Cost Effective & Energy Efficient MBR Systems

C.L. Wallis-Lage*, S.D. Levesque**

***Black & Veatch, 8400 Ward Parkway, Kansas City, MO 64114 USA**
(E.mail: wallis-lagecl@bv.com)
****Black & Veatch, 1120 Sanctuary Parkway, Suite 200, Alpharetta, GA 30009 USA**
(E-mail: levesquesd@bv.com

Abstract

The MBR technology has rapidly gained acceptance as an attractive, flexible solution to plant expansion/enhancement as well as for greenfield facilities due the following attributes: a small footprint technology which can facilitate new and retrofit plant objectives, flexibility to achieve various levels of nutrient removal, and the exceptional overall organic and solids effluent quality. While capital costs of MBRs have become fairly competitive with conventional treatment systems, the operating costs, specifically as related to energy requirements, require additional focus. The key opportunities for energy reduction center on aeration both in the biological basins and the membrane tanks; however, all energy related elements should be considered. 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 areas within the design of an MBR plant which provide the opportunity for a cost effective design which balances CAPEX and OPEX. 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. Key areas of focus with respect to operational energy reduction include membrane scour air operational 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 operational strategies to reduce energy, energy efficient equipment, specifically the aeration equipment, the blowers and the mixers must be selected.

Keywords

MBR, energy, design, operations, equipment, flux enhancers, aeration

INTRODUCTION

The MBR technology has rapidly gained acceptance as an attractive, flexible solution to plant expansion/enhancement as well as for greenfield facilities due the following attributes: a small footprint technology which can facilitate new and retrofit plant objectives, flexibility to achieve various levels of nutrient removal, and the exceptional overall organic and solids effluent quality. However, a review of the MBR systems available in the market identifies significant differences both in design and operation. Plant configuration, the range of operating conditions and equipment design all play heavily on the resulting effluent quality and equally importantly on the operating regime for a given plant.

Within the last decade there as been exponential growth in the MBR field which has sparked an increase in the number of manufacturers. The increased competition has reduced the MBR equipment costs and the escalating commodity prices favored the small footprint design; hence, the capital costs of an MBR plant became very competitive with conventional activated sludge plants. However, a key area of focus within the MBR industry which still needs optimization is energy. Historically, the energy requirement for an MBR typically exceeded that of a conventional activated sludge plant by a factor of 1.5

to 3. A summary of the energy requirement for various operating MBRs is provided in Table 1.

Table 1. Energy Requirements for Various Operating MBRs

Plant	Capacity MLD	MBR Type	Start-up Year	kWh/m3
Brescia, Italy	42	Zenon	2003	0.85
Schilde, Belgium	8.5	Zenon	2004	0.62
Seelscheid, Denmark	11	Kubota	2004	0.9 – 1.7
Nordkanal, Germany	17	Zenon	2004	0.9
Varsseveld, NL	18	Zenon	2005	0.9
Ulu Pandan, Singapore	23	Zenon	2006	0.55

In order for MBR technology to reach the next level of technological excellence, energy requirements must be reduced. As illustrated in Figure 1, the primary energy requirements are related to aeration (66%) with pumping a far second energy requirement (14%). To that end, the key opportunities for energy reduction center on aeration; however, all energy related elements should be considered. In order to provide the most cost effective and energy efficient system, it is important to look at opportunities related to design, operations, and equipment.

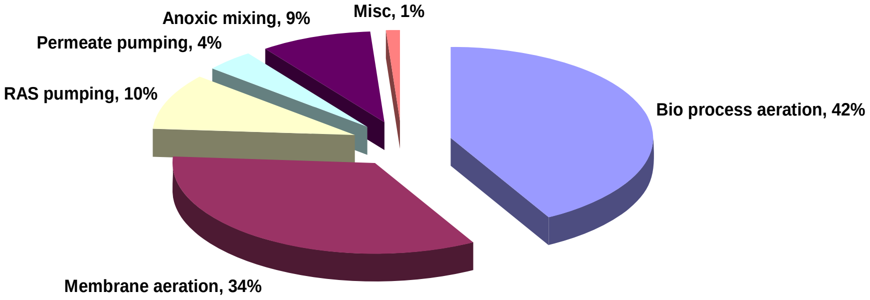

Figure 1. Energy Requirements for an MBR. (Hribljan, June 2007)

DESIGN ELEMENTS TO REDUCE ENERGY

There are several areas within the design of an MBR plant which provide the opportunity for a cost effective design which balances CAPEX and OPEX. 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.

Primary Clarification

With increasingly large MBRs, the natural engineering tendency is to consider the addition of primary clarifiers to reduce the load to the MBR similar to the benefits when designing large conventional activated sludge treatment plants. However, it is important to evaluate the impact of adding primary clarifiers completely. Traditionally, the principal driver for using a primary clarifier has been load reduction in order to: (1) reduce the power requirements associated with aeration, and (2) reduce the biological tank volume. For an MBR, the aeration power requirements are a combination of process air and membrane scour air, with the volume of scour air often equal to or exceeding the process air requirement. With a reduction in organic load, process aeration requirements would reduce; however, the scour air requirements would not change. Consequently, the actual power reduction would only be associated with the process air and would be a much smaller fraction of the overall aeration power compared to a conventional plant. However, there are other energy/O&M related benefits to reducing the organic load to the MBR. Decreasing the organic loading on the MBR process means that for a given flow rate, the MBR process can operate at lower MLSS concentration. This in turn has two key benefits: (1) decreased membrane fouling tendency, leading to longer cleaning intervals and longer membrane life, and (2) increased oxygen transfer efficiency, leading to lower aeration blower power consumption and associated operating cost.

The use of primary clarifiers also adds some additional treatment consideration with respect to the overall energy balance at a treatment plant. Inclusion of a primary clarifier results in a two sludge system which provides the opportunity to use anaerobic digestion. The energy associated with the gas production from anaerobic digestion may be beneficial in the bigger picture and, therefore, outweigh the marginal reduction in energy savings associated with the MBR.

From a design standpoint, the use of primary clarifiers impacts other process elements. There is an opportunity to locate the fine screens downstream of the primary clarifiers which would significantly reduce screenings production and, therefore, screenings handling. Use of primary clarifiers may increase the plant footprint, and the large surface area of primary clarifiers generates significant odors which must be controlled. All of these issues should be considered in combination with the discussion above in the final decision to use primary clarification.

Flow Equalization

The use of the MBR technology has rapidly advanced in recent years from small, satellite (or scalping) plants to large-scale, end of the line facilities. As a result, this newer generation of MBR plants must accommodate flow fluctuations from both diurnal flow variation and storm events. Because membrane sizing is hydraulically driven, alternatives to increasing the number of membranes should be considered if the peak flow is more than twice the average flow, as the economical upper flow limit for membranes in most MBRs is approximately 1.5 to 2 times the average flow rate. Designing membranes to accommodate higher peak flows typically results in fluxes at the average flow which are below the optimized point and significantly increases equipment cost. In addition to cost, there are operational benefits associated with a constant and reasonable flux, e.g., reduced fouling rates hence less frequent intensive cleaning and the opportunity to operate with lower air scour rates. The combination of a reduction in the membrane surface area and operating with a lower air scour rate provides the opportunity for a significant energy reduction. An example of the beneficial impact of equalization and adjusted air scour rates is provided in Table 2 based on using hollow fiber membranes.

Table 2. Energy and Footprint Impact Based on Equalization*

	No Equalization	Diurnal Equalization	Peak Day and Diurnal Equalization
Membrane Surface Area, m^2	151,600	118,440	99,490
Air Scour, m^3/h	60,590	35,460	19,860

* Example Assumptions:

- Peak flow to average flow ratio of 1.5
- Flux: 42 Lmh at peak hr, 33 Lmh at PD, 23 Lmh avg
- Air scour based on 10/10 operation above avg flux, 10/30 operation below avg flux

There are two options for equalization: external and internal. External equalization consists of separate tankage ahead of the biological process tankage. External equalization easily satisfies design requirements, but if the driver behind the selection of an MBR is footprint, an additional facility may be difficult to incorporate on space-constrained sites. External equalization can be used intermittently as an off-line basin to handle storm flows or as an in-line basin to dampen daily flows as well as handle peak day flows. Internal equalization, i.e., sidewater depth variation within the biological process tankage, can be used if the flow variation is not too large. Most plants will be limited to approximately 0.5 – 1.0 m of variation before the aeration blowers are significantly impacted, unless less efficient positive displacement blowers are used. Typically, internal equalization is best suited for dampening the diurnal pattern because the level variation required to manage storm flows effectively tends to be significant and could adversely impact the blower design. For some facilities, a combination of both external and internal flow equalization (see Figure 2) provides a cost effective solution, with the external equalization basin used for off-line storage of storm flows and internal equalization used to handle the daily diurnal variation.

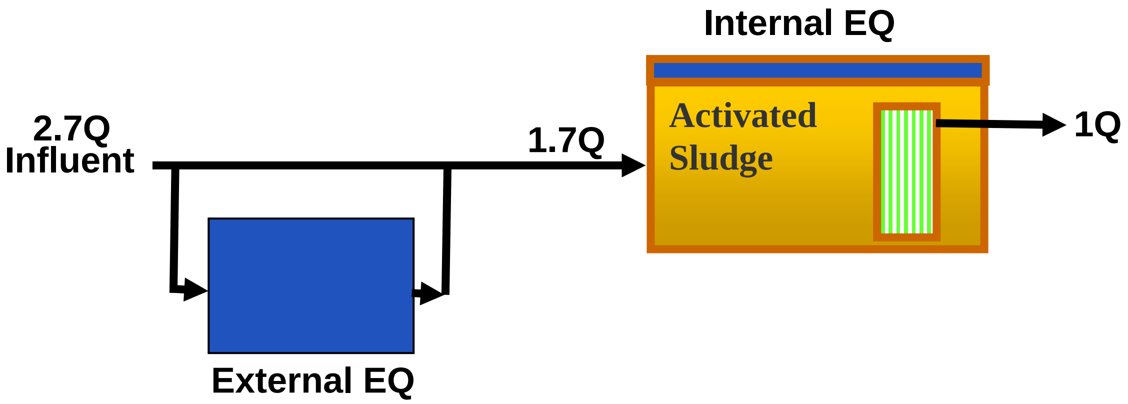

Figure 2. External and internal flow equalization optimizes membrane design.

Balance of Solids

Traditionally, MBR systems have been designed to operate at similar MLSS concentrations in both the aeration basins and the membrane tank. The end result is a very high solids recirculation rate, e.g., 4 – 5 times the influent flow. MBR systems also tend to be designed using smaller process volumes and higher MLSS concentrations than conventional biological processes. The result is suppression of aeration alpha, leading to increased air flow requirements. While it isn't feasible in all MBR designs, under certain circumstances, e.g., the use of primary clarifiers, there is an opportunity to operate with lower MLSS concentrations, hence less mass, in the aeration basins. This mode of operation could reduce the solids recycle flow rate by 50%. The energy reduction is two-fold: (1) reduction in pumping and (2) a potential increase in alpha which improves oxygen transfer efficiency.

Pump Configurations

The three key pumping requirements for an MBR are as follows: solids return, nutrient recycles, and permeate. As noted above, the recycle volume ranges from three to five times the influent flow rate depending on the overall MBR design configuration. The pumping configuration can either be forward pumping (i.e., pumping mixed liquor from the aeration basins to the membrane tanks) or return pumping (i.e., pumping mixed liquor from the membranes to the aeration basins). The preferred configuration is a function of the membrane manufacturer and the membrane tank layout and location, for example, whether new membrane tanks will be constructed or membranes will be retrofitted into existing tanks.

Up to two nutrient recycle pumping steps may be required depending on the nutrient reduction requirements. Because membrane air scour results in elevated dissolved oxygen (DO) concentration in the solids recycle, an independent recycle is typically required to return nitrates from the aerobic portion of the activated sludge basins to the anoxic zone when denitrification is required. Should enhanced biological phosphorus removal be employed, a separate recycle is needed to return solids from the anoxic zone to the anaerobic zone to eliminate DO and nitrate inhibition in the anaerobic zone. 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 flow by gravity. This configuration would require sufficient water depth above the membranes to offset the headloss associated with flux variation, fouling of the membranes, and any downstream processes prior to discharge. If pumping is ultimately required to reach the discharge point, permeate pumps may be the most cost effective selection.

OPERATIONAL ELEMENTS TO REDUCE ENERGY

Hand in hand with the design elements discussed above, are the 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 reduce the overall energy requirements significantly.

Membrane Air Scour

A key factor in the performance of the membranes in an MBR process is the daily maintenance provided by scour air. Air scour can be one of, if not the single largest, energy use in the process. In the last few years, the dominant membrane suppliers have decreased air scour energy requirements, and further improvement is anticipated. This has been one of the factors making MBR processes increasingly competitive with conventional activated sludge processes.

Specifically, various membrane suppliers have used the following techniques to minimize energy consumption:

- Intermittent air scour
- Lower air scour flow rates at lower flux

One membrane supplier, ZENON, holds patents for "cyclic" air scour, but other suppliers have found that reducing airflow to all modules also is effective. ZENON cut scour air requirements by 50% many years ago when they implemented their patented "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. Their most recent development saves additional energy by allowing even longer rest periods between aeration period when the flux is below the average design condition. The system uses "10/10" air scour at high flux and "10/30" air scour at lower flux. The "10/30" air scour works as follows: for 10 seconds, 24 of the 48 modules in a given cassette receive air scour. For the next 10 seconds this cassette does not receive air scour, but air scour is being used in other cassettes. For the next 10 seconds, the other 24 modules in the cassette receive air scour. For the last 10 seconds of the cycle, the cassettes do not receive air scour. So, a given cassette receives air ½ the time, and a given module receives air ¼ of the time. The air scour blowers meanwhile produce air at a constant flow rate. When operating in the 10/30 mode of operation, the energy requirement associated with the scouring air is reduced to 0.1 kwh/m^3.

Another membrane supplier, Kubota, uses continuous aeration but graduates the volume of air based on the flux, e.g., lower air scour rates are used with lower flux. With the Huber system, intermittent aeration occurs based on the rotation of the membrane panels through the aerated portion of the membrane tank. With the Siemens system, a combination of air and water are used to scour the membranes. The end result is that the membrane air scour requirement can vary between 0.18 and 0.73 m^3/m^2/hr of membrane which results in a significant variation in the energy demand associated with membrane maintenance.

Flux Enhancers

One manufacturer is also designing for the intermittent use of membrane performance enhancers - specifically a polymer based product called MPE 50 supplied by Nalco – to reduce the overall membrane footprint and, therefore, air scour. The addition of flux enhancers allows a wider flux operating range and has been used to demonstrate performance benefits both in pilot scale and full scale plants. There are two operating extremes which appear to benefit from the addition of the polymer based flux enhancer. If 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 an energy savings based on the reduction in overall air scour requirements. Extensive testing was completed with King County in Seattle Washington to demonstrate that the Kubota membrane could operate without rapid fouling at approximately 1.5 times their typical peak flux (Enviroquip, 2007). If the membrane quantity is based on minimum temperature which reduces the design flux, full scale testing in Running Springs, California with the Kubota membranes indicated that the addition of the polymer based flux enhancer supported 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. Flux enhancing polymer can also be a means of increasing the short-term capacity of the membrane system which could impact redundancy requirements.

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 for portions of the day when flow is low provides the opportunity to reduce the air scour requirements during the rest period. This mode of operation also enhances membrane performance due to a more consistent flux. Varying the number of basins on line is primarily an opportunity for plants where equalization is not provided.

Optimize DO within the Bio Process

In all wastewater treatment plants which use aerobic treatment, the biological aeration demand is a significant contributor to the plant energy requirements. With an MBR there are two opportunities to reduce the total aeration demand in the biological aeration basins: (1) operate at the minimum DO required to achieve complete treatment, and (2) return the solids from the membrane tank to the oxic portion of the biological basins to utilize the elevated DO which can occur within the membrane tank from the air scour. Historically, the aerobic portion of the biological basins has been operated with a target DO of 2 mg/L in order to consistently achieve performance goals and to minimize the potential for filamentous growth. By using membranes for solids separation in lieu of gravity settling systems, the adverse impact of filaments is significantly reduced. Consequently, aerobic basins could be operated with a residual DO of 1 mg/L, or potentially less, in order to reduce aeration demands. However, it is critical to have sufficient sludge age and hydraulic residence time to achieve the required performance especially with a reduced concentration of DO. With respect to the solids recycle line, returning the solids from the membrane tank to the anoxic zone (if part of the biological basins) could be detrimental to denitrification due to the elevated DO. Depending on the membrane manufacturer, the DO in the membrane tank can vary between 2 mg/L and 6 mg/L. By returning the solids to the oxic zone, there is an opportunity to utilize the DO to offset a small portion of the aeration demands.

EQUIPMENT ELEMENTS TO REDUCE ENERGY

The highest power consumption at a wastewater treatment plant is tied to the aeration system; consequently, optimizing oxygen requirements in addition to operating efficient equipment are important elements in keeping operating costs down. Ancillary equipment such as mixers for anaerobic and anoxic basins in BNR plants should also be closely scrutinized to keep energy requirements low.

Diffused Aeration

Fine bubble diffusers provide efficient oxygen transfer and have been proven to be durable for wastewater treatment plant applications, thus they are the predominant aeration device used today. There are many types of fine pore diffused aeration systems in the marketplace. In general these aeration systems are grouped into porous ceramics, porous plastics and perforated membranes. The perforated membranes include traditional disk and tube membranes as well as panel and strip membrane units, which have significantly higher oxygen transfer efficiency. The size of the aeration system in an MBR is significantly impacted by the aeration demand, diffuser depth, and selection of alpha.

Blowers

For purposes of energy efficiency, single-stage, multi-stage, or turbo centrifugal blowers could be used. For a given capacity, single-stage blowers tend to be more expensive than multi-stage blowers. However, single-stage blowers tend to have greater turndown capability, which could allow fewer, larger blowers to be used for a given situation. The net effect could be a reduction in capital cost. Another advantage of single-stage blowers is that they tend to be more efficient than multi-stage blowers, reducing electrical power consumption.

Many multi-stage blower systems achieve capacity turndown using inlet throttling, which reduces the mass airflow at the blower inlet while keeping volumetric airflow the same. At least one single-stage blower manufacturer uses variable inlet guide vanes and variable outlet diffuser vanes, both under control of a local PLC, to achieve turndown and maximize operating efficiency. Either alone or together with these approaches, a blower system also can use variable speed drives (VSDs).

Turbo blowers are a newer type of single-stage blower that operate at very high speed. These blowers have a number of advantages, including excellent energy efficiency; however they currently are offered only in relatively small capacity.

Mixing

For the un-aerated portions of the activated sludge basins (i.e., anoxic and anaerobic zones), high efficiency mechanical mixing equipment should be used. The most popular choices include submersible propeller blade type pumps by Flygt, EMU and Landia, and top entering, high efficiency mixers which operate with a very low rpm manufactured by Chemineer, Lightnin and Philadelphia Mixer. Recent additions to the mixing marketplace include the INVENT mixer and the EnerSave mixer, which use significantly less energy yet appear to produce similar mixing and performance results.

CONCLUSION

The MBR technology has rapidly gained acceptance as an attractive and flexible solution to plant expansion/enhancement as well as for greenfield facilities. While capital costs of MBRs have become fairly competitive with conventional treatment systems, the operating costs, specifically as related to energy requirements, require additional focus. 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 areas within the design of an MBR plant which provide the opportunity for a cost effective design which balances CAPEX and OPEX. 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.

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