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Submerged Membrane Bioreactor for Wastewater Treatment: Optimal Operating Strategy

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An improved version of a mathematical model describing the discontinuous submerged MBR behavior was used to search for its optimum operating strategy. This model takes into account both the biological treatment of the wastewater and the cake layer formation/removal onto/from the membrane surface.
First was studied the sensitivity of the global conversion of ammonia plus ammonium nitrogen (the objective function) against the main operating parameters (filtration period and air flow). Then an optimization was performed in order to find the set of operating parameters that maximizes the aforementioned objective function. The optimal values thus obtained were then used to predict the performance of the system for two types of permeate recirculation – discontinuous and continuous. The results obtained showed that the former optimal strategy is the most effective.

1. Introduction

Membrane bioreactors (MBRs) used for wastewater treatment are integrated systems with the bioreactors volume divided in two parts using a membrane module. The first is a biologically active part, where the pollutants are consumed by the activated sludge; the membrane keeps the solid particles inside this volume. The second is the permeate volume, from which the product is continuously removed from the MBR. The main advantages of MBRs are higher effluent quality, smaller overall reactor volume compared to the large systems used in conventional activated sludge plants, reduced sludge production (Di Bella et al., 2008, Dialynas and Diamadopoulos, 2009, Meng et al., 2009, Nywening and Zhou, 2009, Teck et al., 2009), good disinfection capability (Le-Clech et al., 2006) and high efficiency in organic removal (Schoeberl et al., 2005).
The main drawbacks of MBRs are the high investment cost, poor oxygenation caused by the long SRT, which implies high concentrations thus large aeration costs (Teck et al., 2009, Temporini et al., 2009), and the membrane fouling (Malamis and Andreadakis, 2009, Meng et al., 2009, Schoeberl et al., 2005).
The primary concern when operating a MBR – or a conventional system, after all – for wastewater treatment are the effluent quality and the operating costs implied. Therefore, the effluent must meet the quality standards that have been set for some of the pollutants and the values of the parameters which are strongly related to cost must be carefully

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chosen – for example, aeration, which is responsible for a large percent of the energy costs in the operation of the MBRs.

Ideally, a biological wastewater treatment system should be low in both investment and operating costs, and MBRs are good candidates observing these constraints. When operated optimally, the drawback of working at high cells density becomes an advantage, because of the increased flow of processed pollutants.

2. The physical model

The experimental set-up (Di Bella et al., 2008) is schematically presented in Figure 1. After passing through a 2 mm screen to remove hair, debris, rags and sand, the wastewater is fed into the reservoir (1). Then the wastewater enters the MBR (2), where the activated sludge removes the carbon and nitrogen-based pollutants. The MBR operates sequentially: first *the filtration period*, when the permeate is withdrawn through the membrane module and stored in the tank (3); then, *the cleaning period*, when both the feeding and the permeate suction are interrupted and a fraction of permeate is pushed back through the membrane module in order to remove the cake formed onto its surface during permeate suction. The wasted sludge, responsible for preventing the accumulation of dead cells in the bioreactor, is continuously withdrawn from the bottom of the bioreactor and stored in the tank (4); *the flow of the recycled permeate equals the flow of the wasted sludge*. The air, essential for the activity of the activated sludge and the perfect mixing of the liquid, is provided through two fine bubble air spargers located at the bottom of the reactor. Another air sparger, located at the bottom of the membrane module, produces bubble swarms with the purpose of continually cleaning, at least partially, the membrane surface. After the membrane has been cleaned, the permeate suction is resumed ant the process continues cyclically until the entire volume of water stored in tank (1) passes through the bioreactor.If the effluent

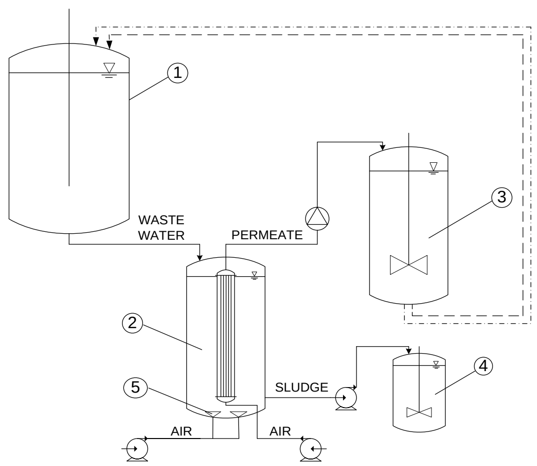

Figure 1. The experimental set-up:1.wastewater tank; 2.membrane bioreactor; 3.permeate tank; 4.sludge tank; 5.air sparger

is not suitable for discharge into the environment at the end of the operating period, the residual concentration of the pollutants can be reduced further by recycling the permeate back into the wastewater tank. This can be done in two ways: discontinuously, when the permeate tank replaces the feeding tank (1), or continuously, when a fraction of the permeate is fed into the storage tank containing the raw wastewater.

The mathematical model

The mathematical models describing the biological wastewater treatment using MBRs can be lumped into three categories: kinetic, fouling and integrated models. The kinetic models are based on the activated sludge models (ASMs) (Di Bella et al., 2008, Ferraris et al., 2009, Nelson, 2009), modified to take into account the formation and degradation of the soluble microbial products (SMPs). The fouling models are based upon solid-liquid separation, with the filtration process replaced by an ideal settler with unitary efficiency, or upon the resistance-in-series representation. The mathematical model used in this study is an integrated one, meaning that it couples a kinetic and a fouling model and considers also the formation and degradation of SMPs (Di Bella et al., 2008). In the sub-model for the biological process – based on the ASM1 – the organic matter is lumped into two groups: the soluble matter that can pass through a 45 μm filter and the particulate matter, larger than 45 μm, which is retained in the bioreactor by the membrane module. The microorganisms are classified into heterotrophs and autotrophs and the lag phase appearing when the operating conditions are changed is disregarded. The equations are derived from mass balances for all the components of the wastewater and also for SMPs and dissolved oxygen. The physical sub-model (Di Bella et al., 2008, Li and Wang, 2006) describes the formation of the cake onto the surface of the membrane during the filtration period and the removal of the cake during the backwashing.

3. The performance criteria

The performance of the system, quantifying whether the MBR is working at optimal or near-optimal conditions, was chosen to be the global conversion of ammonia plus ammonium nitrogen, defined as the ratio between the quantity of nitrogen transformed in the biological process by the time de global conversion is evaluated and the initial quantity of nitrogen existing in the feed tank and the reactor (1 and 2, see Figure 1 for details):

$$C_{NH}(t) = 1 - \frac{V_{PERM}(t)\cdot \bar{S}_{NH}^{PERM}(t) + V_W(t)\cdot \bar{S}_{NH}^{W}(t) + V_R\cdot S_{NH}(t) + V(t)\cdot S_{NH}^{FEED}}{(V_0+V_R)\cdot S_{NH}^{FEED}} \quad (1)$$

Due to its importance in the quality of the effluent, the global conversion of the soluble biodegradable substrate, S_S, was also computed. However, only the global conversion of ammonia has been used in the optimization process, as the ammonia is the most aggressive pollutant.

4. Results and discussions

As mentioned before, the MBR operating period has a filtration stage, when the MBR is fed with wastewater, the permeate is sucked through the membrane module and the wasted sludge is removed from the bottom of the reactor, and a backwashing step, when the feeding and the permeate suction are interrupted, but not the wasted sludge removal; a flow of permeate equal to the waste flow is recycled form the permeate tank into the reactor, through the membrane module to remove de cake from the surface of the membrane; the duration of this step is determined by the quantity of solids deposited on the membrane during filtration.

The mathematical model describing the MBR system has initially been solved for the recommended values of the operating parameters: filtration period (t_F = 9 min.) and volumetric mass transfer coefficient ($k_L \cdot a_V$ = 2.5 h^{-1}), whose value depends upon the air flow introduced in the bioreactor (Di Bella *et al.*, 2008). The backwashing period was fixed at t_B = 1min, and the ratio between permeate and waste flow was two. The global conversions of the two substrates are presented in Figure 2. The decrease in the slope of the ammonia conversion that can be observed after 11 h is the result of the increased consumption of this substrate in the bioreactor (not shown here), which is not the case for the carbonaceous substrate. However, although the ammonia concentration in the bioreactor after 11 h is zero, its global conversion is slightly larger than 0.7 due to the high concentrations in the permeate and waste flows at the beginning of the discontinuous operating period, when the concentration of microorganisms was too low to have a high transformation flow and the pollutants remained untransformed for a rather long period of time. To identify if the system is sensitive to changes in the filtration period and volumetric mass transfer coefficient (if true, these could be seen as command variables for the optimization process; the backwashing time is not fixed, but it depends upon the quantity of solids deposited on the membrane, which means that if the filtration period is optimized, the cleaning period will be optimized as well), several simulations of the mathematical model were carried out. The results are expressed as final global conversion of the two substrates against each of the two variables and can be seen in Figure 3. When plotted against the filtration period both final conversions have a maximum, situated not far from the value used by Di Bella et al. (2008). The

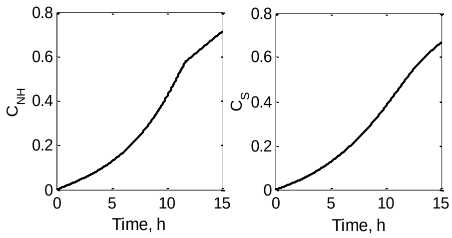

Figure 2. Global conversions of the ammonia and carbonaceous substrates (the base case)

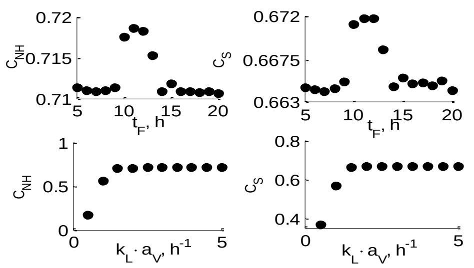

Figure 3. The variation of the final conversion of ammonia and soluble substrate with the filtration period and volumetric mass transfer coefficient

volumetric mass transfer coefficient, however, has a significant influence only for values smaller than 1.5 h^{-1}, after which a plateau is reached. This suggests that, from an economical point of view, it is desirable to work with the value situated at the beginning of this plateau. But the two parameters are not independent: when the simulations were carried out for the filtration period, the mass transfer coefficient was fixed at 2.5 h^{-1}, and when the influence of the mass transfer coefficient was studied, the filtration period was fixed at 9 min. Both parameters were chosen as command variables in the optimization process. The sensitivity analysis was also performed for the permeate/waste flow ratio, for values between 1 and 10, but the results showed that the final global conversion increases asymptotically with this ratio, therefore the upper range value was used for all subsequent simulations. The optimization process was carried out using the genetic algorithm toolbox from Matlab^{TM} and the objective function described by Eq. (2). The filtration period varied within 5-20 min and the air flow within 0.18-0.72 m^3/h. The optimal values for the two parameters are: t_F = 13.8 min. and Q_{air} = 0.7 m^3/h, corresponding to a specific mass transfer coefficient of 5.8 h^{-1}.

$$f_{obj} = 1 - C_{NH}^{end} \quad (2)$$

As shown in Figure 4, the performance of the system improves when working with these new values, but the final concentrations for the readily biodegradable substrate and ammonia in the permeate tank are still significantly larger than zero (not shown here). One strategy to enhance the performance of the system is to recycle the permeate, this way allowing the active biomass to further degrade the residual pollutants. The justifying reason for the discontinuous recirculation of the permeate is the high biomass concentration at the end of the operating period, which means that the microorganisms are capable to consume the residual pollutants from the permeate. As can be seen in Fig 5, dashed line, both conversions have an important increase, even if the substrates concentrations in the influent are lower than in the previous cycle and the operating conditions are far from being optimal for the new feeding.

The continuous recirculation finds its justification in the need of reducing the high concentration of the pollutants in the effluent at the beginning of the treatment process. This strategy gives the same performance as the single period operated system and the discontinuous recirculation until the point where ammonia vanishes from the bioreactor (around 10 h), after which a slow decline in the performance is observed. This happens

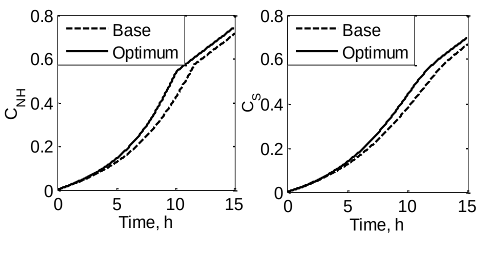

Figure 4. Global conversions of the ammonia and carbonaceous substrates before and after the optimization.

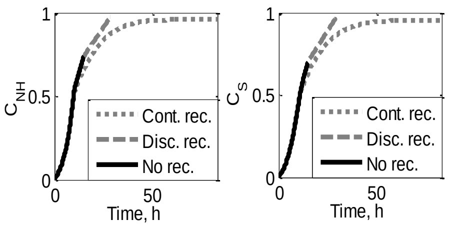

Figure 5. Global conversions of the ammonia and carbonaceous substrates for the three operating strategies

because the concentrations of the substrates in the feeding tank are continually decreasing as compared to the values at which the biomass was exposed in the other two cases (Fig 5). Even if this strategy gives a final conversion close to the discontinuous recycling, the working time needed makes it less attractive.

5. Conclusions

In this work, an improved mathematical model was used to find the set of operating parameters that maximizes the global conversion of ammonia in a MBR. These values were then used to study the performance of the system for two types of permeate recycling: discontinuous and continuous. The results thus obtained show that the former is the most efficient strategy, in terms of ammonia removal and required time.

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