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Investigation of Energy and Operation Flexibility of Membrane Bioreactors by Using Benchmark Simulation Model

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Abstract
The demand of industrial development leads to sustained increase of energy demands for wastewater treatment, and increasingly stringent wastewater effluent limits has imposed huge pressure on existing facilities. The aims of this study is to investigate operation and energy flexibility of membrane bioreactors (MBRs) for municipal wastewater treatment by mathematical modelling. Compared to conventional active sludge technology, MBR has better treatment performance and it can achieve complete retention of solids and very high COD removal. Based on variable electricity price structure, appropriate optimization strategy can save 9-41% energy cost without violating exiting discharge standards. The results of dynamic simulation revealed that, under variable energy price structure. Wastewater treatment plants with MBRs can provide significant energetic flexibility for reducing energy cost and ensure the stability of effluent quality.

Keywords Aeration control; benchmark simulation model; membrane bioreactor; energy; wastewater treatment

INTRODUCTION

Food-water-energy nexus presents complex and intertwined concerns about sustainable management of limited resources. Water consumption for various uses, such as domestic, agriculture and industry, has increased by 2~3 times than that of population growth (Gude, 2015). Increased sanitation needs for protecting human health and aquatic resources led to sustained increase of energy demand for wastewater treatment in many regions (Gude, 2015). Furthermore, extensive industrialization has accelerated the use of various persistent organic pollutants, surfactants, industrial chemicals and pesticides, which have bioaccumulation, carcinogenicity and toxicity (Khan et al., 2018). Increasing emerging pollutants, that have adverse effects on human health, in natural water sources, pose a challenge to existing wastewater treatment industry (Khan et al., 2018).

Membrane bioreactor (MBR) technology that can combine activated sludge process with membrane filtration have been widely used for treatment of both industrial and municipal wastewater when high effluent quality is required for discharge and water recovery (Judd, 2016). In addition, membranes reduce footprint of activated sludge plants by replacing secondary clarifiers, which makes MBRs an attractive technology for municipal applications (Santos et al., 2011). Small footprint is a significant advantage of MBRs, especially for cities where land is scarce or land price is expensive (Xiao et al., 2019). Compared to conventional active sludge (CAS) treatment process, MBRs can increase effluent quality significantly due to superior biomass retention and rejection of particulate organics from effluent. MBRs technology also have significant advantage in removing a wide range of emerging pollutants such as antibiotics, pesticides and industrial chemicals (Khan et al., 2018). Over the last twenty years, the market penetration of MBRs has maintained sustained growth up to 15% driven by increasing water scarcity and increasingly stringent legislations (Judd, 2016; Santos et al., 2011). The development of MBR technology promotes progress in wastewater treatment industry and stimulates confidence of market to accept new technologies. Now, MBRs are implemented in more than 200 countries, in which around 40 municipal plants have over 100 megalitres per day in capacity (Judd, 2016).

The most significant demerit of MBRs is high energy cost due to high air demand to ensure bio-oxidation of pollutants and avoid membrane fouling. Fouling, a major factor that impact the MBR performance, can reduce permeability and increase transmembrane pressure of membrane. Therefore, fouling control in MBRs causes significant operating costs (Mannina and Cosenza, 2013). Although a lot of research have been carried for understanding membrane fouling mechanisms, it is still difficult to reach a consensus on the optimal conditions for MBR operation. Aeration usually accounts 50% of the total energy consumption in conventional wastewater treatment plants (WWTPs), and for MBRs, membrane aeration can cost about 35% of the energy consumption (Gabarrón et al., 2014). Typically, the energy consumption of MBRs is two-four times higher than that of traditional treatment process, which exceeds its advantages in terms of treatment quality (Suh et al., 2013). As a result, proper optimization strategies for MBR aeration are necessary to reduce the operation cost of MBRs and to increase their competitiveness.

The increased penetration of renewable energy to overall energy mix led to increased uncertainty in power generation due to dynamic and less predictable nature of renewable sources such as wind and solar (Giberti et al., 2019). As a result, a demand for energy flexibility, which can provide several benefits for both power generators and end-users, became apparent. Energy flexibility of large consumers such as WWTPs can be transferred to economic benefits under complex contracts with power providers, i.e. variable tariff structures, charges/subsidies applied to peak demand. As a result, WWTPs need to take ‘a set of actions to reduce electric demand when contingencies such as emergencies or congestion occur that threaten supply demand balance and/or market conditions occur that raise electric supply costs’, which is defined as demand response (DR) (Goli, 2012). DR does not necessarily mean reducing the energy consumption, but it can make consumers pay less by smart usage of energy due to shifting or shedding their consumption when there is high wholesale market prices or malfunction of system reliability (Shaaban and Petinrin, 2016). By applying DR, consumers can manage their electricity cost to reduce the risk of power outages, postpone capacity investments by adjusting their energy demand according to the fluctuation of electricity supply (Bitaraf and Rahman, 2018). Variable energy price structures provide potential energy flexibility for WWTPs to reduce their operation costs. Therefore, operators of WWTPs need more explicit tools to qualify the benefit provided by energy management and applying DR strategies. MBRs can also benefit from dynamically changing energy prices by using aeration control for pollutant removal and membrane scouring.

This paper focuses on DR potential of MBRs for municipal wastewater treatment. In order to investigate flexibility of MBRs in the context of variable energy prices, benchmark simulation model for MBRs (BSM-MBR) described in Maere et al. (2011) was used and its performance was tested in terms of energy cost and treatment efficiency in six different operation scenarios.

MATERIALS AND METHODS

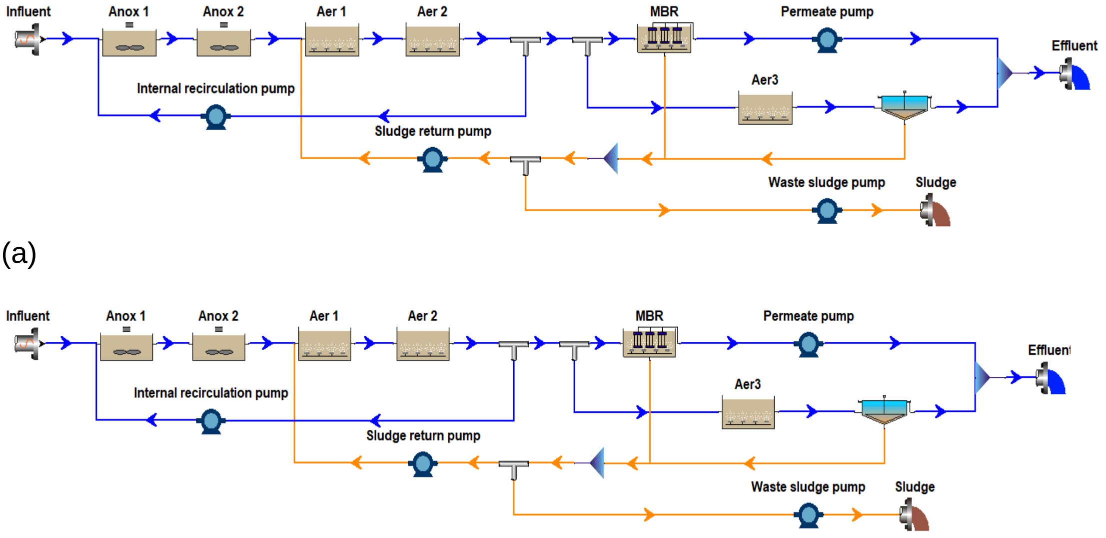
Implementation of BSM-MBR model

Benchmark Simulation Model for Membrane Bioreactors (BSM-MBR) (Maere et al., 2011) that is based on Benchmark Simulation Model No.1 (BSM1) (Gernaey et al., 2014) was used in the study. A modified version of BSM-MBR was implement into Biowin 6.0 (EnviroSim, Canada) software which uses plant wide activated sludge digestion model (ASDM). Considering the difference in definition of some state variables between ASDM and Activated Sludge Model No.1 (ASM1) (Henze et al., 2000), which is used for describing the biological processes in BSM1, parameters including biokinetics and stoichiometry was modified to match the results of default BSM-MBR outputs (Maere et al., 2011).

The general configuration and layout of BSM-MBR is shown in Fig 1a. Each bioreactor has the same volume of 1500 m^3. The depth of anoxic and aerobic bioreactors is 5 m and the membrane tank is 3.5 m. The membrane area and packing density was set to 71500 m^2 and 47.5 m^2, respectively (Maere et al., 2011). Specific membrane aeration demand (SAD_m) was set to 0.3 Nm^3/h per m^2 of membrane area which results in an airflow of 21450 Nm^3/h. Fine and coarse bubble aeration was used for aerobic bioreactors (Aer 1 and 2) and membrane tank, respectively. Fine bubble air flow for Aer1 and 2 was set to 4250 and 2250 Nm^3/h, respectively.

In Biowin, membrane flux is not a fixed operational parameter and it is calculated based on the influent flow and membrane surface area of MBR. At average influent flow, the flux was calculated as 10.63 L/m^2h (LMH), which is lower than values reported in exiting literature about municipal sewage treatment

(Judd, 2016). In the steady state simulation of BSM-MBR, the plant treated an influent flow of 18446 m^3/d, producing a permeate flow of 18246 m^3/d and wasted sludge flow of 200 m^3/d (Maere et al., 2011). Mixed liquor was recirculated from the second aerobic tank to the first anoxic tank at a rate of 55338 m^3/d (3 times the average influent flow) to recycle nitrate (Maere et al., 2011). In addition, sludge was recirculated from the membrane tank to the first aerobic bioreactor at the same flow rate, providing sufficient biomass inoculation and distribution evenly over the whole tanks (Maere et al., 2011).
In order to evaluate the performance of a hybrid wastewater treatment system, a dual-stream model (Fig 1b) consisting of a MBR process and a conventional activated sludge (CAS) process was built based on BSM-MBR model. The CAS stream consisted of a 5m-depth aerobic bioreactor of 1500 m^3 and a 4m-depth secondary clarifier of 2000 m^3 (Gernaey et al., 2014). Modified Vesilind model was used to describe settling process in the secondary clarifier.



(a)

(b)

Figure 1. (a) BSM-MBR configuration; (b) Dual-stream configuration

Electricity tariff structure

It is important to evaluate the potential energy flexibility of WWTPs based on a realistic energy price structure. The energy cost model based on the research of Aymerich et al. (2015) was used as time-of-use (ToU) electricity tariff structure. The price structure consisting of On-peak, Mid-peak and Off-peak times and it is shown in Fig 2. The logic of control strategies is reducing the aeration cost at on-peak time and testing the impact of this operation on the MBR treatment performance.

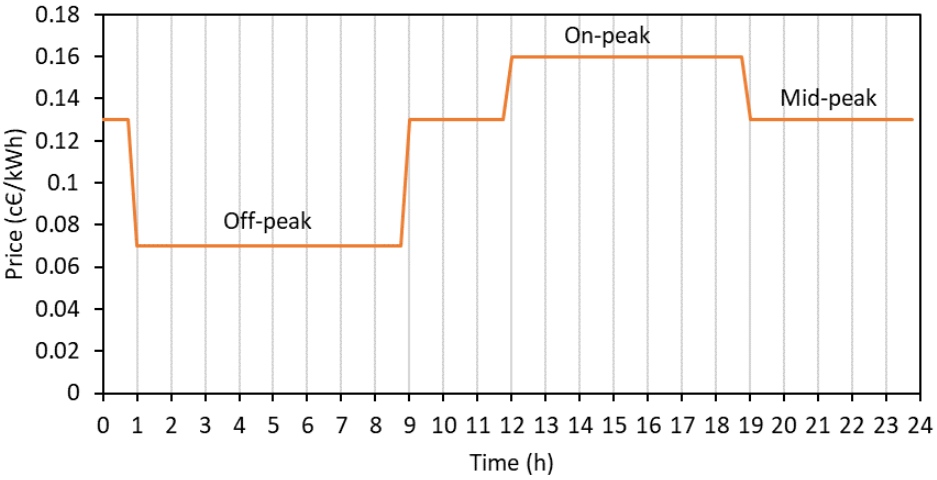


Figure 2. Electricity price tariff structure used in the study

Scenario development and evaluation

In order to verify the energy flexibility of WWTPs under the ToU electricity tariff structure, six scenarios were developed. In each scenario (Table 1), steady state simulation was first run with constant influent flow and then a 28-day dynamic dry weather simulation was performed starting from the result of steady state simulation (Gernaey et al., 2014).

Table 1. Scenarios used in the study

Scenario	Description
S0	BSM-MBR open loop (without any controllers)
S1	DO controlled in the 1st and 2nd aeration tanks
S2	S1 together with DO control in membrane tank
S3	S1 together with SADm control in membrane tank based on electricity price
S4	S2 together with dual-stream (MBR for treatment of 70% influent) treatment for the whole day
S5	S2 together with dual-stream (MBR to treat 70% influent) treatment at on-peak time

BSM-MBR open loop simulation without any controllers was considered as the default scenario (S0) (Maere et al., 2011). Scenario 1, 2 and 3 were used to investigate the flexibility of aeration in MBR. In scenario 1 (S1), DO concentration was controlled at 1.5 mg/L by using a PI controller (Table 1). Similarly, in scenario 2 (S2) DO concentration in membrane tank was maintained at 5 mg/L. SAD_m was adjusted inversely proportional to electricity price such as 0.1, 0.2, 0.3 Nm^3/m^2h at high-peak, mid-peak and off-peak periods, respectively, in scenario 3 (S3). Membrane was scoured at a higher intensity when the electricity cost was higher, whereas air scouring was reduced at high-peak periods.

Table 2. Parameters of PI DO controller

Parameter	Unit	Aer1	Aer2	Aer3	Membrane tank
DO set point	mg/L	1.5	1.5	1.5	5
Proportional gain	mg m^3/L h	500	500	500	2000
Integral time	d	0.002	0.002	0.002	0.002
Minimum air flow rate	Nm^3/h	4500	2500	1500	7150
Maximum air flow rate	Nm^3/h	660	660	660	21450

In the scenario 4 and 5, a dual-stream treatment system was investigated. These two scenarios represents a case in which existing tanks and infrastructure are available on site to combine CAS process and MBR into a hybrid system (Fig. 1b). In scenario 4, 30% of influent was distributed into CAS stream and the DO concentration in Aer 1, Aer 2 and membrane tanks were controlled as in S2. Furthermore, the DO in third aerobic bioreactor (Aer 3) was regulated at 1.5 mg/L. In order to verify the flexibility of dual stream system, in scenario 5 (S5), CAS stream only works at on-peak time.

The treatment performance of the WWTP was evaluated based on the ninety-five (95) and fifty (50) percentiles of effluent COD, NH_4-N and NO_3-N concentrations, Effluent Quality Index (EQI) and net EQI. The ninety-five (95) and fifty (50) percentiles are defined as the part of effluent concentration that are exceeded 5% or 50% of the time in the last week of simulation. EQI (Eq 1) is weighted sum of average pollutant loads over the 7 last days of the simulation. Net EQI (Eq 2) describes EQI in excess of the discharge limit and is calculated based on the instantaneous difference between the concentration and discharge standard of each parameter.

Table 2. Discharge standards and weighing factors for effluent parameters

Parameter (Ci)	**Discharge standard ($C_{i,\ limit}$)(g/m^3)**	**Weight (w_i) (g pollution unit/g)**
Total suspended (TSS)	30	2
COD	100	1
Biochemical oxygen demand (BOD)	10	2
TN	18	-
Total Kjeldahl nitrogen (TKN)	6	30
NH_4-N	4	-
Oxidized nitrogen (NO_2-N+NO_3-N)	12	10

$$\mathrm{EQI} = \frac{1}{t_{obs} \cdot 1000} \int_{t=7\ days}^{t=14\ days} [\sum_{i=1}^{n} C_i(t) \cdot w_i] dt$$
Equation 1

$$\mathrm{Net\ EQI} = \frac{1}{t_{obs} \cdot 1000} \int_{t=7\ days}^{t=14\ days} \{\sum_{i=1}^{n} Max[0, C_i(t) - C_{i,limit}] \cdot w_i\} dt$$
Equation 2

RESULTS AND DISCUSSION

Treatment performance

The effluent quality in obtained in dynamic simulation of different scenarios are shown in Table 3. As shown in Table 3, the plant could achieve high COD removal, nitrification and denitrification efficiency. The plant achieved full nitrification in all scenarios thanks to the efficient retention of nitrifiers by the membranes. Effluent COD concentrations were similar in S0, S1, S2 and S3, however it slightly increased when dual-stream treatment (MBR and CAS) was applied in S4 and S5. Controlling DO concentration in aerobic reactors (S1, S2, S3) significantly reduced effluent nitrate concentration due to less penetration of DO into anoxic tanks. This is also indicated by remarkably decreased net EQI. Over aeration in MBRs can retard their denitrification performance depending on the plant configuration. Therefore, efficient control of aeration is crucial for optimized MBR performance.

Table 3. Treatment performance of the system in different scenarios

Scenario	**50%-95% of COD concentration (mg/L)**	**50%-95% of NO_3-N concentration (mg/L)**	**50%-95% of NH_4-N concentration (mg/L)**	**EQI (kg/d)**	**Relative change of EQI (%)**	**Net EQI (kg/d)**	**Relative change of net EQI (%)**
S0	31.4-34.1	11.4-16.1	0.1-0.3	3126	-	139	-
S1	31.4-34.1	10.8-15.7	0.1-0.4	3023	-3.3	111	20.1
S2	31.4-34.1	10.7-15.7	0.1-0.4	3004	-3.9	106	23.7
S3	31.4-34.1	10.7-15.5	0.1-0.4	3005	-3.9	101	27.3
S4	33.9-35.9	11.5-13.6	0.1-0.4	3320	6.2	49	64.7
S5	32.2-35.8	11.1-15.9	0.1-0.4	3188	2.0	159	14.4

Dual-stream scenarios (S4 and S5) showed similar NH4-N removal performance. On the other hand, slightly higher effluent COD concentrations compared to single MBR configuration were observed due to uncaptured biomass flocs in the final clarifier. CAS process without filtration transferred suspended solids into the final effluent which also had a negative impact on effluent COD concentrations. This is also reflected by elevated EQI parameter values. On the other hand, net EQI in S4 was significantly lower than the MBR scenarios. This is mainly due to improved denitrification efficiency of the system. In S4, 30% of the influent wastewater was treated in CAS system, operated at a DO concentration of 1.5 mg/L, for the whole day and the mixed liquor was recycled to anoxic zone. This reduced the oxygen return to anoxic tanks and enhanced denitrification performance. However, the result of S5 showed negative effect of dual-stream operation on nitrogen removal performance, increasing net EQI by 14%. This may be due to improper DO control in CAS which received discontinuous feeding (only at on-peak time between 12:00 and 19:00). An On/Off controller may be more suitable instead of PI controller for this particular case. Krzeminski et al. (2012) evaluated three full-scale MBR plants (one stand-alone MBR and two hybrid MBRs) in the Netherlands and found there is also no substantial difference in single and hybrid MBR effluent quality by analysing the performance data. In addition, compared to CAS process, MBRs are more often impacted by unsteady-state conditions, causing operational perturbation such as poorly filtration of activated sludge (Krzeminski et al., 2012). Dual-stream systems have better stability of treatment performance, in which the CAS stream provides hydraulic and biological buffer zone to ensure more stable conditions for the activated sludge in the plant (Krzeminski et al., 2012).

Thus, it can be concluded that the selection of a dual-stream MBR configuration for municipal WWTPs has no significant impact on effluent quality, especially with respect to the current discharge standards. Nevertheless, potential differences in the effluent quality should be considered in terms of the disinfection and total suspended solids concentration. However, the aging rate of membrane may be faster in dual-stream system because the membranes have often shorter out of operation periods compared to the membranes in stand-alone configurations (Krzeminski et al., 2012), causing adverse effect on treatment performance.

Energy performance

Table 4 gives the cumulative energy cost calculated by using ToU electricity price structure and cumulative aeration energy of the plant. Compared to S0, all optional strategies can reduce energy cost. Controlling DO in aerobic bioreactors (S1) had only a minor impact on aeration energy demand and total energy costs. It is clear that the energy cost of MBRs is dominated by the membrane aeration costs and controlling airflow for membrane scouring is the most critical operation strategy. The results of S2 and S3 show that there is large potential for saving energy by using flexible aeration control in MBRs, achieving energy cost saving that ranges of 28%-38%. S2 employs PI controller for adjusting DO concentration in membrane tank based on oxygen demand of biomass especially for nitrification. On the other hand, a very simple aeration strategy was adopted for membrane tank by taking the energy costs in to account. Thus, less air was fed during high-peak time for avoiding high energy costs. Decreased scouring of membrane at peak flow times may have an adverse effect on fouling but this might be compensated by implementing increased scouring rates during off peak energy price time. It is worth mentioning that proper distribution of membrane aeration based on variable electricity price tariffs can significantly decrease plants energy bill.

Table 4. Comparison of scenarios based on cumulative aeration energy demand and cost for 28 days

Scenario	Cumulative Energy Cost (€)	Relative change of cumulative energy cost (%)	Cumulative aeration energy (kWh)	Relative change of cumulative aeration energy (%)
S0	58977	-	408708	-
S1	53679	-9	360575	-12
S2	36871	-38	211977	-48
S3	42523	-28	283584	-31
S4	34613	-41	202738	-50
S5	36285	-39	209208	-49

S4 and S5 demonstrate that dual-stream WWTPs have operation flexibility under variable electricity price structure. When retrofitting existing CAS plants to MBRs, making use of parallel treatment trains such as bioreactors and clarifiers can offer flexibility to the system. Furthermore, CAS facilities can act as buffer tanks in cases of high influent load or peak-time electricity price. Moreover, dual-stream treatment can reduce the air demand and energy cost by about 50% and 40%, respectively. Gabarrón et al. (2015) evaluated two optimization strategies (buffering the influent flow and optimizing both of biological aeration and membrane air-scouring) which are applied in the hybrid MBR in Northeast Spain. They reduced the specific energy demand by 14%. Krzeminski et al. (2012) found that hybrid wastewater treatment process can save at least 17% operational costs compared to a single MBR process. Therefore, in the case that old infrastructure such as CAS system is still in good condition, a dual-stream configuration is usually a better strategy.

CONCLUSIONS

The energy management in WWTPs is attracting more and more attention due to the changing energy market and the popularization of MBR technology. However, there is still very little knowledge about the optimization of MBRs and quantifying the economic benefit of energy flexibility in MBRs. This study investigated the energy management of MBRs by using benchmark simulation model. The performance of optimization strategies was evaluated with EQI and ToU electricity tariff structure. The result of dynamic simulation showed that proper control operation can save 9%-41% of the total energy cost. It is concluded that WWTPs with MBR configuration have energy flexibility under variable energy price structure. In the future, models that combines flexible energy management technologies with economic analysis can better help optimize the process of wastewater treatment and develop energy saving strategies.

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