage the structure of flocs reducing their size, and releasing EPS in the bioreactor thus increasing fouling phenomenon [13,14].

Despite the useful insights gained by previous experimental studies, there are still some gaps in the understanding of the roles played by the overall operating conditions in the definition of the optimal conditions for reducing fouling (i.e., economic costs) and, on the other hand, for optimizing system performances in terms of effluent quality. Experimental studies may present some limits in terms of both economic costs and investigation time requirements. Furthermore, experimental studies may offer only a limited and narrow spectrum of possible alternatives, and consequently not all the possible combinations of operating conditions can be explored. Consequently, comprehensive knowledge is still lacking and many aspects are still controversial [2].

In this context, MBR mathematical models are a useful tool to predict membrane fouling and to select which operating conditions have to be optimized to reduce energy costs (e.g., [15]). MBR models may allow exploring a wide range of operating conditions and comparing different solutions prior to their effective realization/application. However, studies on a joint simulation of both biological and physical processes for MBR are rare (among others, [16–18]) and research on the evaluation of system performance and energy consumption for MBR are at a somewhat elementary state.

In particular, from the literature three MBR modeling approaches can be pin down [58]: biomass kinetic models, membrane fouling models and integrated models. The kinetic models are based on the activated sludge models (ASMs) which have been properly adapted [29]. In more detail, the ASMs have been modified to take into account the formation and degradation of the soluble microbial products (SMPs) in the MBR [15]. Actually, in the technical literature among the kinetic models, the hybrid models, which are basically a coupling of the ASMs and the SMP formation/degradation process, are also defined. In contrast to the kinetic models, the hybrid models enable describing the influences of SMPs in the biological processes and effluent quality [5]. Regarding the second approach of MBR models, i.e., membrane fouling ones, many mathematical modelling approaches have been considered to simulate the fouling phenomenon so far: some of them are basically straightforwardly based on solids–liquid separation and simulate filtration processes as ideal settler with unitary efficiency [22]. Other models consider specific physical approaches: cross flow filtration and mass transport models [21,22]. Nevertheless, membrane fouling is generally evaluated by employing the resistance-in-series model [58] or, rarely, empirical models [59]. Finally, the integrated models, basically couple the kinetic models with the fouling one (such as the resistance-in-series model) and often consider the formation and degradation of SMP. Among the published integrated models only a few models take into account the relationships between the reversible fouling (i.e., cake layer) and the biological processes (among others, [15–17]). Recently Zuthi et al. [60] addressed the importance of using integrated modeling approach with the use of resistance-in-series models to better simulate the membrane fouling, as physical mechanisms of membrane play a vital role.

In the wastewater treatment plant (WWTP) field several optimization studies have been carried out for the assessment of the best operating conditions obtained by minimizing the operational costs and keeping high plant performances in terms of effluent quality. However, such studies refer mainly to CAS systems (among others, [19–21]). Despite the useful results from previous literature studies, the transferability of the results derived for CAS is limited and cannot be directly referred to MBR which requires dedicated and ad-hoc studies [22]. To overcome such an issue, Maere et al. [23] presented an optimization study for evaluating different MBR control strategies based on an ad-hoc platform. Such platform was realized on the basis of the existing COST/Benchmark Simulation Model No.1 (BSM1) [24,25] widely used as a procedure for designing and evaluating control strategies for CAS systems. By using the proposed platform (BSM-MBR) the authors quantified, for both steady and dynamic conditions, the energy requirement in terms of aeration, pumping and mixing. Despite the useful insights gained from the study [23] there are some criticisms on the results due to the simplified modeling approach. An ideal membrane was assumed and some biological/physical processes deemed to be crucial for MBR (e.g., pore fouling, interaction between biological and physical processes etc.) were not taken into account. Furthermore, phosphorus removal was not taken into account; such a fact is quite common in integrated MBR modeling studies where phosphorus removal is scarcely studied [5,26,27].

The above literature review shows that a comprehensive analysis of interactions among the relevant operating conditions simultaneously considering both biological (including phosphorus removal) and physical processes is lacking so far. Bearing in mind such considerations the main aim of this paper is to provide hints for selecting the best MBR management strategies for energy saving and maintaining high effluent quality. For this purpose, the influence of the aeration intensity, the duration of filtration/backwashing cycles and the number of membrane cleanings on the MBR energy demand has been investigated. In more detail, the problem statement for the pursue of this study is: how can we select the best operating conditions in terms of aeration and duration of filtration/backwashing for an MBR system by limiting fouling?. To accomplish such goals an integrated MBR model able to account for both biological and physical processes was employed. The integrated MBR model was applied to a University Cape Town (UCT)–MBR pilot plant and calibrated by means of measured data gathered during previous studies [16,28]. Five scenarios were analyzed and compared in terms of energy requirements, effluent quality, and economic costs.

2. Materials and methods

2.1. The MBR model

The study was performed by using an integrated ASM2d-SMP-P MBR model developed in previous studies [16,17]. The model describes both biological and physical processes that occur in an MBR system and is divided into two sub-models: a biological and a physical sub-model. The MBR model involves 19 biological state variables and 79 parameters (kinetic, stoichiometric, physical and fractionation-related). The biological sub-model simulates the biological processes according to the ASM2d [29] and includes the production/degradation processes of soluble utilization associated products (SUAP) and of soluble biomass associated products (SBAP). More specifically, the biological sub-model includes anaerobic, aerobic and anoxic hydrolysis processes of both UAP and BAP [16,30]. Six hydrolysis processes introduce four parameters: the fraction of BAP and UAP generated per biomass decayed (respectively, f_{BAP} and f_{UAP}) and the hydrolysis rate coefficient for S_{BAP} and S_{UAP} (respectively, $k_{H,BAP}$ and $k_{H,UAP}$).

The stoichiometric, composition and kinetic rates for the reaction processes are expressed according to the classical ASM matrix format [16]. In particular, the biological reaction rate of a component (i), at time (t), r_i is derived by means of the equations:

$$r_i = \sum_{j=1}^{m} \nu_{i,j}\rho_j \quad (1)$$