Operations Simulator for MBRs on the Windows .NET Platform – AquaNET Aquifas - Full Scale Verification and Energy Optimization

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ABSTRACT

A MBR operations simulator was developed based on the IWA ASM2d model for activated sludge and on the IWA principles for biofilm modeling. The graphical interface was developed using the Windows .NET platform. The interface has separate menus for designers and operators. The model allows the user the option to simulate the MBR and the whole plant. The whole plant interface includes headworks, primary, secondary, sludge handling, digestion and dewatering facilities.

Several features related to plant operations were included in the simulator. These include: (a) varying the cyclic air scour on-time fraction; (b) flow pacing or changing the aeration at different times of the day; (c) reducing the MBR recycle while managing the solids flux; (d) reducing the operating DO in the aeration zone upstream of membrane cell; (e) reducing the aeration in the MBR cell such that it simultaneously meets both the air scour and process demand requirements; (f) computing the characteristics and removals in the biofilm growing on membranes in the membrane cell or in biofilm support media. These features are based on experiences with operation of MBRs with hollow fiber and flat sheet modules, and in-line and side-line cross flow submerged membranes.

The simulator was verified against observations made a full scale plants. It was able to predict reduction in energy observed through reduction in operating DO to within 94% of actual values at Redlands, CA; it was able to predict reduction in energy by changing the MBR cycle times to within 99% of observed values at Traverse City, MI. Its predictions of optimized energy requirements (0.36 KWH/m^3 of flow treated) were consistent with measurements following optimization at the Ulu Pandan, Singapore plant (0.38 KWH/m^3). For flat sheet membranes, it predicted 0.45 KWH/m^3 of flow treated, which was consistent with the best values reported. Based on this verification of its ability to predict optimization in full scale facilities, the model can be used as a tool for operations optimization in existing systems and to improve the design and MBRs.

KEYWORDS

Membrane Bioreactor, Energy, Operator, Optimization, AquaNET, Aquifas, Windows .NET

INTRODUCTION

Membrane Bioreactors (MBRs) were introduced in the 1990s as alternatives to replace the clarifier (liquid solids separator) in secondary treatment activated sludge systems. Today, the liquid solids separation can be configured as:

1. In-stream tanks with membranes (*eg*: hollow fibers by Zenon and Siemens, flat sheet by Kubota)
2. Side-stream tanks/modules with membranes that are external to the main reactor (*eg*: Norit cross-flow, Mann-Hummel).

The liquid flux through the membranes is maintained by air or liquid scour across the surface of the membrane (or a combination), together with periodic backflush with liquid and chemicals.

The MBRs have several advantages. They offer a lower footprint by virtue of elimination of secondary clarifiers. They generate a water quality that is equivalent to filtered secondary effluent that is generally amenable for indirect reuse.

At the same time, they pose two challenges. Analysis of data from several full scale MBRs show that the energy and chemicals required over what is required in activated sludge systems operated for BNR or ENR, based on standard operating procedures recommended by manufacturers, is averaging 200% of activated sludge plants. The additional energy required is for air scour, which depending on the type of MBR can be equal to the process aeration energy requirement, higher MBR recirculation rates, additional methanol required for denitrification, and energy for permeate pumps.

OPERATIONS SIMULATOR DEVELOPMENT

Methodology

The research and technology development effort focused on three elements:

1. Understand the significant advances made by the manufacturers in the past five years and analyzing the data from the plants which have reduced energy required to operate MBRs.

2. Develop a plant operations simulator that

    a. Can be used for various MBR process configurations (in-line, side-line or cross flow, tangential flow), aeration configurations (cyclic, continuous and flow paced aeration) and types of media (hollow fiber, flat sheet);

    b. Include features that are used to optimize each MBR process configuration and media type.

3. Verify the simulator against full scale data from MBRs – this helped evaluate the algorithms, improve their accuracy in replicating changes made at plants, both for energy and process effluent parameters, and improve the speed of computations.

Features

Some of the features included in the simulator are:

1. Vary the cyclic air scour on time fraction over a range from 20% (Mann-Hummell MBRs) to 25% (Zenon at some plants such as Traverse City, MI) to 50% (Redlands, CA) to 100% (during high flow).

2. Flow pace or change the aeration at different times of the day (Kubota flat sheet and others) instead of cyclic aeration

3. Reduce MBR recycle from a standard 4Q to 2Q (as in Newater, Singapore) while managing the solids flux on the MBRs

4. Reduce operating DO in the aeration zone upstream of MBR tank (as in Redlands, CA) or reduce both the DO and size of the aerobic zone (as in Kubota flat sheet systems)

5. Reduce the aeration in the MBR cell such that it simultaneously meets the air scour and process demand requirements (as in hollow fiber applications at Redlands, CA and Traverse City, MI; various Kubota systems), while controlling effluent quality and backpulse.

6. Compute the characteristics and removals in the biofilm growing on membranes in the membrane cell.

7. Compute the effect of biofilm in Integrated Fixed Film Activated Sludge (IFAS) configuration in cells upstream of the membrane cell.

Programming Language and Data Structure

The Windows .NET platform was selected for developing the software (Microsoft Windows .NET, 2009). The programming language is C#. It is supported by additional code that is written on Excel with Visual Basic applications.

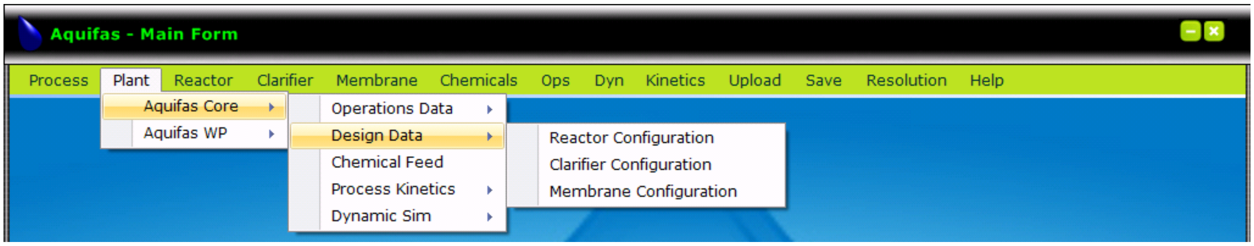
The graphical interface and the back end code allows the user to simulate MBRs and other types of plants (conventional activated sludge, CAS, IFAS, Moving Bed Biofilm Reactors, SBRs with and without biofilm, trickling filters, biofilters) within the same model.

The data files are arranged such that two users at two different locations can exchange the plant data file and graphics files easily by email. Each file is less than 100 KB. The data is in a xml file; the plant graphics are in two files created for the program: (a) an .aqi file for MBR reactor and membrane cell; (b) an .aqw file for all unit processes including headworks, primary treatment, fermenters, solids handling – thickening, digestion, dewatering, post treatment). The .aqi and aqw files are small (less than 100KB). The files can be stored locally on any drive and can be shared between users. This allows users in various geographic locations around the world to work on the same file, to add to it, update it and help each other trouble sheet and improve a process. The user is not limited by access to a server or a dongle to run the program.

Data Interfaces and Files Optimized both for Operations and Design

The menus and interfaces within the model were created with two customer segments (user groups) in mind: designer and the operator. The two approaches are shown in Figure 1.

Menu For the Designer – configure the reactor and membrane cell through the Plant, Design Data Menu



Menu for the Operator – configure the Reactor and Membrane through icons on the Main Form

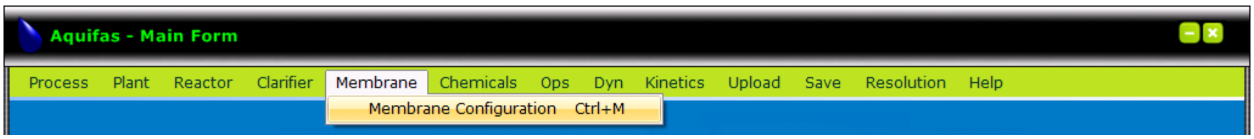


Figure 1. Separate menus for the Designer and the Operator

Figure 2 shows the menu that is used to create the reactor layout and store its properties. One can create configuration of 1 to 12 cells in series. The type of cell is selected from the drop down menu and dropped into the workspace. One then clicks on the cell to enter the properties (Figure 6). Figure 3 shows one of five review and validation menus that allow the user to verify the accuracy of data entered before running the program.

Figures 4 and 5 show two examples of whole-plant configurations used with MBRs. One can include processes such as dual screening, primary clarifiers, fermenters; thickening, aerobic and anaerobic digestion, solids handling, and chemical treatment of recycles from solids handling. The digesters can be specified as holding tanks or as true digesters. Anaerobic digestion includes a complete phosphorus mass balance and chemistry for biological excess P removal, and chemical precipitation as struvite and vivianite.

The properties of each cell, unit process or flow stream can be accessed by clicking on the icon in the workspace. Figures 6, 7 and 8 show some of the tabs under the properties of the membrane cell. This part of the model allows one to enter:

1. Dimensions (enter the dimensions of the MBR cell and other cells);
2. Aeration parameters including operating DO;
3. Feeds (influent, supplemental carbon, chemical), recycle streams;
4. Multiple trains or split the recycles between cells; and
5. Amount of biofilm support media or simulate a biofilm layer on the membranes.

Figures 9 and 10 show parts of the data interface where one can enter various design and operating parameters. This is data for the plant and process that is stored in directly in the XML file and does not pass through the .aqi file. Figure 8, shows how the different recycle rates for different MBRs are entered for hollow fiber in-line MBRs (*eg*: Zenon, Hydranautics) and side-line MBRs (*eg*: Norit cross-flow). One can also use this section of the model to evaluate the impact of different recycle rates and optimize the recycle.

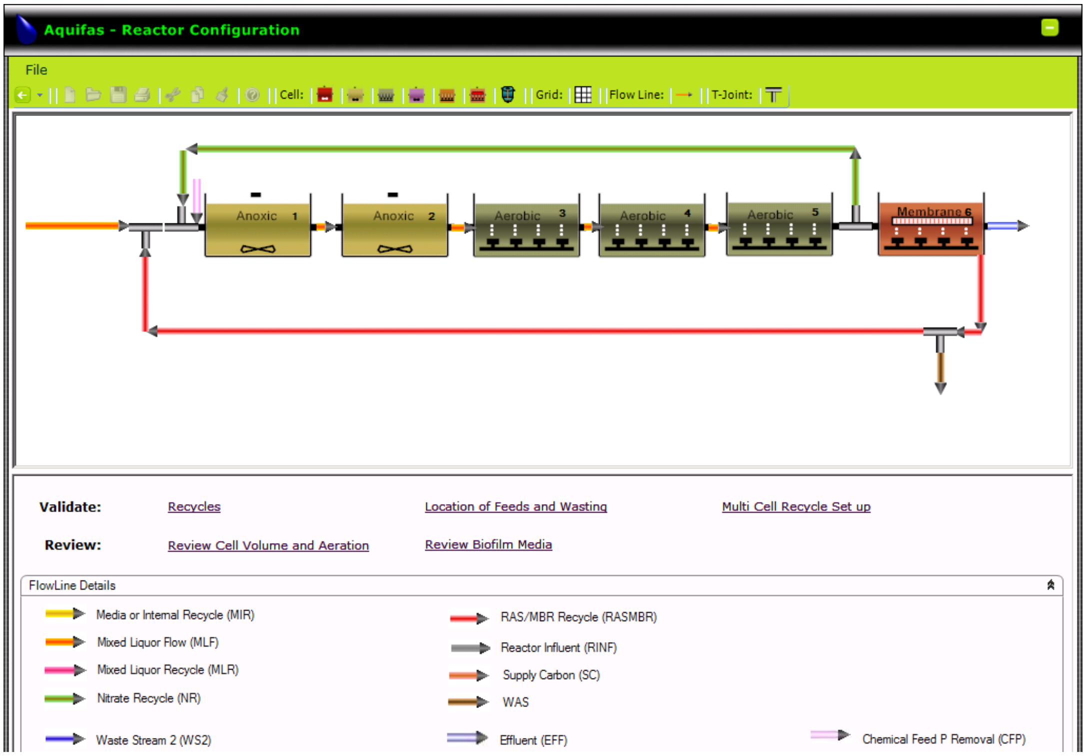


Figure 2. Reactor Configuration Interface to set up the MBR configuration in AquaNET version of Aquifas

	Units	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Cell 7	Cell 8	Cell 9	Cell 10	Cell 11	Cell 12
Tank Name		Anoxic	Anoxic	Aerobic	Aerobic	Aerobic	Membrane	-	-	-	-	-	-
Computed Cell Volume	m3	1050	1050	1190	1190	1190	1240	-	-	-	-	-	-
DO Specified	mg/L	0.05	0.05	1.0	1.0	1.0	4.5	-	-	-	-	-	-
Depth of Tank	m	3.5	3.5	3.5	3.5	3.5	3.1	-	-	-	-	-	-
Height of diffusers	m	0.24	0.24	0.24	0.24	0.24	0.24	-	-	-	-	-	-
SOTE at 12 foot or 3.65 m		0.24	0.24	0.24	0.24	0.24	0.16	-	-	-	-	-	-
Diffuser/ Surface Aerator Blade Fouling or Wear		0.92	0.92	0.92	0.92	0.92	0.98	-	-	-	-	-	-
Alpha		0.45	0.45	0.50	0.5	0.5	0.5	-	-	-	-	-	-

Figure 3. Review Cell Volume and Aeration (DO, SOTE, fouling, alpha) by clicking the Review button in the Reactor Configuration Interface

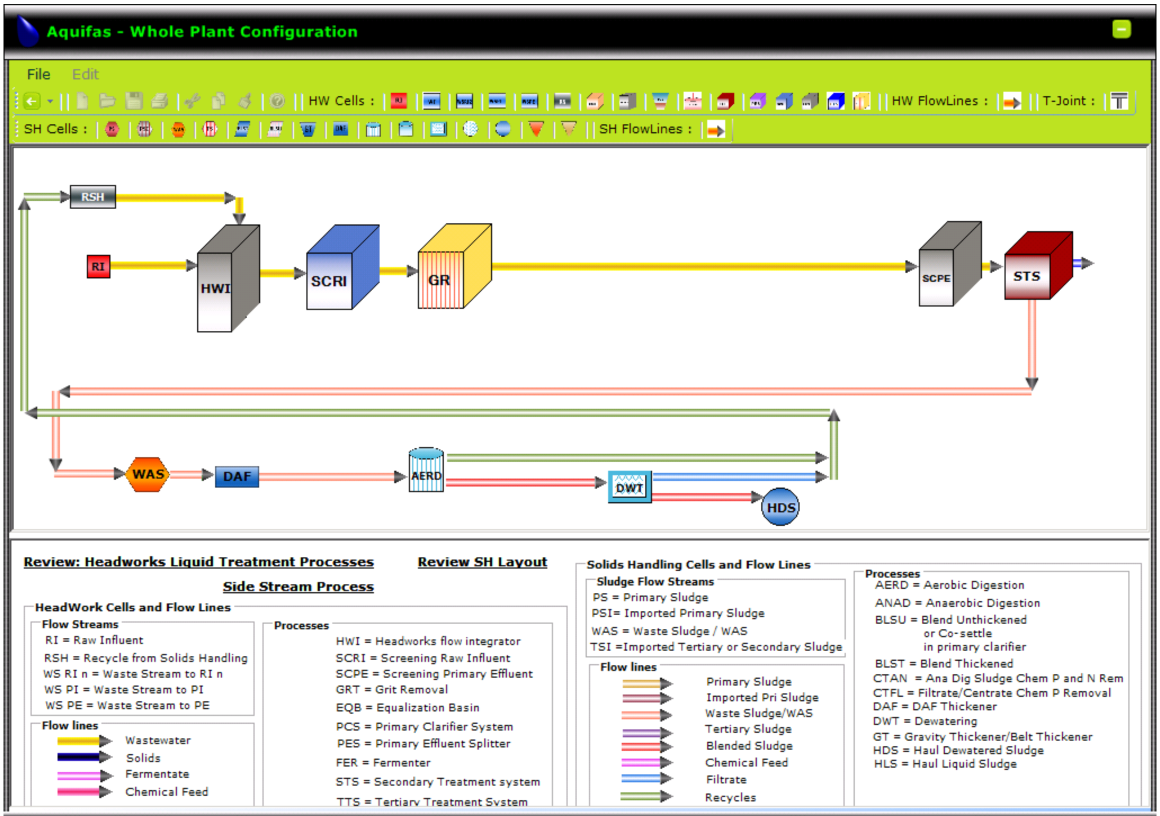


Figure 4. Example of a whole plant configuration for MBR system, as may be seen in a small plant

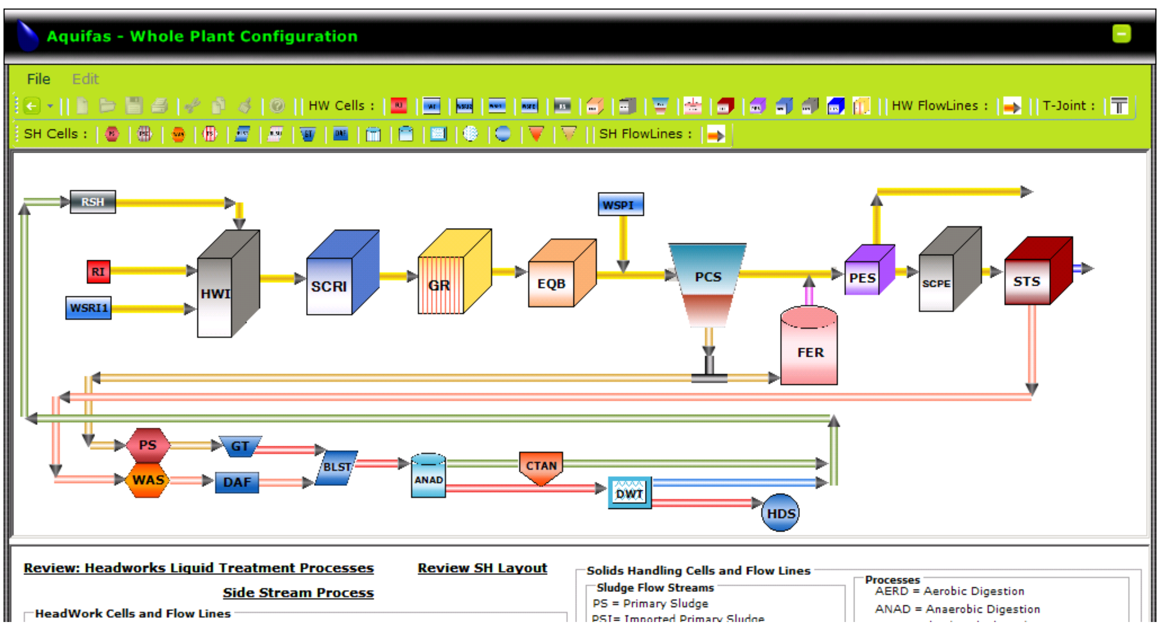


Figure 5. Example of a whole plant configuration of a MBR with dual screening and anaerobic digestion, as may be seen in a larger plant

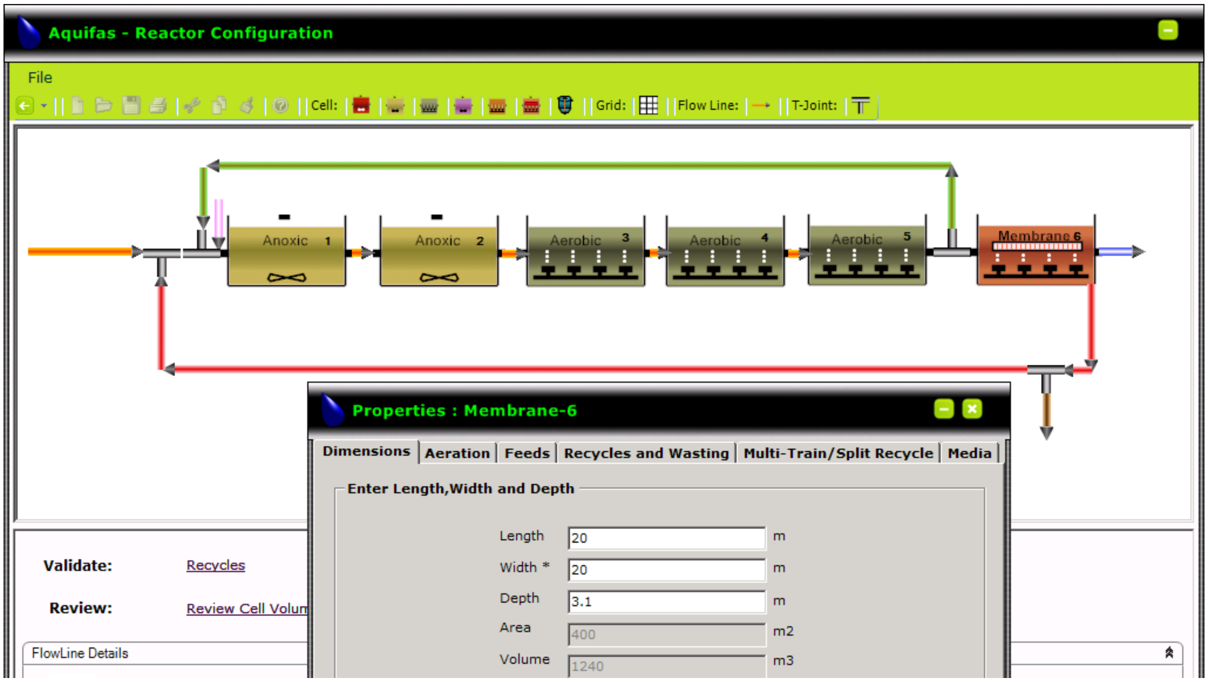


Figure 6. Graphical User Interface (GUI) to enter properties of Membrane Cell – Dimensions (5 cell configuration shown)

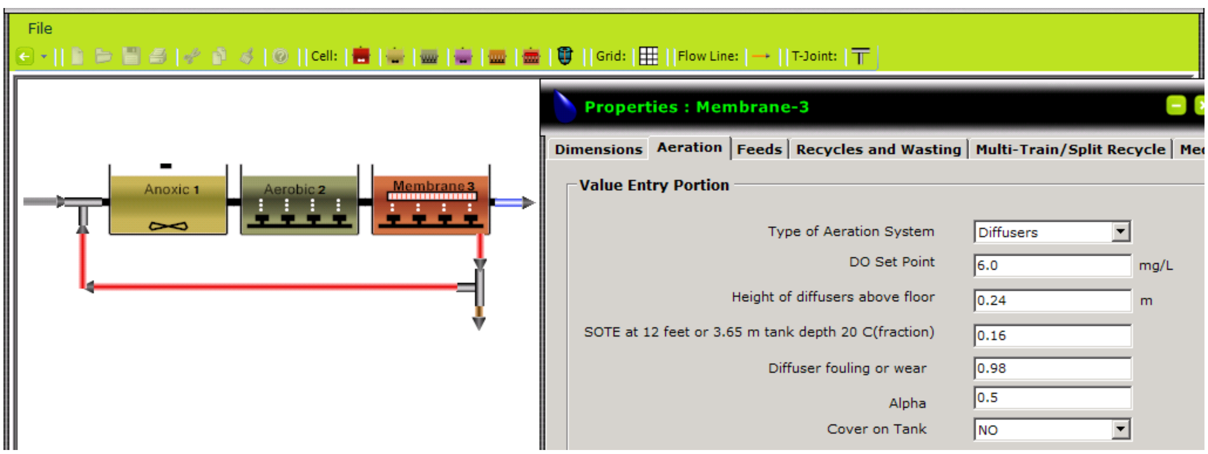


Figure 7. GUI to enter properties of Membrane Cell for Aeration for Air Scour (3 cell configuration shown)

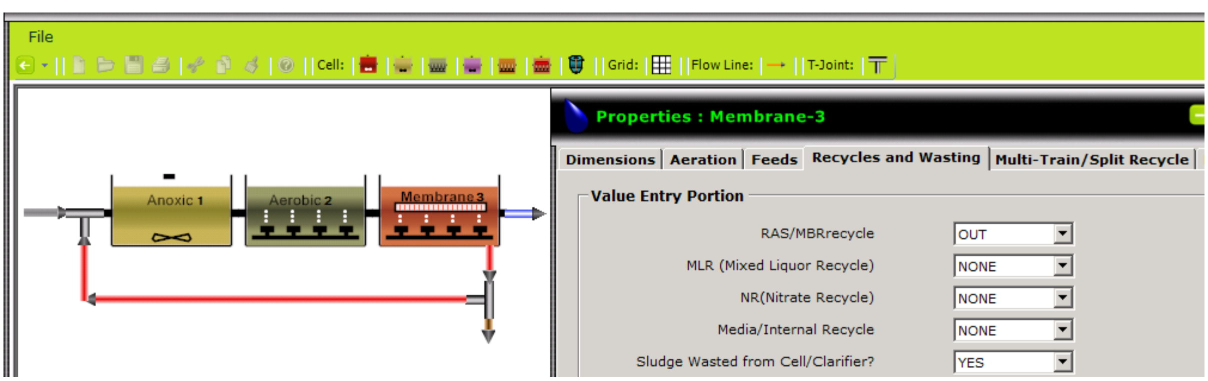


Figure 8. GUI to enter properties the membrane cell for MBR Recycle and Wasting (3 cell configuration shown)

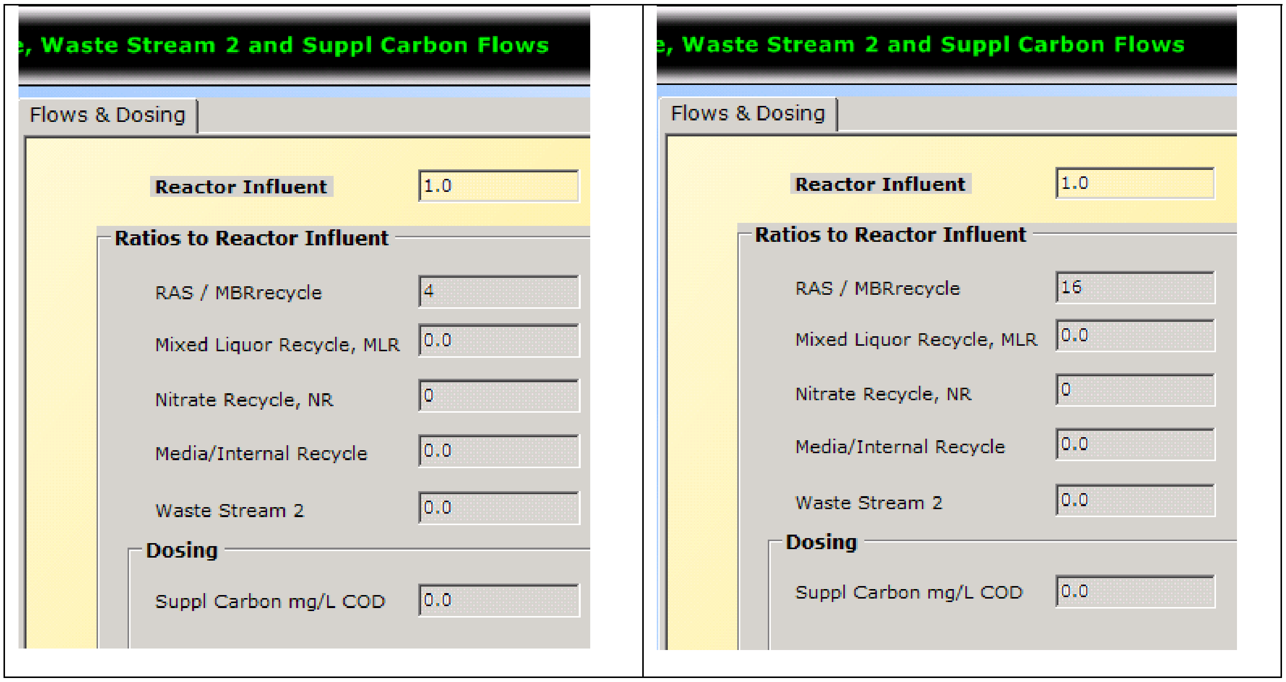
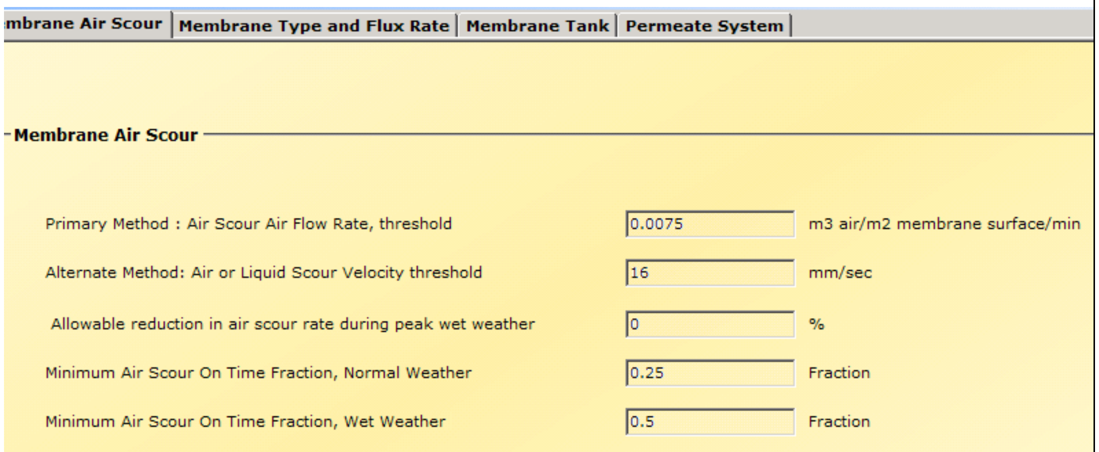


Figure 9. Define Recycle Rates for In-line submerged membranes (left) and Side-line External or Cross Flow membranes (right)

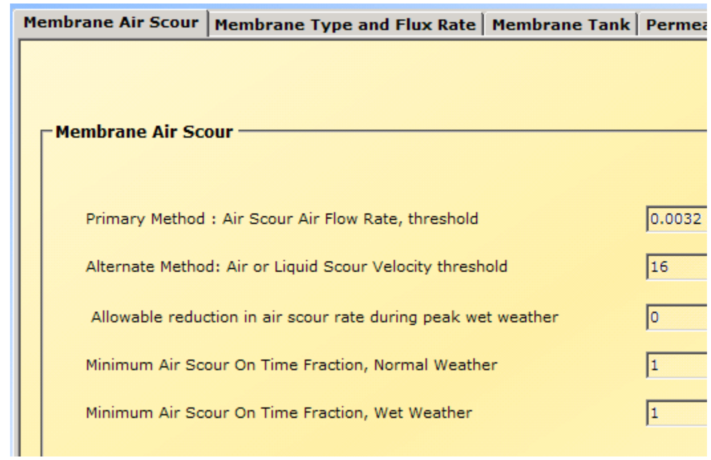
Figure 10 shows a part of the membrane data interface. It can be used for hollow fiber and flat sheet membranes. The features included help replicate the layout and energy optimization routines in MBRs for hollow fiber and flat sheet membranes. One enters the specific surface area of membranes as applied in the membrane cell (applied SSA) for different types of MBRs. The hollow fiber application has a higher applied SSA (52 m^2/m^3 at 40% fill) as compared flat sheet (22 m^2/m^3 at 33% fill). The interface allows the user to define if the air scour rate that needs to be satisfied and its pattern (continuous or cyclic aeration). For hollow fibers, a 25% on-time (such as 10 sec on, 30 sec off) with hollow fibers as implemented at the Traverse City, MI, plant or 50% on time at Redlands, CA, plant is simulated by specifying the on-time fraction. The threshold for air scour rate has to be met during the on time fraction. A typical value of the threshold is 0.0075 m^3/m^2 membrane surface/min. For flat sheet or other membranes that are aerated continuously and the air scour rate is varied with flow over a 24 hour period, one enters the time averaged value of the threshold for air scour rate. A typical value for flat sheet membranes is 0.0032 m3/m2 membrane surface/min. After completing steady state simulation, one can run a dynamic simulation during which DO in the membrane cell and the corresponding air scour is specified every 15 minutes over a 24 hour period.

The model has been developed to optimize the cell size, aeration and air scour energy in MBRs. One can change the DO setpoint in the aerobic cell and MBR cell (as shown in Figure 7) to evaluate the plant performance with different aeration and energy consumption rates.

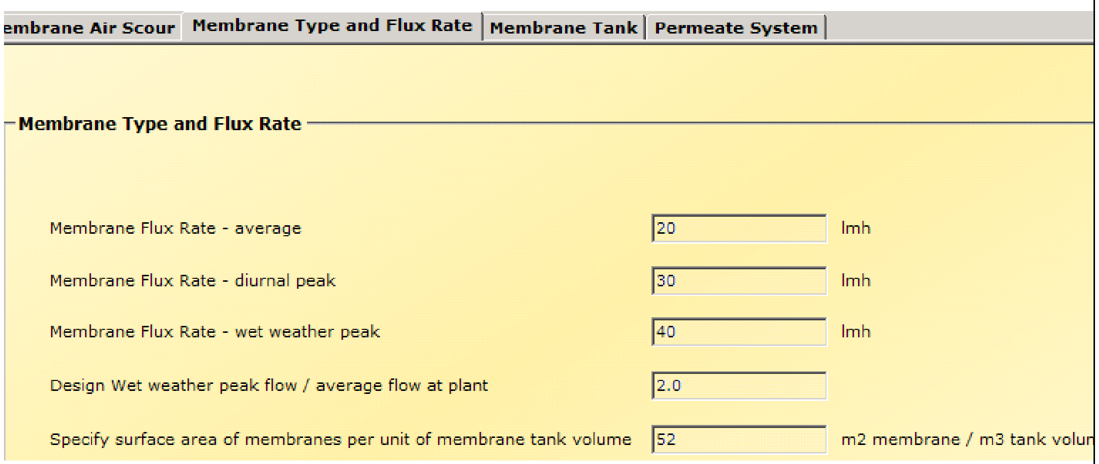
Hollow Fiber Membrane Air Scour



Flat Sheet Membrane Air Scour



Hollow Fiber Flux Rate and Specific Surface Area Applied



Flat Sheet Flux Rate and Specific Surface Area Applied

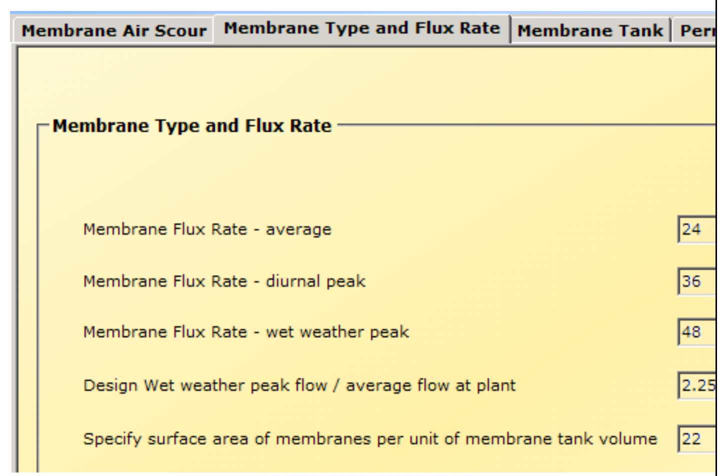


Figure 10. Membrane Air Scour, Flux Rate and Specific Surface Area Applied – Typical Values for Hollow Fiber and Flat Sheets

Note: For the alternate method, the velocity threshold of 16 mm/sec can be for air bubble or for liquid flow against the membrane.

RESULTS - FULL SCALE VERIFICATION

This section of the paper compares the results of simulations to the actual changes in energy and effluent quality measured at MBR plants that have implemented certain optimization routines. This step helps verify the model by measuring its accuracy prior to its use as an operations tool

Strategy 1 – Reduction in DO in the Aerobic Cell of MBR

Table 1 shows the results of optimization at Redlands, CA. In Feb 2005, the plant was operating at 17,000 m^3/d (4.5 MGD). The plant was operated in a MLE configuration but with only one anoxic cell that had 16.5% of the volume, followed by an aerobic zone 67% of the volume and a MBR cell with 16.7% of the volume. Zenon hollow fiber membranes are used in the MBR cell. A picture of the actual plant is shown in Figure 11. The configuration created for simulating the plant is shown in Figure 12. The aerobic zone had a length to width ratio 2:1 with limited longitudinal mixing. It was simulated better when it was divided into two aerobic cells.

Prior to Feb 2005, the plant operated the aerobic cell with a DO of 2.5 mg/L. The MBR cell was aerated cyclically with an aeration pattern of 10 sec on and 10 sec off (50% on-time fraction) and had a DO around 8 mg/L. The 4Q MBR recycle carried a substantial amount of DO over to the anoxic cell. The small anoxic cell combined with some backmixing from the aerobic cell to the anoxic cell limited the denitrification in the anoxic cell. The effluent NOxN was 20 mg/L which was above the target of 10 mg/L for discharge to the groundwater. Table 1 shows that the model was able to predict this condition reasonably accurately for a full scale plant.

In Feb 2005, the operator reduced the DO in the aerobic zone from 2.5 to an average of 0.5 mg/L. The reduction in DO in the aerobic zone increased the amount of ammonia and soluble biodegradable COD entering the MBR cell. This increased the process demand in the MBR cell and dropped the DO from 8 mg/L to 6 mg/L. Denitrification improved because there was less DO in the recycle to the anoxic cell, less backmixing from the aerobic cell to the anoxic cell because of the reduction in the intensity of aeration, and enhanced denitrification within the aerobic zone (simultaneous nitrification and denitrification) at a MLSS of 8000 mg/L. The effluent NOxN decreased from 20 mg/L to 5.7 mg/L. The effluent ammonium-N increased from 0.1 to 0.8 mg/L because the plant did not have automated DO control. As a result, the aeration could not be matched to the load. This was not a concern at this plant because the limit was in terms of oxidized N and total nitrogen. If automated DO control was installed, the plant would have achieved a lower effluent ammonium-N.

Table 1 shows a comparison of the results predicted by the model to the results observed, both before and after the change made in Feb 2005. The model was able to predict the effluent quality. What is more important is that the actual reduction in power consumption was 140 KW and the model predicted 132 KW. This is within 94% of actual results. The MLSS and sludge production was within 5%.

Strategy 2 – Reduction in Aeration On-time Fraction in the MBR Cell (Change in Cyclic Aeration)

The Traverse City, MI, MBR plant operates for biological excess P and N removal. It has one anaerobic cell (5.5% of volume), three pre-anoxic cells (7, 6 and 6% volume, respectively), three aerobic cells (20% volume each) and one MBR cell (15.5% of the volume). During the period of this evaluation, the plant was operating at 16,800 m^3/d (4.44 MGD). The MBR recycle of 2.3Q from the MBR cell to the first aerobic cell. There is a nitrate recycle of 3.3 Q from the third aerobic cell to the first anoxic cell. Finally, there is a mixed liquor recycle from the third anoxic cell to the anaerobic cell.

Originally, the plant was operated similar to Redlands with 2.5 mg/L to 4 mg/L DO in the aerobic zone and 50% on-time fraction in the MBR. However, this was changed in 2007 to operate with 25% on-time fraction (10 sec on and 30 sec off). This change resulted in a 18% reduction in daily power consumption from from 7800 to 6400 KWH. Table 2 shows that the simulator computed a reduction from 7824 to 6408 KWH, accurately reflecting the 18% reduction in energy. The simulator was also able to predict the effluent ammonium-N and phosphorus levels. The MLVSS and sludge production were within 5%. The difference in the inert SS was because the model run was without the chemical trim for phosphorus. The plant used a small amount of chemical trim. The chemical dose was not available.

Table 1. Observed and Simulated Conditions at Redlands, CA, before and after optimization of aeration

Comparison of Observations to Model Results		Condition 1		Condition 2	
		Aerobic DO 2 mg/L		Aerobic DO 0.5 mg/L	
Data to Model Predictions at Redlands		Observed	Modeled	Observed	Modeled
Aerobic Zone DO	mg/L	2	2	0.5	0.5
Membrane Cell DO	mg/L	8	8	6	6
MCRT	days	15	15	15	15
MLSS	mg/L	~8000	7950	~8000	7950
Effluent NH4N	mg/L	0.1	0.1	0.8	0.7
Effluent NOxN	mg/L	~20	19.5	5.7	4.8
Note: The plant did not use automated DO control.					
The observed DO level is an average; in Condition 2, where the oxygen provided is optimized to be close to the process demand, the effluent NH4N and NOxN fluctuated because the DO control was not automated. This resulted in a higher effluent NH4N and NOxN than would be observed otherwise.					
The modeled condition was for the average load.					

The plant observed a reduction in power consumption of 140 KW. The model predicted a reduction of 132 KW. Accuracy was to within 94% of actual value.

Table 2. Observed and Simulated Conditions at Traverse City, MI, before and after optimization

	Observed Data	Model Predictions
Flow, MGD	4.44	4.44
MLSS MCRT, days	12.5	12.5
Temp, C	16.1	16.1
MLSS, mg/L	5839	5930
Fraction VSS	0.71	0.75
Chemical trimming	Low	Not applied
Model 10-10 Aeration + Air Scour, KWH/day	7800	7824
Model 10-30 Aeration + Air Scour, KWH/day	6400	6408
Reduction in Energy	18%	18%
Effluent NH4N, mg/L	0.5	0.3
Effluent TP, mg/L	0.4	0.6

The plant used a certain amount of chemical trim, which is responsible for the difference in effluent OP. Data was not available on the exact amount of the chemical dose. The effluent OP computed by the model is without the chemical trim.

Figure 11. Picture of the Redlands MBR Plant, Redlands, CA

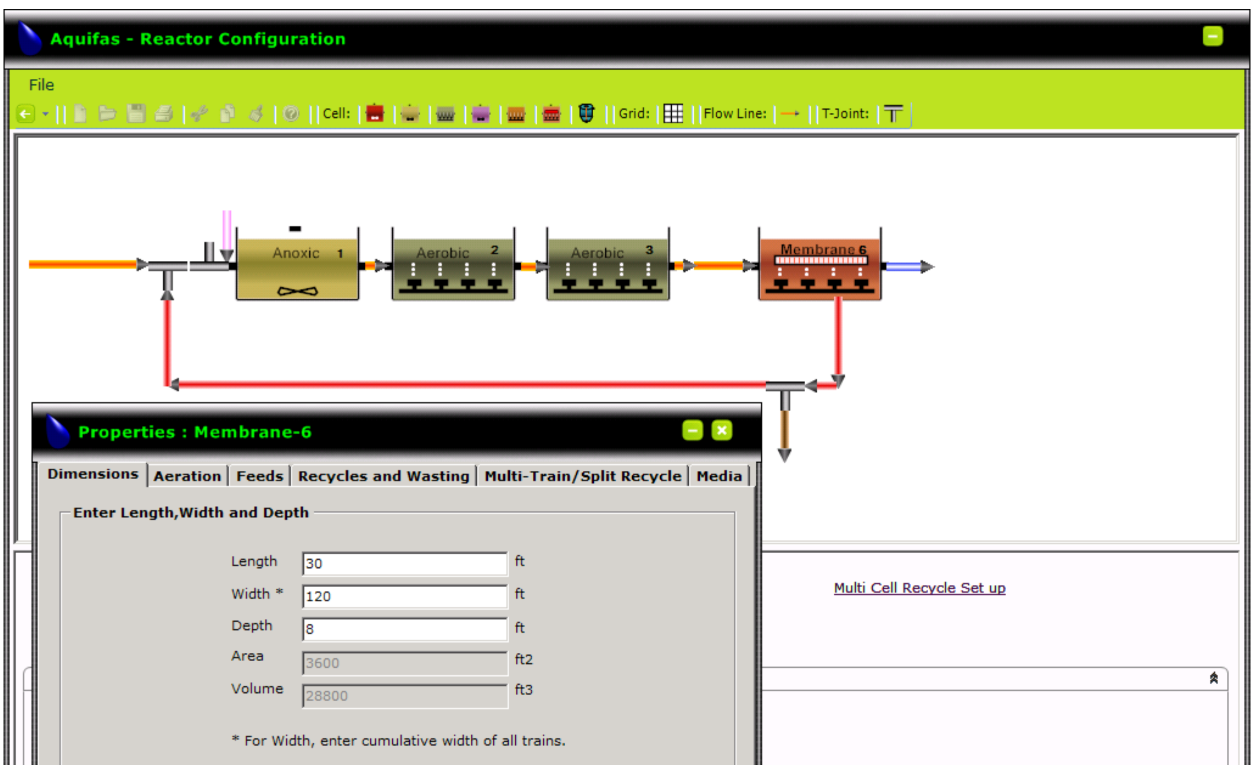


Figure 12. Configuration of the Redlands MBR Plant for the purposes of simulation

Width of each train is 20 feet or 6.1 m, there are 6 parallel MBR trains

DISCUSSION

The analysis at several full scale plants, including those in Tables 1 and 2, showed that the model was able to predict to within 95% the changes that would be observed if the DO levels were reduced, if the air scour patterns were changed, either by changing the on-time fraction or the air scour air flow rate. It had similar accuracy in terms predicting the overall power consumption because it predicted the sludge production and effluent quality with sufficient accuracy, as a result of which the mass balance on oxygen and aeration was close to the actual values. This information can then be used to:

a) simulate changes that can be made to a plant to reduce energy consumption while achieving BNR or ENR permits;

b) reduce chemical feed rates (supplemental carbon, cation addition for P removal); and

c) optimize designs of hollow fiber and flat sheet MBRs.

The discussion presented below shows how one can benchmark hollow fiber and flat sheets against a CAS system optimized for energy. It can also be used to improve the design of both types of MBRs. The model input shown in Figure 7 was used to generate the following example of optimization for a hollow fiber and flat sheet MBR. The flow rate was 20,000 m^3/d. The COD and TKN were 350 mg/L and 35 mg/L, respectively. The MBR was run at a mixed liquor temperature of 12 C.

Examples of Design and Operations Optimization

Hollow Fiber Parameters

The following parameters were used to set up the hollow fiber membrane system. During the design process, one should get the actual values from each supplier.

Air scour rate = 0.0075 m^3 air / m^2 membrane surface / min during the on time (= 0.45 m^3 air/m^2 membrane surface / h = 10.8 m^3 air/m^2 membrane surface/d) – Figure 7. *This condition has to be satisfied during the on time fraction of the cycle.*

Flux rates - 20 lmh (12 gfd) at normal flow; 30 lmh at peak diurnal, 40 lmh at peak day.

lmh = liters of liquid drawn through membrane / m2 membrane surface area / day

gfd – gallons of liquid drawn through membrane / ft2 membrane surface area /day

Wet weather peak day flow allowed as a multiple of average day flow = 2.

Allowable reduction in air scour rate during wet weather peak day flow – typically 0%.

As part of design optimization, one should determine if the air scour rate can be temporarily decreased during the wet weather peak day flow. This number will come into play if the membrane surface area is determined by the wet weather peak day flow. For example, if the wet weather peak day flow is 2.2 x average daily flow and the wet weather flux through the membrane is 2 x average flux allowed (40 lmh as compared to 20 lmh), then the membrane surface area required to handle peak day wet weather flow is 10% higher than the flux required for the average flow. The blower size for air scour will be determined by the wet weather peak day flow unless one can temporarily reduce the air scour rate by 10% during the peak day.

Specific surface area (SSA) of membranes at 100% fill in membrane tank = 130 m^2/m^3

Liquid volume displaced in membrane cell at 100% fill = 33%

Percent fill = percent of membrane cell volume occupied by the membrane modules = 40%.

SSA and liquid volume displaced will depend on the supplier of the membrane.

The liquid volume displaced at 100% fill is the volume of mixed liquor displaced if the membrane cell had was filled to a theoretical maximum of 100%.

Actual fraction of mixed liquor volume displaced in the membrane cell = (fill volume fraction) x (liquid volume fraction displaced at 100% fill) = (0.4) (0.33) = 0.133

DO in aerobic zone prior to optimization = 3.0 mg/L.

DO in the membrane cell when aerated continuously prior to optimization = 9.9 mg/L.

This is DO level that equates to an air scour rate that just satisfies the threshold.

At a mixed liquor temperature of 12 C, this mode of operation resulted in power consumption of 558 KW for aeration and air scour.

Hollow Fiber Optimization

As per the observations at Redlands, CA, one can reduce the DO in the aerobic cells. For this optimization, we reduce the DO to 1 mg/L at 12 C and at a 20 day MCRT.

As per the operating mode implemented at Traverse City, MI and Ulu Pandan, Singapore, we will reduce the air scour on-time fraction from 1.0 to 0.25. Typical schedule on GE-Zenon membranes is 10 sec on and 30 sec off, resulting in a 0.25 on-time fraction.

In AquaNET Aquifas, the air flow to the membrane cell is calculated based on the DO level specified for the membrane cell. The air flow is checked against the air scour threshold specified at the beginning of the example.

The DO in the membrane cell could be reduced from 9.9 to 5.5 mg/L (Table 4, Figure 8). At this DO, the flow to the MBR cell was 4.6% above the threshold for air scour (Table 3). The effluent COD, ammonium-N and oxidized-N were satisfactory (Table 3, Figures 9 and 10).

The nitrate recycle was eliminated. It was not necessary with a MBR recycle of 3 to 4Q.

The DO level in the membrane cell that satisfies the air scour is a function of load of unassimilated COD and NH_4N entering the MBR cell. Lowering the MCRT increases the concentrations entering the MBR cell. Raising the MCRT will reduce the concentrations and decrease the MBR cell DO up to a point until the change in concentrations is very small. After this, the increase in MLVSS will increase the endogenous oxygen demand and keep the operating DO fairly constant. For this example, the hollow fiber system was run at a 20 day MCRT. One could run this system at a higher MCRT, such as 30 days, at which the MLSS would increase from 5500 to 8500 mg/L.

<u>Validation of Optimization against Results at Ulu Pandan, Singapore</u>

The reduction in the aerobic cell DO and on-time fraction for air scour reduced the aeration and air scour energy requirements from 560 KW to around 280 KW (Figures 8 and 11, Table 3). The equated to an energy requirement was 0.36 KWH/m^3 flow. This number was compared against the results observed at Ulu Pandan, Singapore (Guihe *et al*., 2008). The total power consumption for the same optimization routine implemented at Ulu Pandan was 0.38 KWH/m3.

Ulu-Pandan was operated at 23,000 m^3/d operated at 292 mg/L COD and 48 mg/L TKN. The total MBR plant energy required was 0.57 KWH/m^3. Of this, 67% of the energy was for aeration and air scour. This equates to 0.67 x 0.57 = 0.38 KWH/m^3. When the model was run for the same wastewater strength as observed at Ulu Pandan, the optimum value predicted is 0.35 KWH/m^3. This value is 8% lower than the observation made in 2008 at Ulu Pandan. However, Guihe et al. (2008) mentioned that they expect that they would be able to get down to a value to 0.30 KWH/m^3 in the future. This is consistent with predictions from the model when the aerobic zone DO is reduced below 1 mg/L at higher temperatures.

<u>Comparison to a Benchmark Conventional Activated Sludge System</u>

A conventional activated sludge (CAS) system was run with the model at a 20 day MCRT and 12,600 m^3 tank volume (15 hour HRT). It was operated for the same flows and loads and optimized to run at a DO of 2.5 mg/L at 12 C. The power required for aeration was 240 KW. This shows that the when optimized, the energy consumption for the hollow fiber MBR was approximately 20% higher than the CAS system.

Flat sheet Parameters

Membrane modules with flat sheet membranes have a lower specific surface area compared to mudules with hollow fiber membranes. The SSA of a flat sheet module may be 45 to 67 m^2/m^3, as compared to 130 m^2/m^3 for a hollow fiber.

> Reference: Kubota RW 400 membrane module has a surface area of 580 m^2 surface area in a module that is 4.29 m high x 0.65 m wide x 3.1 m long . SSA = 67 m2/ m3. (Kubota, 2010)
>
> Kubota ES 200 module has 160 m2 of surface area in a module that is 2.03 m high x 0.62 m wide x 2.92 m long. SSA = 43.5 m2/m3.

One could use two different strategies to optimize the design and operation of flat sheet MBRs. The first strategy is to reduce the total system volume and sacrifice a little on the energy optimization. The second strategy is to reduce the system wide energy but operate with a slightly higher volume. The following example discusses the first strategy.

In implementing the first strategy, the volume of the aerobic zone upstream of the MBR may be reduced such that it is substantially smaller aerobic cell compared to the hollow fiber. The aerobic volume is only 1050 m^3, as compared to 3570 m^3 for hollow fiber (Figure 9). The aerobic cell is designed to reduce the biodegradable and particulate COD concentration entering the MBR cell downstream but not nitrify all of the ammonium-N. This helps limit the risk of plugging up the membrane with particulate material. The higher volume of the MBR cell relative to the hollow fiber application (3000 m^3 as compared to 1240 m^3) insures that the MBR cell will be able to nitrify the ammonia entering the cell. The higher volume is required to accommodate the surface area of membranes with modules that have a lower SSA compared to hollow fiber.

The following parameters were used to set up the flat sheet membrane system. During the design process, one should get the actual values from each supplier.

Air scour rate = 0.0075 m^3 air / m^2 membrane surface / min.

Allowable reduction in air scour during wet weather peak day flow – simulated at 0%.

Minimum Air Scour on time fraction during normal weather = 1.

Minimum Air Scour on time fraction during wet weather = 1.

Wet weather peak day flow allowed as a multiple of average day flow = 2.

Specific surface area of membranes at 100% fill = 67 m^2/m^3 for flat sheet

Percent of liquid volume displaced in membrane cell at 100% fill = 50%

Percent of membrane cell tank volume occupied by the membrane modules = 33%

Flux rates - 24 lmh (14 gfd) at normal flow; 36 lmh at peak diurnal, 48 lmh at peak day at 12 C.

The SSA, liquid volume displaced and flux rates have to be verified with the supplier.

DO in aerobic zone = 1.5 mg/L. DO at 12 C in the membrane cell = 7.8 mg/L at a time averaged air scour rate of 0.0075 m^3/m^2/min.

At a mixed liquor temperature of 12 C, this mode of operation resulted in power consumption of 700 KW for aeration and air scour (Figure 8).

Flat Sheet Optimization

The flat sheet MBR was optimized to operate with a DO of 1 mg/L in the aerobic cell and a DO of 2.5 mg/L in the membrane cell at 12 C.

Air scour was flow and load paced. The air scour rate, averaged over a 24 hour period, was 0.0032 m^3/m^2/min (Table 4). This value is close to values used in certain Kubota systems.

Table 4. Aeration Pattern for a Flat Sheet – Rate of Air Scour and Percent of Time

	Max Rate 0.0075		
	m3/m2/min		
Fraction of Max Rate	Actual Rate m3/m2/min	Percent of time of day	Time Weighted m3/m2/min
20%	0.0015	20%	0.0003
30%	0.00225	50%	0.001125
50%	0.00375	10%	0.000375
80%	0.006	10%	0.0006
100%	0.0075	10%	0.00075
Average		100%	0.00315

The nitrate recycle was eliminated as part of the optimization. The configuration was run at MCRT of 30 days and at a MLSS above 8000 mg/L to reduce the total volume. As mentioned earlier, the MCRT and MLSS are higher than those used for the hollow fiber run.

The power requirement for aeration and air scour was 373 KW (Table 3 and Figure 8). This equated to an energy consumption of 0.44 KWH/m^3 of flow treated. The value was compared to the best value reported Livingston (2008) for flat sheet MBRs. The best value for 1.5 MGD MBRs was 0.66 KWH/m^3. Of this value, 67% was for aeration and air scour. This would then equate to 0.45 KWH/m3, which is consistent with the model's prediction.

The power requirement for the flat sheet configuration was 90 KW higher than the hollow fiber configuration. This was because the:

1. Time averaged air scour of 0.0032 m^3/m^2/min was higher than the time averaged air scour rate of 0.0018 m^3/m^2/min for the hollow fiber. The value for hollow fiber is 0.25 x 0.0075 m^3/m^2/min, based on a 25% on-time fraction.

2. MCRT of 30 days was higher than 20 days used for the hollow fiber. This generates less sludge and increases oxygen demand. The higher MCRT is required with a smaller aerobic zone volume upstream of the MBR cell.

3. Value for alpha decreased at the higher operating MLSS of 10000 mg/L in the MBR cell, as compared to of 7200 mg/L for the hollow fiber (Figure 9).

Approximately 50 KW of the difference of 90 KW was because of the difference in time averaged threshold for the air scour. If, in the future, the flat sheet membranes can be operated at lower air scour, the difference in energy requirements will be smaller (Figure 11).

The configuration of cells for the flat sheet (Figure 9) was optimized for total volume. The volume for the flat sheet system for treating 20,000 m^3/d of flow was 6150 m^3 (inclusive of the MBR volume), as compared to 6910 m^3 for the hollow fiber. The small aerobic zone upstream of MBR limited the ability to lower the MCRT because this would increase the particulate material, ammonia and soluble biodegradable COD ($SCOD_{bio}$) entering the membrane cell. Increasing the aerobic volume and reducing the MLSS to increase the alpha would reduce the energy requirement by lowering the alpha. When the aerobic zone volume was increased from 1050 to 2100 m^3, and the time averaged threshold was reduced to 0.001875 m^3/m^2/min, which is the equivalent to the hollow fiber operated with 0.25 on-time fraction, the power consumption decreased to 301 KW (Table 3, bottom and Figure 11).

Additional Opportunities for Optimization

The simulator can be used to evaluate how best to manage the wet weather flows and reducing the membranes that have to be put in service during wet weather. This includes active management of the membrane recycle rate (reducing it from 4Q, which is recommended as a default in the US, to a lower rate, such as 2Q, as used at Singapore). This can be done if the operator uses the simulator to manage the MCRT, and where possible, reduce MCRT to reduce the MLSS, as long as the simulator indicates that the ammonia and soluble BOD going to the membrane module will not increase above certain thresholds.

A separate paper (Sen et al., 2010) discusses the effect of biofilm growth on membranes. There is a thin biofilm layer that develops on flat sheet membranes when a relatively small aerobic volume is used upstream of the MBR cell. It is possible that biofilm support media installed in the aerobic zone of a MBR can help reduce the operating MLSS. The reduction in MLSS can help improve the alpha and reduce the energy. The savings in energy can offset part of the cost of the media.

CONCLUSIONS

1. An operations simulator was developed for MBRs to help operators optimize their plant to simultaneously improve effluent quality, reduce energy consumption and reduce chemical costs.

2. The simulator has separate interfaces for the designer and operator.

3. The simulator is able to predict to within 95%, the actual energy savings observed in full scale plants, while predicting the effluent quality.

4. The simulator can help MBR operators reduce energy requirements by as much as 50%.

5. The simulator can help MBR operators operate their systems at energy levels similar to typical conventional activated sludge (CAS) systems and at 20% above the energy levels required in CAS systems that are also optimized for energy.

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Table 3. Summary of Results from AquaNET Aquifas following Optimization

Hollow Fiber at 20 day MCRT

47	Part III: Feedback	MLSS		SCODbio	NH4N	NO3N	OP	VAS VSS	VAS TSS	AOR	Blower/SA	Chem P	Suppl Alk	Chem P	Supp Alk
48		mg/L	% VSS	mg/L	mg/L	mg/L	mg/L	kg/d	kg/d	kg/d	KW	kg/d	mg/L	Dose	Dose
49	Results OK	5456	69%	1.95	0.25	4.17	0.50	1312	1903	5465	281	58.89	0.00	Increase	OK
51	Cell Number	1	2	3	4	5	6	7	8	9	10	11	12		
52	Cell Type	Anoxic	Anoxic	Aerobic	Aerobic	Aerobic	embrane C	Offline	Offline	Offline	Offline	Offline	Offline		
53	DO Computed, mg/L	0.05	0.05	1.00	1.00	1.00	4.50	4.50	4.50	4.50	4.50	4.50	4.50		
54	Membrane Cell	Air scour, mm/sec		13.62	-14.8%	% above threshold			Air Scour,m3/m2/min	0.00784791	4.6%	%above threshold (primary criterion)			
55		Is Footprint sufficient		Yes			Aeration+Air Scour	281	KW	Footprint required, m2		258		Membrane	41667
56		Is Air Scour sufficient		Yes			Air Scour	94	KW	Footprint provided, m2		400		Surf Area, m2	
57															

Converge / Res Interface / Res Summary / Results / Res SState Graphs / Res Dyn Graphs / Res Inf Char / o Clarifier Config / o Membrane

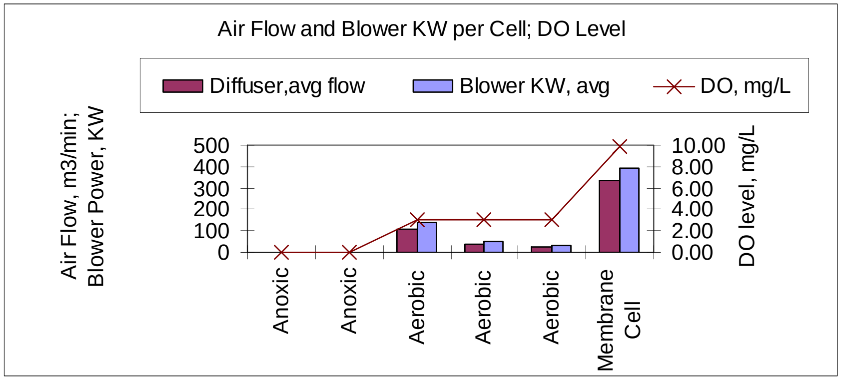
Flat Sheet at 30 day MCRT

47	Part III: Feedback	MLSS		SCODbio	NH4N	NO3N	OP	VAS VSS	VAS TSS	AOR	Blower/SA	Chem P	Suppl Alk	Chem P	Supp Alk
48		mg/L	% VSS	mg/L	mg/L	mg/L	mg/L	kg/d	kg/d	kg/d	KW	kg/d	mg/L	Dose	Dose
49	Results OK	8552	67%	1.82	0.27	4.35	0.50	1065	1586	6071	373	62.65	0.00	Increase	OK
51	Cell Number	1	2	3	4	5	6	7	8	9	10	11	12		
52	Cell Type	Anoxic	Anoxic	Aerobic	lembrane C	Offline	Offline	Offline	Offline	Offline	Offline	Offline	Offline		
53	DO Computed, mg/L	0.05	0.05	1.00	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50		
54	Membrane Cell	Air scour, mm/sec		3.48	-80.7%	% above threshold			Air Scour,m3/m2/min	0.00320272	1.7%	%above threshold (primary criterion)			
55		Is Footprint sufficient		Yes			Aeration+Air Scour	373	KW	Footprint required, m2		355		Membrane	39063
56		Is Air Scour sufficient		Yes			Air Scour	233	KW	Footprint provided, m2		600		Surf Area, m2	

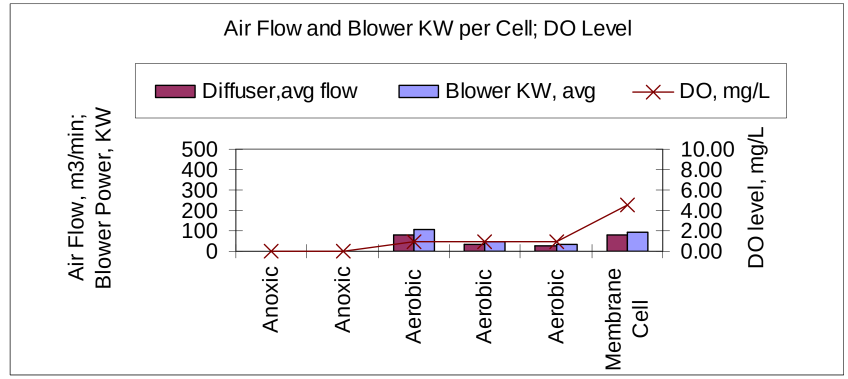
Flat Sheet at 30 day MCRT, Alternate configuration and with lower air scour threshold and larger aerobic volume upstream of MBR

47	Part III: Feedback	MLSS		SCODbio	NH4N	NO3N	OP	VAS VSS	VAS TSS	AOR	Blower/SA	Chem P	Suppl Alk	Chem P	Supp Alk
48		mg/L	% VSS	mg/L	mg/L	mg/L	mg/L	kg/d	kg/d	kg/d	KW	kg/d	mg/L	Dose	Dose
49	Results OK	7345	65%	1.87	0.26	4.06	0.50	1043	1594	6179	301	62.99	0.00	Increase	OK
51	Cell Number	1	2	3	4	5	6	7	8	9	10	11	12		
52	Cell Type	Anoxic	Anoxic	Aerobic	lembrane C	Offline	Offline	Offline	Offline	Offline	Offline	Offline	Offline		
53	DO Computed, mg/L	0.05	0.05	1.00	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25		
54	Membrane Cell	Air scour, mm/sec		2.03	-88.7%	% above threshold			Air Scour,m3/m2/min	0.00187479	0.0%	%above threshold (primary criterion)			
55		Is Footprint sufficient		Yes			Aeration+Air Scour	301	KW	Footprint required, m2		355		Membrane	39063
56		Is Air Scour sufficient		NO			Air Scour	136	KW	Footprint provided, m2		600		Surf Area, m2	

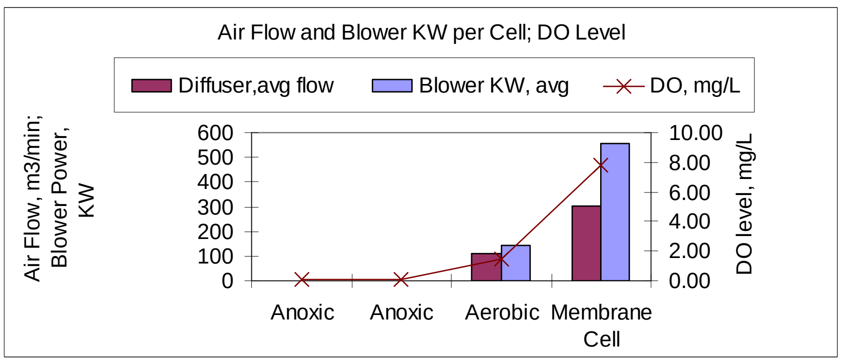
Hollow fiber before optimization – 558 KW



Hollow fiber after optimization – 281 KW



Flat sheet before optimization – 700 KW



Flat sheet after optimization – 373 KW

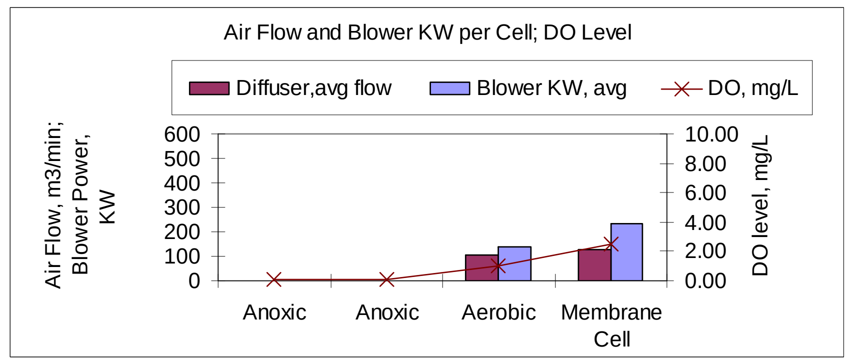


Figure 8. Hollow fiber and flat sheet MBRs before and after optimization (20,000 m3/d of flow at 350 mg/L COD, 35 mg/L TKN)

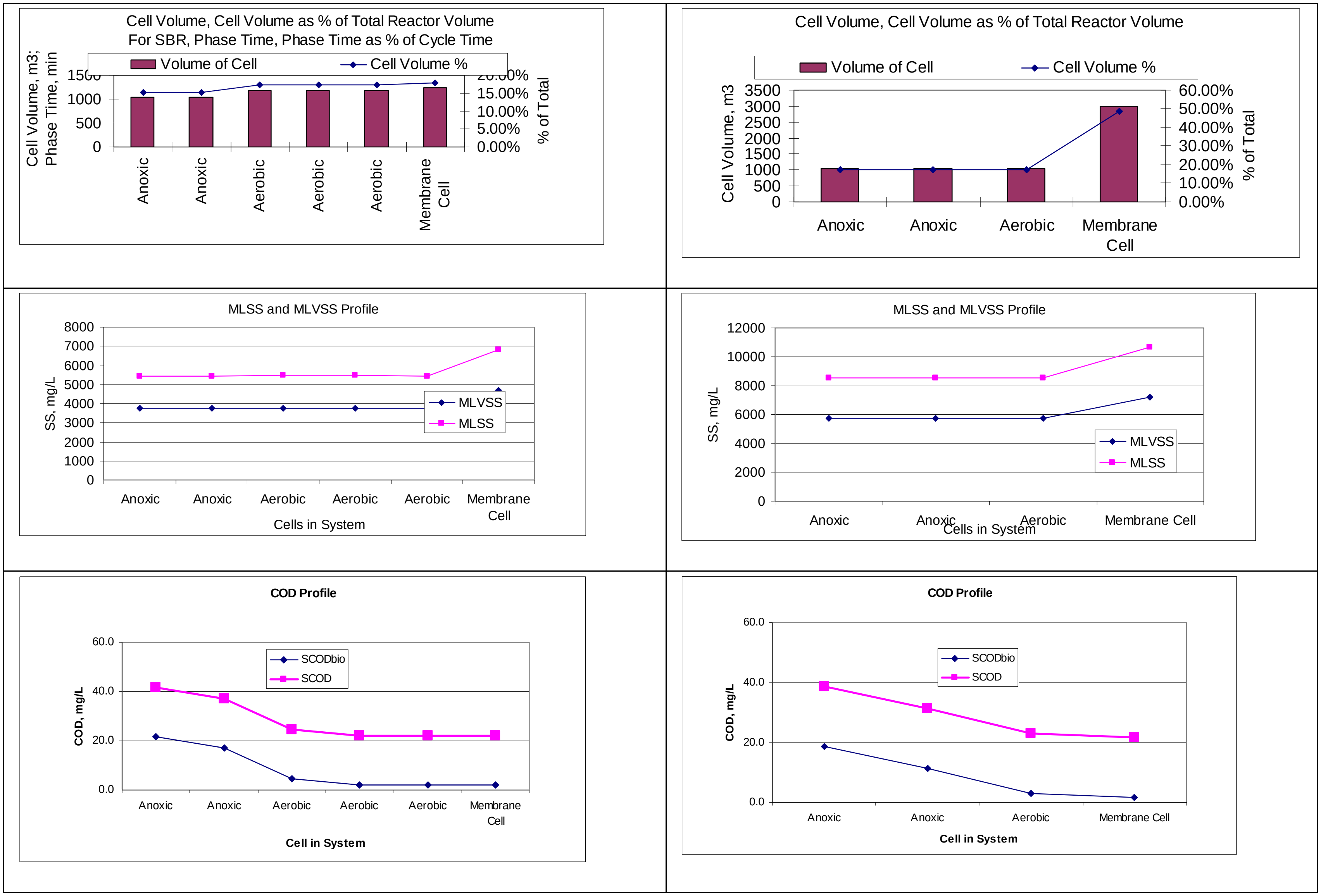


Figure 9. Volume, MLSS, MLVSS and COD profiles for Hollow Fiber (left) and Flat Sheet (right) after optimization

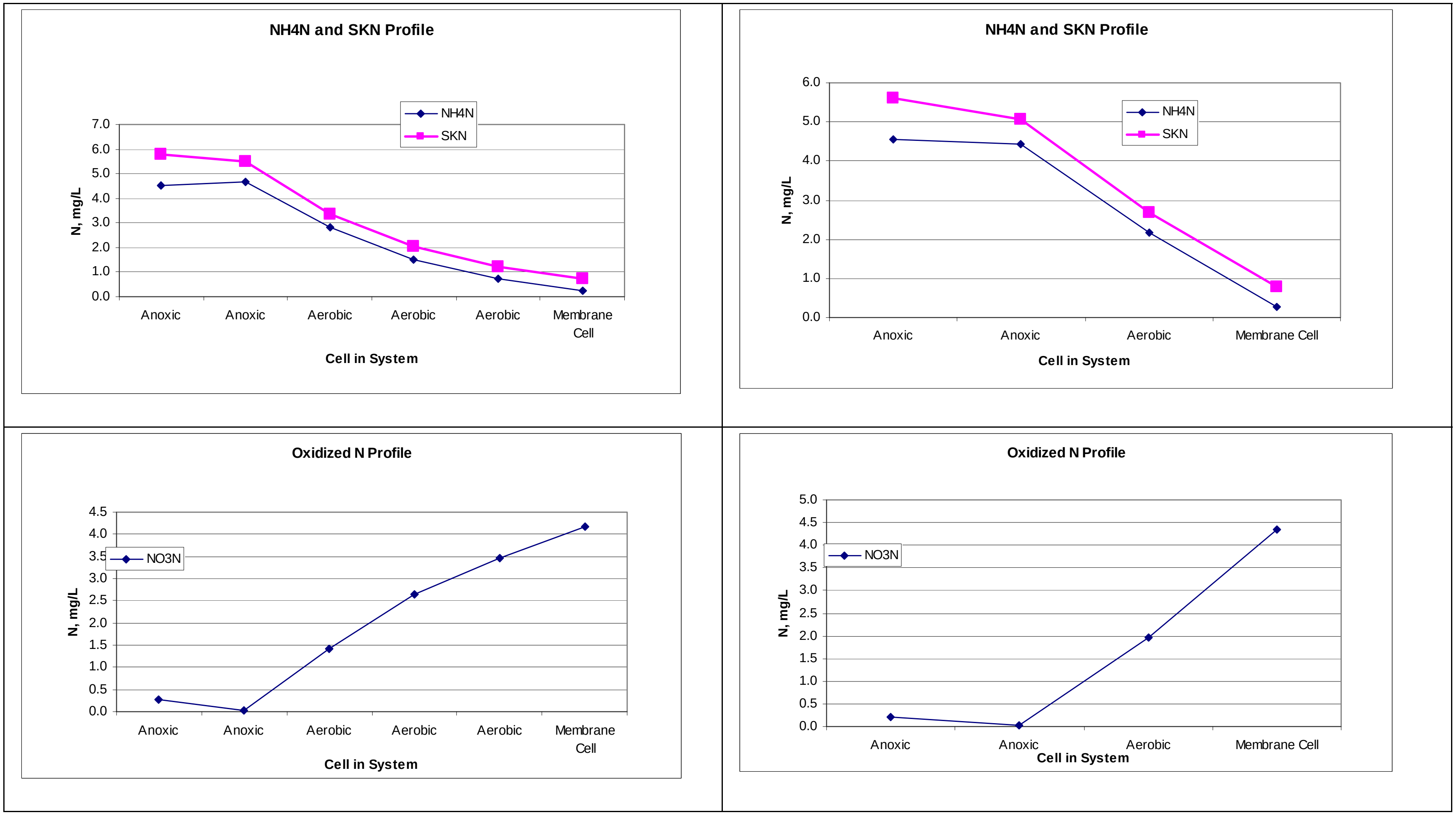


Figure 10. Ammonium-N and Oxidized N Profiles, Hollow Fiber (left) and Flat Sheet (right) after optimization

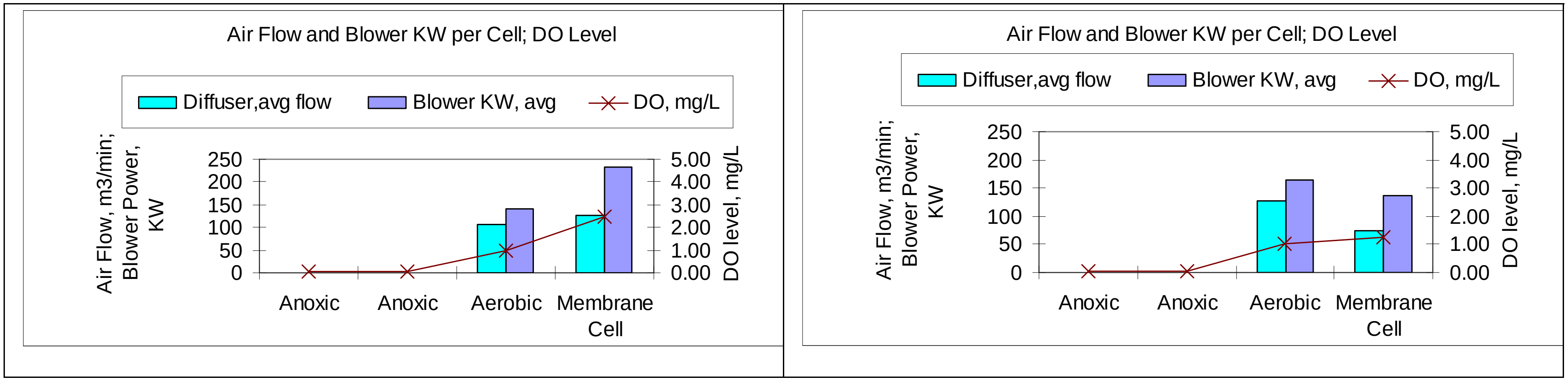


Figure 11. Diffuser air flow, Blower KW and DO for Flat Sheet in Current Configuration (373 KW) and Future Configuration optimized for power consumption (301 KW).