Energy Optimization Practices for Sustainable Operation of MBR Wastewater Treatment Systems

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Abstract

Membrane bioreactors (MBRs) represent wastewater treatment systems integrating biological degradation and membrane filtration. Although these systems have broad benefits, their disadvantages are mainly associated to high cost involving capital cost for membrane units and operation cost corresponding to energy consumption for aeration and for high pressure gradient between the raw influent and the treated effluent. MBR energy requirements are about twice the conventional treatment methods. MBR capital cost became competitive to conventional treatment systems, due to the market availability of low cost membrane modules; however, limited efforts have been made toward reduction of operation costs. Potential processes for the reduction of energy demand in MBRs include application of primary clarification ahead of the MBR, flow equalization, solids adjustment between the aeration and the membrane basins, and pump configuration. In addition, the implementation of certain operation modes, such as air scouring of membranes, and fouling control, might contribute to low power consumption.

Keywords: *Energy optimization, Sustainability, MBRs,* Wastewater treatment, Membrane fouling

List of Acronyms

MBR	*Membrane Bioreactor*	*CASP*	*Conventional Activated Sludge Process*
SAF-MBR	*Staged Anaerobic Fluidized Membrane Bioreactor System*	*MMV*	*Magnetically induced Membrane Vibration*
RTMBR	*Rotating Tubular Membrane Bioreactor*	*SADp*	*Special Aeration Demand Permeate*
AFMBR	*Anaerobic Fluidized-bed Membrane Bioreactor*	*COD*	*Chemical Oxygen Demand*
MFC	*Microbial Fuel Cells*	*DO*	*Diluted Oxygen*

1. Introduction

Membrane bioreactor systems have become a promising wastewater treatment technique combining activated sludge and membrane separation; it is a process resulting in a high quality effluent independent of settling characteristics of the biomass. Membrane bioreactors have several advantages over the conventional activated sludge systems, including stable and high effluent quality, easy operation and complete removal of bacteria. However, membrane bioreactors may have several problems due to membrane fouling, which therefore result to high operation and maintenance costs. Membrane fouling reduces membrane permeability and therefore increases the energy consumption in a membrane bioreactor [1].

2. Energy Consumption

Energy requirements are of primary interest in MBRs and include influent supply; retentate recycling; permeate (effluent) withdrawal and aeration. As illustrated in Figure 1, the primary energy requirements are related to aeration (66%), while pumping is a far second energy component (14%). Therefore, the key measures for energy reduction are focused on aeration; however, all energy related elements should be considered in a well designed system. In order to provide the most cost effective and energy efficient system, critical factors should be considered during the whole life time of the system i.e. in design, operation, and equipment [3].

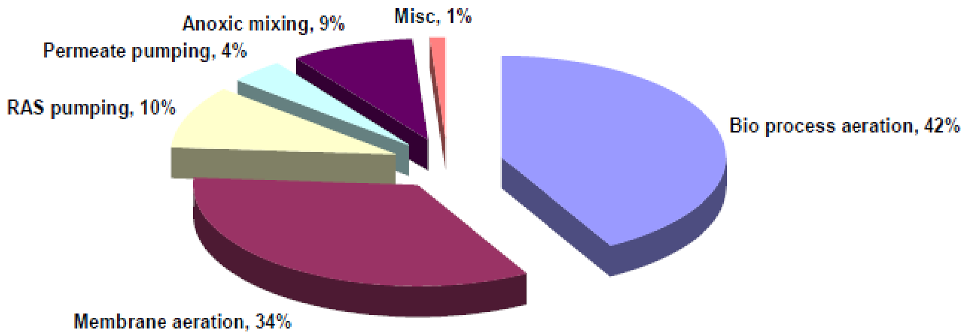

Fig. 1: Energy consumption in the various processes of an MBR system [3].

Power consumption for the aeration of an MBR consists in energy for oxygen supply to the activated sludge microorganisms and energy for membrane scouring aiming to fouling control. Efforts toward reduction of air supply to the microorganisms are limited, as this component is directly related to the activated sludge microfauna activities [2]. The characteristic MBR configurations i.e. the immersed type and the side-stream configuration may have substantial differences in aeration. Aeration in the latter case is given by fine bubble aerators of high oxygen efficiency. However, turbulent aeration mode is achieved in the immersed MBR systems, with significant cross-flow of the mixed liquor, resulting to membrane surface scouring. Aeration cost in this configuration represents about 90% of the total cost, whereas the corresponding percentage in side-stream MBRs is about 20%. However, total energy consumption of the side-stream system is usually two orders of magnitude higher than that of submerged systems [4].

The energy consumption by an MBR may reach up to 8 kWh/m^3 although values as low as 0.14 kWh/m^3 have been reported [4]; MBR energy demand for treatment of municipal wastewater may be 2–4 times higher than the conventional activated sludge process (CASP) [5].

3.Process Energy Optimization Practices

Reduction of energy requirements may be achieved by adjustment of the aeration: it can be adjusted to the minimum level required for complete nitrification. Therefore, less aeration results to energy savings while the development of anoxic micro zones is promoted, leading to higher nitrogen removal rates. In addition, oxygen transfer to the anoxic zone should be negligible, reducing thus the anoxic reactor volume. As a result, these adjustments contribute to lower equipment and energy demands, as the aerobic/anoxic sludge recirculation loop is not required anymore.

Nitrification and denitrification processes should be implemented in one tank frequently aerated providing aerobic and anoxic time phases, rather than using two separate tanks,. In these systems, nitrogen reduction is achieved by aeration control reaching up to 90% with appropriate control. The concept of the so-called intermittent denitrification has been applied in a number of MBR installations. [6]

The emergence of submerged MBRs that utilize fairly economical polymer-based membranes and require less energy than external MBRs has tremendous potential in large scale-high volume throughput municipal wastewater treatment plants worldwid. The potential of on-site reuse of the MBR effluent for washing or transport purposes offers several cost benefits such as reduced fresh water requirements, lower sewer costs, and potential for direct discharge to surface water. [7]

- **Commercial Membrane types**

MBR operation is usually time-based, with constant aeration and fixed filtration sequences (cycles), which are generally proposed by the membrane suppliers or selected according to the operator's experience [8]. Commercial membranes types are offered today by several manufacturers, such as:

1. The MemPulse™ Membrane Bioreactor (MBR) System from Siemens Water Technologies. A mechanical device is used that supplies irregular pulses of air to the MBR module. This increases scouring effectiveness, decreases operation and maintenance costs, and reduces energy consumption (from 5367 kWh/day in a traditional MBR system to 2783 kWh/day). The system can be used in with a wide range of municipal and industrial wastewater treatment applications [2]. With the Siemens system, a combination of air and water is used to scour the membranes [3].
2. The Kubota flat sheet MBR where continuous aeration is used and the volume of air is based on the flux, e.g., lower air scour rates are used with lower flux [3].

3. The Zenon hollow-fiber MBR, Zenon holds patents for "cyclic" air scour which cycled air on and off in 10 second intervals. The change in scour air operation reduced their energy requirements in the membrane tank to 0.2 kWh/m^3 [3].

- **Design elements to reduce Energy**

There are several locations offering the opportunity for a cost effective design such as use of primary clarification ahead of the MBR, use of flow equalization, adjusting the balance of the solids between the aeration basin and the membrane basin, and pump configuration (Table 1).

Table 1: Design elements to reduce Energy [3]

Primary Clarification
(1) Reduce the power requirements associated with aeration (a combination of process air and membrane scour air, with the volume of scour air often equal to or exceeding the process air requirement), and (2) Reduce the biological tank volume. The decrease of the organic loading of the MBR provides the potential of operating at lower MLSS concentration for a given flow rate, resulting to: (a) Decreased membrane fouling tendency, leading to longer cleaning intervals and membrane life, and (b) Increased oxygen transfer efficiency, leading to lower blower power consumption.
Flow Equalization
The combination of a reduction in the membrane surface area and the lower air scour rate results to significant energy reduction.
Balance of Solids
The MBR systems: (1) Have been designed to operate at similar MLSS concentrations in both the aeration basins and the membrane tank. (2) Tend to be designed using smaller process volumes and higher MLSS concentrations than conventional biological processes. The energy reduction is twofold: (a) Reduction in pumping and (b) Potential increase in aeration, improving oxygen transfer efficiency.
Pump Configurations
The three key pumping requirements for an MBR include solids return, nutrient recycle, and permeate withdrawal. Innovative plant configurations using in-wall pumps or low head submersible pumps can minimize the energy requirements for the nutrient recycle pumps. Permeate from the membranes may be pumped or flow by gravity depending on the membrane configuration and hydraulic constraints. The optimum configuration to minimize energy is to gravity flow.

- **Operational elements to reduce Energy**

There are various operational elements that influence the overall energy efficiency of the MBR design. Currently the single largest energy cost is aeration – both for the biology and for the maintenance of the membranes. Hence, opportunities to reduce aeration have the potential to significantly reduce the overall energy requirements (Table 2). [3]

Table 2: Operation elements to reduce Energy.

Membrane Air Scour
Air scour represents almost the highest energy demanding process. The following techniques are used to minimize energy consumption: (1) Intermittent air scour - based on the rotation of the membrane panels through the aerated part of the membrane tank. A combination of air and water my be used to scour the membranes, which results in a significant variation in the energy demand associated with membrane maintenance. (2) Lower air scour flow rates at lower flux - the decreased scour air operation may decrease the energy requirements in the membrane tank to 0.2 kWh/m^3. Energy saving may be achieved by allowing longer rest periods between aeration periods when the flux is below the average design condition or by using continuous aeration where the volume of air is a function of the flux [3, 4].
Flux Enhancers
The addition of flux enhancers allows a wider flux operating range and has been used to demonstrate performance benefits: (1) When the membrane quantity is driven by peak flow, the flux enhancer allows operation at a higher flux than traditionally accepted, without excessive or rapid fouling, which results in both an initial cost reduction based on the quantity of membranes installed as well as energy savings based on the reduction in overall air scour requirements. (2) When the membrane quantity is based on minimum temperature which reduces the design flux, the addition of a polymer based flux enhancer supports the operation at a more aggressive flux at a lower temperature without adverse impact on the membrane performance. By operating at a higher flux, the membrane quantity and the associated energy requirements can be reduced. [2]
Optimize Membranes in Service
Matching the number of membrane trains in service with the plant flow is an operating strategy that can reduce energy, as the membranes which are not in service do not require the same degree of air scour as those in service. Consequently, taking membrane tanks out of service when flow is low provides the opportunity to reduce the air scour requirements during the rest period. [2]
Optimize Dissolved Oxygen (DO) within the Bio-Process
Reduction of the total aeration demand in the aeration basins may be accomplished by: (1) Operate at the minimum DO required to achieve complete treatment, and (2) Return the solids from the membrane tank to the oxic part of the biological basins to utilize the elevated DO which can occur within the membrane tank from the air scour. Consequently, aerobic basins could be operated with a residual DO of 1 mg/L, or less, in order to reduce aeration demands [2].

- **Recent models for Energy Optimization of MBRs**

The technological improvements of membrane modules resulted in the production of membranes with less energy requirements. A list of the more recent models used for energy optimization of MBR systems are given below.

Integrated system of MFC and MBR

Microbial fuel cells (MFCs) are devices that use bacteria as catalysts to oxidize various substrates and recover electricity. One approach to reduce the barriers and improve its applicability is to incorporate MFC into existing wastewater treatment processes (Figure 2). The MFC may partially offset the energy consumption in MBR process by generating electricity, and thus enables a more sustainable wastewater treatment process. In addition, MBR is more suitable to be coupled with MFC than SBR or other processes, due to the continuous - flow operating mode. [9]

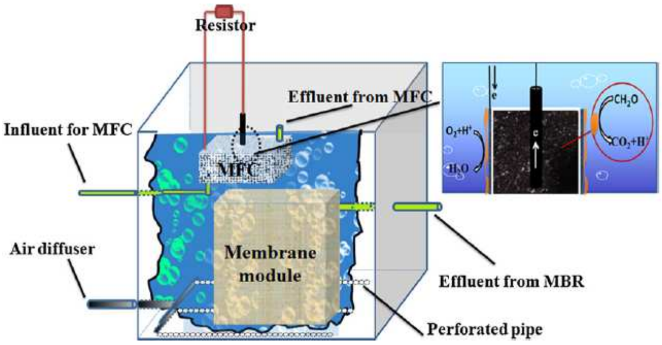

Fig. 2: Schematic of the MFC–MBR integrated system. [9]

Staged anaerobic fluidized membrane bioreactor (SAF-MBR) system

In order to reduce energy costs for membrane fouling control, a staged anaerobic fluidized membrane bioreactor (SAF-MBR) system has been proposed, consisting in an anaerobic fluidized-bed reactor (AFBR) followed by an anaerobic fluidized-bed membrane bioreactor (AFMBR), as shown in Figure 3. The primary energy requirement is dedicated for recycling the reactor liquid to fluidize the GAC (0.011 and 0.036 kWh/m^3 for the AFBR and AFMBR, respectively, resulting in a total power energy requirement of 0.047 kWh/m^3. Electric energy can be produced by combustion of the produced methane, and the net energy available for system operation is then 0.082 kWh/m^3. [10]

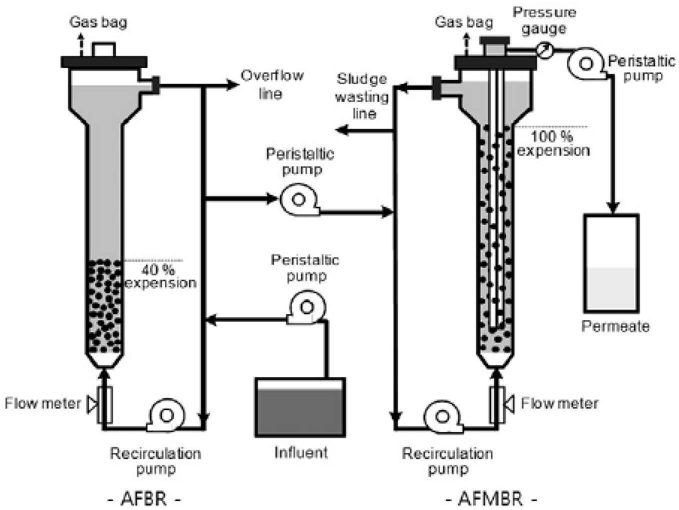

Fig. 3: Schematic diagram of the SAF-MBR system. [10]

Automatic control system

Automatic control system is an innovative process where the desired aeration rate is estimated and adjusted accordingly by the information from process instrumentation. The membrane-performance-based control system was validated at semi-industrial pilot scale with different membrane configurations achieving a maximum energy saving of 21%, with respect to the minimum aeration recommended by membrane suppliers, without visibly interfering on membranes fouling and without affecting the biological nutrient removal [11].

Magnetically induced membrane vibration (MMV) system

A novel magnetically induced membrane vibration (MMV) system is proposed as an alternative shear enhancement device for fouling control in MBRs. In the MMV system, a magnetically induced vibration of the membrane is applied in order to provide shear at the liquid membrane interface (Figure 4). The module consists in one or more membranes that are integrated in the MMV module. The system includes a vibration driver, an electric wire, a vibration engine and the actual vibrating module. As the vibrating device is integrated into the membrane module, while the movement is magnetically induced, it is expected to experience less friction, to consume less energy and to have a very flexible vibration control. The movement orientation of the vibrating part faces the narrow face of the module in order to both prevent the bumping of liquid onto the membrane and minimize the associated energy loss [12].

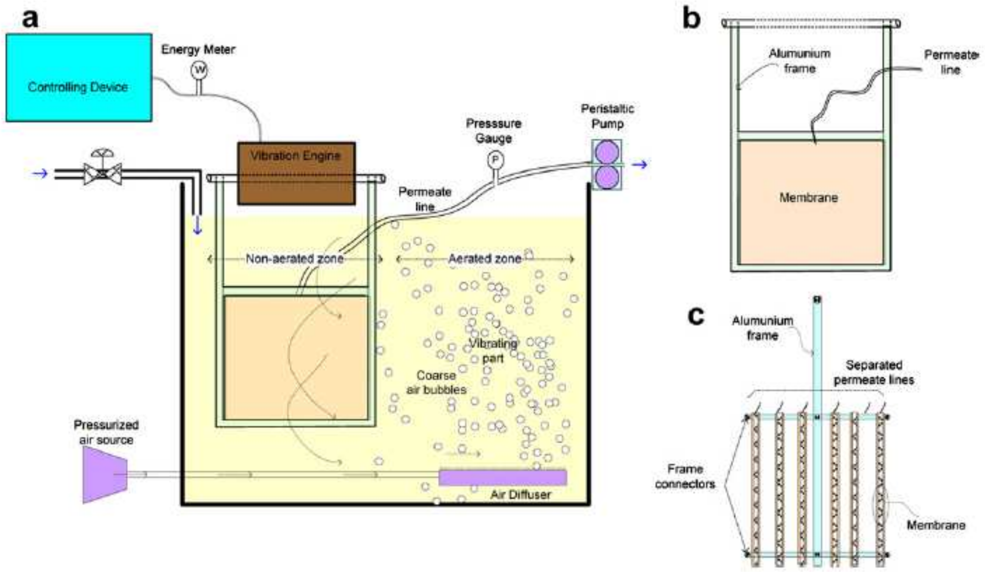

Fig. 4: Schematic diagram of the (a) HT-MBR setup equipped with the MMV system, (b) MMV module in front view, and (c) MMV module in side view, showing the parallel position on the multiple membranes mounted [12].

- **Other Methods to Control Fouling**

Fouling control that inevitably occurs in MBR operation may be achieved by implementation of appropriate measures for the adjustment of several key parameters. The most important strategies are concentration polarization suppression, optimization of physical and chemical cleaning protocols, pre-treatment of feed wastewater, and mixed-liquor modification.

Fouling related to concentration polarization can be reduced either by promoting turbulence or by reducing flux. High shear stress over the membrane surface is required for prevention of fouling due to concentration polarization. However, increased membrane aeration rate is usually expensive.

Since membrane aeration contributes significantly to the energy demand, efforts have been focused on reducing aeration whilst maintaining membrane permeability. Progress has been achieved in aeration efficiency by the use of new jet aeration and cyclic aeration systems. In practice different aeration systems for biological system and for membrane fouling control are used, aiming to efficient energy utilization for both processes [4]. The reduction of permeate flux is always associated to low fouling rate, although more membrane modules have to be installed resulting thus to high capital cost. Slug bubbling in flat sheet MBRs is an energy saving bubbling regime to replace free bubbles where SADp (special aeration demand permeate) values are reduced significantly [13].

A novel rotating tubular membrane bioreactor (RTMBR) has been employed to achieve shear-enhanced membrane filtration. Nevertheless, the analysis of energy consumption revealed that by increasing rotary speed to mitigate membrane fouling was much more energy saving and efficient than increasing aeration rate. When only rotary speed was modified to reduce membrane fouling rate (from 0 to and 10 rpm), the energy consumption increased from 1.2 to 2.1 and to 3.0 kWh/m^3 permeate respectively, and membrane fouling rate reduced by 9.56% and 19.03%, respectively. However, when aeration rate was increased in order to achieve same reduction in membrane fouling rate, the energy consumption increased from 1.2 to 5.4 and to 9.6 kWh/m^3 permeate, respectively. Therefore, it can be concluded that, when an equal reduction in membrane fouling rate is achieved, the used energy is much higher by employing aeration than rotation, suggesting that rotation is much more efficient than aeration. However, the comparison of total energy demand in the RTMBR and commercially available MBRs (the energy consumption of which can be as low as 0.4 kWh/m^3 product water) reveals that RTMBR does not have any advantage over the latter systems [14].

The use of flocculants and coagulants such as aluminum or ferric chloride has been investigated for fouling. control Furthermore, the addition of adsorbent reagents such as powdered activated carbon (PAC) has been found to improve the membrane performance by decreasing the level of organic compounds responsible for membrane fouling.

The cleaning protocol is mainly dictated by the desired operation net flux. Usually the protocol suggested by the manufacturer is followed as a guideline, and the existing plants usually work in the sub-critical regime. However, cleaning protocol has been studied intensively by many researchers where the key parameters of interest are duration and frequency of the cleaning and the back-flush flux. [5]

4. Conclusions

The MBR technology has rapidly gained acceptance as an attractive and flexible solution to plant expansion/enhancement as well as for greenfield facilities. Although capital costs of MBRs have become fairly competitive to conventional treatment systems, the operating costs, especially those related to energy consumption, require additional focus. The total energy consumption by MBRs can in some cases reach values between 6 and 8 kWh/m^3. In order to provide the most cost effective and energy efficient system, it is important to explore opportunities related to design, operations, and equipment.

There are several processes within the design of an MBR plant challenging toward a cost effective design. These include use of primary clarification ahead of the MBR, use of flow equalization, adjusting the balance of the solids between the aeration basin and the membrane basins, and pump configuration.

Hand in hand with the design elements are the various operation elements that influence the overall energy efficiency of the MBR design. Currently, the single largest energy demanding step is aeration – both for the maintenance of healthy microfauna and for the operation of the membranes. Hence, opportunities to reduce aeration have the potential to reduce the overall energy requirements significantly. Key areas of focus with respect to energy reduction include membrane scour air operation strategies, the use of flux enhancers to allow a wider flux operating range, optimization of the number membranes in service and the oxic operating conditions within the biological basins. Along with the operation strategies, energy efficient equipment, specifically the aeration equipment, the blowers and the mixers must be selected.

Fouling control in MBR operation may take place by the adjustment of several key parameters. The most important strategies are concentration polarization suppression, optimization of physical and chemical cleaning protocols, pre-treatment of feed wastewater, and mixed-liquor modification.

Finally, from the standpoint of the more recent models used for energy optimization of MBRs, the SAF-MBR system has excellent potential as a low-energy high efficiency cost-effective wastewater treatment system. A novel magnetically induced membrane vibration (MMV) system is proposed as an alternative shear enhancement device for fouling control in MBRs while the MFC is a promising approach to partially offset the energy consumption in MBR process by generating electricity, and thus enabling a more sustainable wastewater treatment process.

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