Aeration System Design for Energy Savings

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ABSTRACT

With the recent increases with energy cost and the requirements of Biological Nutrient Removal (BNR), the design and control of an aeration systems has become one of the most important parts of the design of the activated sludge process. A well designed aeration system can save significant amounts of energy and provide a stable BNR effluent by meeting the required dissolved oxygen set points at the lowest possible pressure. A poorly designed aeration system will bleed oxygen into the anoxic zones, lowering the potential denitrification capacity of the plant, and will waste power. The goal of the paper will be to describe the process of designing an aeration system and to present a case study of an advanced aeration control system based upon variable oxygen uptake rate.

KEYWORDS

Aeration control, process optimization, nutrient removal, model based control, set point control, dissolved oxygen (DO) control.

INTRODUCTION

With the recent and future increases of cost for energy, operating a wastewater treatment plant (WWTP) as efficiently as possible has become one most important factors that operators and managers are facing today. The implementation of a properly designed aeration control system has been shown to reduce aeration energy by 25 to 40 percent (EPA 1989).

An aeration system can be broken into three separate parts: airflow generation, airflow distribution, and aeration control. Aeration generation consists of aeration blowers. Airflow distribution consists of air piping, air control valves, and diffusers. Aeration control consists of blower control, air flow calculations, airflow meters, and dissolved oxygen meters. A good aeration system will need all three parts to work well together. If one aspect of design is lacking, the other two aspects will be affected and will likely cause the DO set point to be missed, the permit to be violated and energy to be wasted.

METHODOLOGY

The following sequence of calculations and design decisions can be used to provide a cost effective energy efficient aeration system.

Process Oxygen Requirements

The first step of designing an aeration system is calculation of oxygen transfer requirements (OTR). The amount of oxygen required is dynamic, and will vary by time and location within the aeration basin. Oxygen demand is dynamic because the influent loading is diurnal as shown in Figure 1, and the biological reaction changes along the basin length as shown in Figure 2.

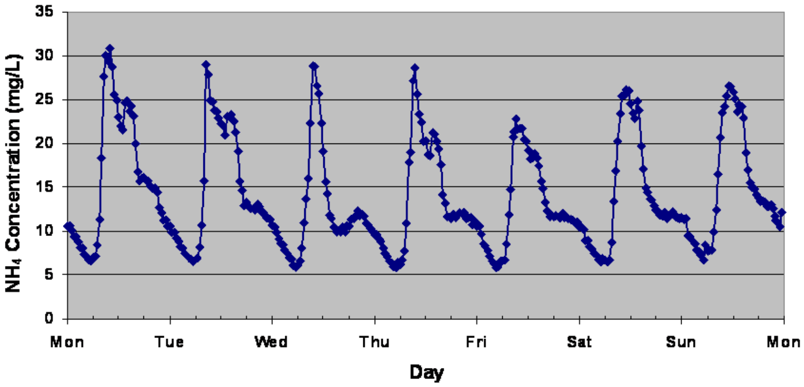


Figure 1: Seven days of influent ammonia readings

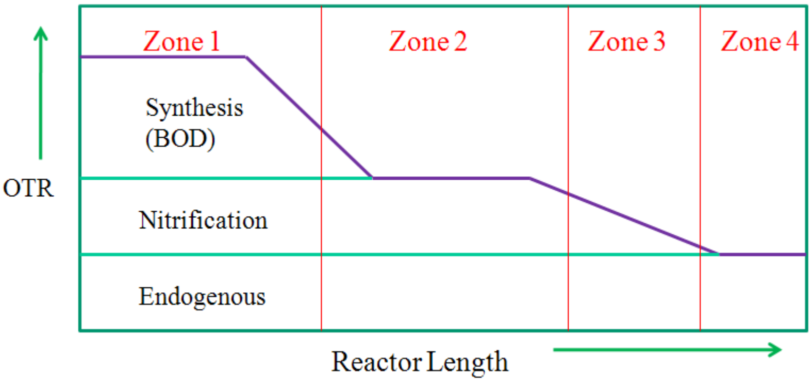


Figure 2: Biological reactions along the length of the aeration basin

The calculation of OTR can be done by hand or spreadsheet for steady-state assumptions, but commercial activated model simulation software packages such as GPS-X by Hydromantis, Hamilton, Ontario or Biowin by Envirosim, Hamilton, Ontario that can calculate the OTR dynamical, will provide values closer to reality. As with all activated sludge simulations, the better the influent data the better the results. Influent diurnal loading data of BOD, TKN and TSS is recommended, if possible. . The results from the simulation will provide the complete range of OTR needed to calculate airflow requirements as shown in Figure 3.

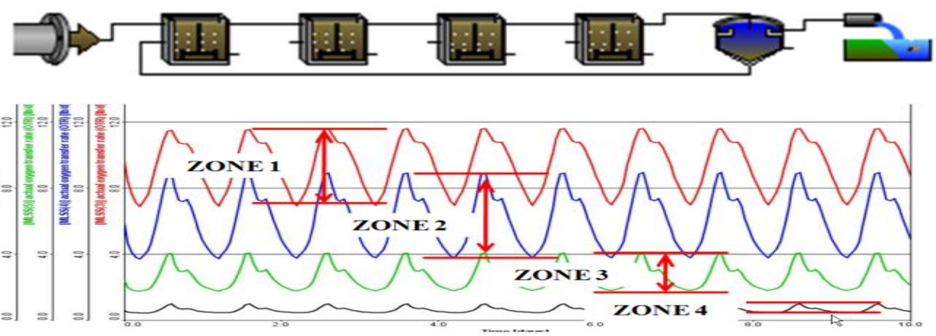


Figure 3: Biological reactions along the length of the aeration basin

Air Flow Calculation

Calculation of airflow is the next step after calculation of the process oxygen requirement. The amount of airflow required to achieve oxygen transfer requirement is dependent upon the diffuser selection and layout. Therefore, the calculation of airflow can only be completed after diffuser design is complete.

There are two common types of diffusers available on the market, fine-pore and coarse bubble. Fine-pore has become the design standard for activated sludge process because of the higher standard oxygen transfer efficiency (SOTE) compared to coarse bubble. SOTE is the percentage of the airflow's oxygen that is transferred into the clean water at standard conditions. Fine-pore diffusers provide higher oxygen transfer because a larger volume of smaller diameter bubbles are created by the diffuser, thereby increasing the surface area of gas transfer.

The SOTE is not only influenced by the diffuser type, but also the depth of the diffusers and the airflow per diffuser ratio. All SOTE values are based on testing performed at the diffuser manufacturer's facility with clean water at standard conditions. A conversion from SOTE into field oxygen transfer efficiency (OTE) that takes into account of the influence of the activated sludge on gas transfer is necessary. Equation 1 from the Fine Pore Aeration Systems Design Manual (EPA, 1989) calculates the ratio of (OTE/SOTE) that is seen in the field and is used to calculate the required airflow needed to meet the OTR.

$$\frac{OTE}{AOTR} = \alpha F \cdot \theta^{(T-20)} \left(\frac{\tau \cdot \beta \cdot \Omega \cdot C^{*}_{\infty 20} - C}{C^{*}_{\infty 20}} \right)$$

Equation (1):

α : Process water mass transfer ÷ Clean water mass transfer
F : Fouling factor
T : process water temperature, C
$\theta^{(T-20)}$: Mass transfer at T ÷ Mass transfer at 20C
β : process water DO saturation ÷ clean water DO saturation
Ω : field atmospheric pressure ÷ standard atmospheric pressure
C : Process water DO concentration
$C^{*}_{\infty 20}$: Steady-state DO saturation at 20C and 1 atm

The design of the activated sludge process affects the overall efficiency so layout of the diffusers needs to take account of this to ensure the design conditions are meet in a energy efficient way.

Hydraulic Design: The aeration tank reactor type, complete mix or plug flow, has different effects on the OTE. The plug flow reactor will have a higher concentration of pollutants in the beginning of the process that decreases the alpha value and increases the potential for fouling. As the concentration of pollutants decreases along the length of the reactor, the alpha values will increase and the potential fouling will decrease. Complete mix reactors have a uniform alpha value and fouling within the tank. A complete mix tank uses more air compared to a plug flow tank meeting the same effluent quality because the volume of the complete mix tank must be larger.

Processes Selection: Low Food/Biomass Ratio (F/M Ratio) or high solids retention time (SRT)processes tends to have a higher alpha value compared to high F/M ratio or low SRT processes.(EPA, 1989)

Diffuser Layout: After choosing the the alpha for each aeration zone, the airflow calculation can be performed. The amount of diffusers required per zone can be calculated using an airflow to diffuser ratio at a specific design scenario (i.e. max month). Then the ratio is checked against other scenarios to make sure it is within the the design guides of the diffusers type. During most designs the turndown may be adequate, but for a facility that may be starting at a low flow condition, additional diffusers may need to be added later for future flow capacity. The airflow per diffuser ratio and diffuser density may change the SOTE, so the calculation should be re-analyzed after completion of the diffuser layout.

If possible, it is recommended that a calibrated dynamic activated sludge model is used to calculate the airflows using the diffuser transfer efficiency parameters and layout. The results from the simulation will provide the complete range of airflows needed for analysis. Airflow can be analyzed by creating a histogram of the data, and calculating maximum and minimum month and day values at current loadings and design loadings. Figure 4 is an example of a histogram chart of airflow at a biological nutrient removal facility. The histogram was able to locate potential data outliers, and show the complete airflow range required for the aeration system piping, control valves and blowers.

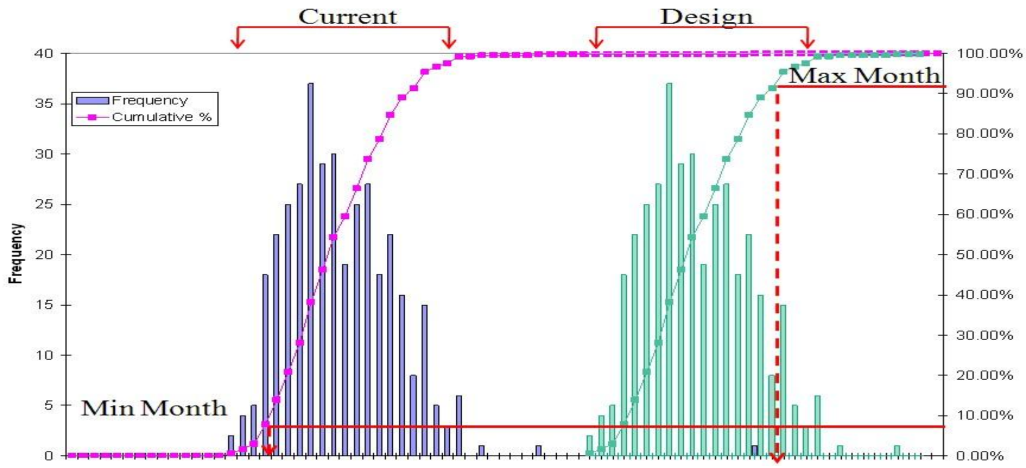
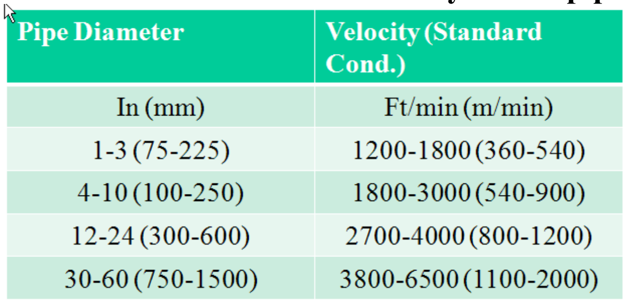


Figure 4: Airflow Histogram

Process Piping

The sizing of the piping system is the next step after the airflow range has been determined. If the pipes are too big, the aeration system may be difficult to control. Likewise if the pipes are too small, the the potential headloss may require larger horsepower blowers. Table 1 is from the Wastewater engineering: treatment and reuse book by (Tchobanoglous, 2003). Table 1 provides recommended pipe size based upon the estimated standard velocity within the pipe.

Table 1: Standard airflow velocity within pipe diameters (Tchobanoglous, 2003).



Pipe Diameter	Velocity (Standard Cond.)
In (mm)	Ft/min (m/min)
1-3 (75-225)	1200-1800 (360-540)
4-10 (100-250)	1800-3000 (540-900)
12-24 (300-600)	2700-4000 (800-1200)
30-60 (750-1500)	3800-6500 (1100-2000)

Calculating the pressure drop within the aeration piping system can be accomplished using a spreadsheet using the Darcy-Weisbach method (EPA, 1989). For more complex aeration systems with several control zones, it is recommended that a piping design software be used, such as Flow of Fluids by Engineered Software Inc., Lacey, WA. The software has an easy user interface and can be used to size the control valves as well, and can be used for both airflow and water piping systems. Figure 5 is an example of a piping layout of an aeration system.

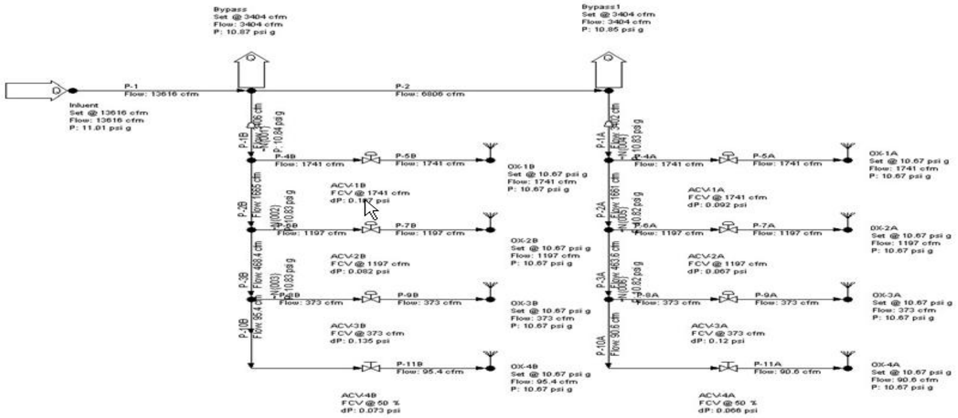


Figure 5: Piping layout of an aeration system

Blower Selection and Sizing

The selection and sizing of the blower system is the next step to be accomplished. The total airflow and pressure requirements were calculated during the sizing of the piping, control valves and diffusers. Blower power is directly related to airflow so it is essential for the blowers to supply the required airflow range during both current and future loadings. To meet the broad range of of airflow requirements, adequate blower turndown is needed. Turndown can be accomplished by installing multiple blowers with turndown capabilities. All blowers have limited turndown, some better than others. Blower turndown depends upon how the turndown is accomplished (i.e. VFD, inlet valves). The use of the airflow histogram can help determine the number of blowers and the required turndown. A blower range overlaid on the airflow histogram is shown below in Figure 6. It is important to note that there is a required airflow operation overlap between blowers to allow easy transition between blowers turning on and off.

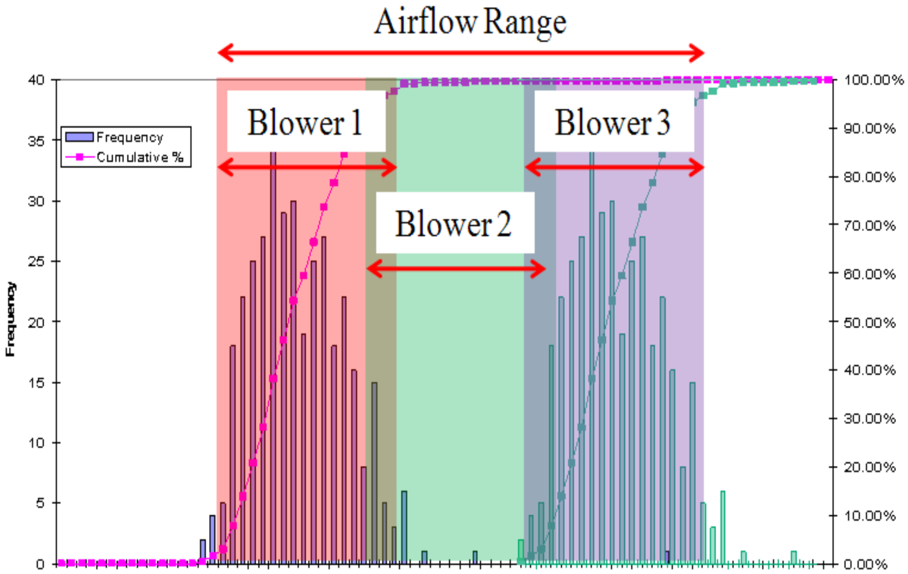


Figure 6: Airflow histogram with blower range

Aeration Control System

Excessive and inadequate aeration can lead to operational problems for the treatment process efficiency and settling. Inadequate aeration during high loading can lead to ineffective treatment of ammonia, and increased SVI due to low DO sludge bulk. Excessive aeration can also lead to higher SVI because of floc breakup. Process control is the only practical way a well designed activated sludge system can effectively be manipulated to meet treatment goals, satisfy oxygen demand, minimize operational problems associated with inadequate or excessive aeration, and minimize aeration energy consumption. The incorporation of an effective advanced process control system for activated sludge process can result in energy savings in the range of 25 to 40 % (EPA, 1989).

The successful application of an aeration control system is dependent upon a successful operation of control system components. Control system components must be correctly sized and installed to insure successful operation. Each aeration control zone should have the following equipment and control components:

Equipment Components

Air Control Valves: The valves need to be sized to operate between 30 to 70% open. Below or above that range, the control valves become difficult to control. The valves should also be installed downstream of the air flow meters to minimize airflow disturbances.

Air Flow Meters: There are several different types of airflow meters in the market (I.e. mass flow rate, orifice plates, etc.) Each work well when installed correctly. All airflow meters require a minimum setback distance upstream and downstream of the airflow meter to allow accurate readings. Review and apply the manufacturer’s airflow meter installation guidelines.

DO Meters: The optical-based DO meters have become the standard at municipal WWTPs in recent years due to reliable readings and limited maintenance required or the device. The DO meters should be installed half way to two-thirds of the way down the length of the aeration control basin.

Control Components

Air Flow Calculation: The airflow calculation is the amount of air change required to bring the DO reading back to DO set-point. There are two methods used for calculating the airflow: Proportional-Integral (PI) control and Deterministic algorithm:

PI Control: Is a common feedback controller widely used in industrial control systems. The controller uses the proportional and integral values, and the difference between the DO set point and reading to calculate air flow change. PI controllers are meant for linear-type systems. When PI control is used as aeration control, which is nonlinear, the controller needs to be detuned for stability purposes.

Deterministic algorithm: Is a feedback control approach for calculating the required air flow change based upon a model of the aeration system.

Blower Control: The blower control manipulates the blower speed or inlet valves to supply the amount of airflow required to meet the DO set-points. The blower control can use pressure or total air flow to control the blower air flow change.

Poinciana WWTP No 2 Aeration System

The methodology mentioned above for designing an aeration system was used at Poinciana WWTP No. 2 (Poinciana) located in Kissimmee, FL. The WWTP has been operational since May of 2010. The Poinciana project converted the plant to a 22,700 m^3/d (6 mgd) rated modified ludzack ettinger process from the existing 11,350 m^3/d (3 mgd) rated sequencing batch reactor process. . The project required a complete new aeration system including blowers, diffusers, and control equipment.

During the design process, GPS-X was used to simulate the required OTR needed for the design using historical influent data and supplemental diurnal sampling. The OTR data and minimum required alpha and SOTE were forwarded to the diffuser manufacturer to optimize diffuser layout design.

After the diffuser design was complete, GPS-X simulation was modified with the diffuser information and calculated the range of airflow required to meet the oxygen demands.

At Poinciana three types of blowers were analyzed, Tri-lobe positive displacement, multi-stage centrifugal, and high speed direct drive turbo. The tri-lobe positive displacement blowers with VFD for speed control was selected based upon a 10 year present value cost analysis and the ability of turndown,. The final design allowed provisions for the installation of five additional blowers. The blowers have a turndown of 60 to 70% with VFD control, which allowed great operational flexibility.

The aeration control system consisted of four control zones in each train, with each control zone having an air control valve, air flow meter, and DO Meter. The aeration system equipment is controlled by the Bioprocess Aeration Control System (BACS).

BACS Description

The aeration control system uses airflow, temperature, DO measurements, and oxygen saturation to calculate an oxygen uptake rate factor (OURf) in each zone. The OURf can be used to trend the actual OUR within the aeration control zone. An example of how well the OURf trends the actual OUR is shown below in Figure 7, which is a GPS-X simulation of an activated sludge process actual OUR and OURf in the first aeration zone.

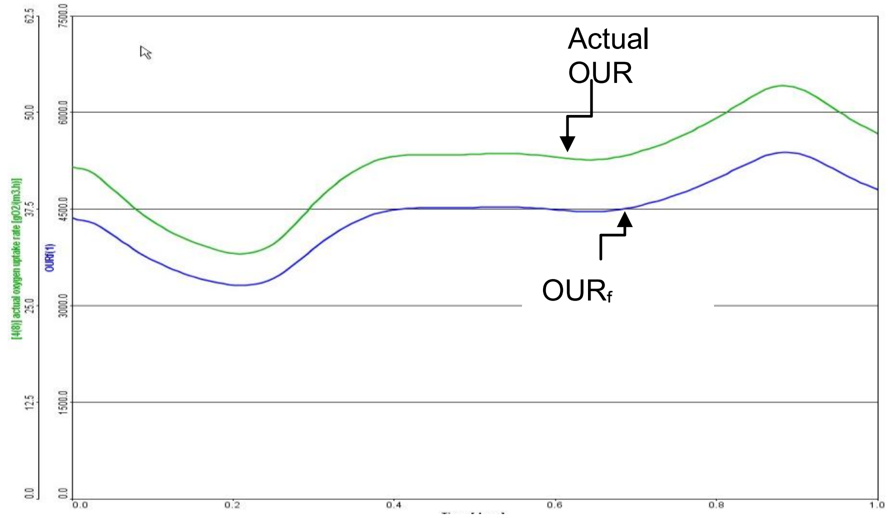


Figure 7: OURf versus Simulated OUR

Airflow Calculation
The calculation of the airflow set point is based upon the weighted average of two techniques of calculating the required airflow to meet the DO set point. The first technique is considered predictive feedback control which uses two methods of using the OURf to calculate the airflow set point. The second technique is a feed forward method that uses ammonium measurements to calculate the change in OUR based upon loading.

Technique 1: Predictive Feedback Control

Method 1: It is assumed that the loading does not change from control time steps T0 to T1, and the change in OUR is due to the required change in DO to match the set point. The concept is that the reaction rate changes with the DO concentration based upon the Monod kinetics.

Method 2: The method consists of predicting the OURf at time T1 based upon the previous increase in OURf from time time T-1 to T0.

Airflow Calculation
The two OURf values calculated in the predictive feedback technique are averaged based upon a ratio of the two. The default value ratio is 30% Method 1 and 70% Method 2. The airflow is then calculated using the weighted average OURf. The calculation of airflow is a function of temperature, DO set point, and oxygen saturation. A graphical description of the two methods is shown below in Figure 8.

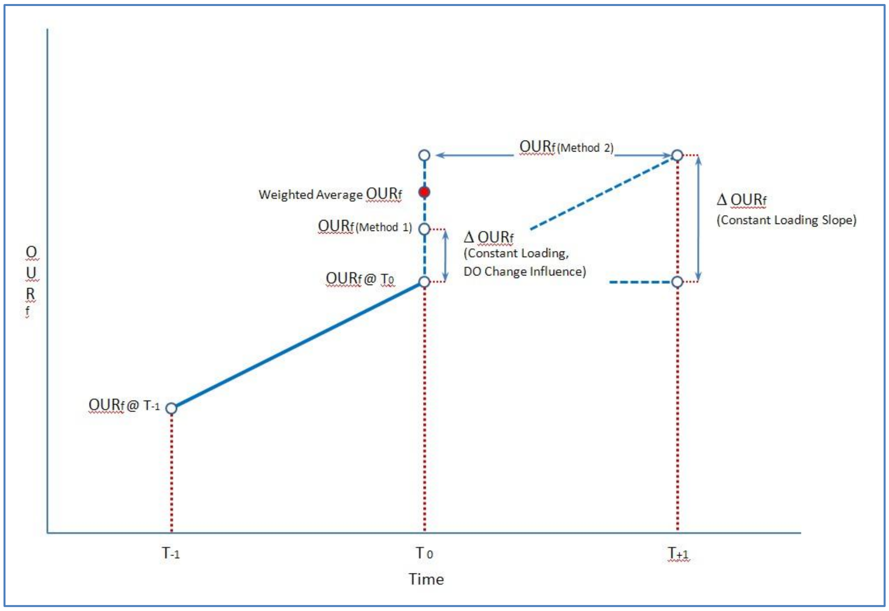


Figure 8

Technique 2: Feed Forward Control

A challenging aspect of providing a stable and robust aeration control system is the proper response to process disturbances. The most direct way to accomplish the goal of the control system is to first quantify the influent load by strategically locating ‘loading sensitive’ in-situ instrumentation at the beginning of (or directly before) the first oxic zone and then preemptively responding to this information before the load disturbs the oxic zone’s DO reading. Because an accurate BOD/COD loading measurement cannot be collected in real time, an online ammonia analyzer can be utilized as an indirect indicator of BOD/COD loading. To do this, first one must correlate BOD/COD concentrations with ammonia concentrations throughout the day. Tests on the influent for both BOD/COD and ammonia concentrations performed at different points throughout the day allow for the establishment of such a first-order proportional relationship.

Once an estimate for the current oxygen demand of the influent is gauged, this information is processed by an algorithm based on the Activated Sludge Model (ASM) to estimate the current OUR and the proper airflow rate required to correctly compensate for any changes in the OUR in the incoming wastewater since the last control calculation.

Airflow Set Point

As mentioned above, the calculation of the airflow set point is based upon the weighted average of the predictive feedback and feed forward techniques of calculating the airflow required to meet the DO set point. The ratio of the weighted average is dependent upon field verification of the feed forward model. In the event that the ammonia signal is low quality or lost, the system’s backup control formulates the proper control response by applying only the predictive feedback control technique.

Valve Control

At regular intervals, the aeration control system sends a total airflow set-point to the blower control, and then positions the air control valves to distribute the air to each aeration zone based upon the calculated airflow set point for each zone.

The valve positioning logic uses the actual individual butterfly valve's Cv curve to calculate an approximate new valve position to satisfy the airflow set point. After giving the valve control logic a sufficient amount of time to adjust to the desired airflow, the valve locks in to a final position to prevent unnecessary additional starts of the actuator for the remainder of the control cycle. When a new air flow set point is calculated – the valve lockout is lifted and the control logic restarts.

The valve control includes dynamic most open valve logic to promote low system pressure by having one of the control valves become the most open valve (MOV) at 85% open and allows the other control valves to seek their position to meet the airflow requirements. When a control valve that is not the MOV is calculated to be at greater percent open than the MOV, then that valve becomes MOV, and the previous MOV will be able to close.

Advantages

The process-based control concept allows the aeration control system to respond accurately to any changes in the operating conditions and influent loading. It differentiates the aeration control system from a PI control loop that has a fixed gain independent of the process changes, so outside of a narrow band for which it is tuned, the PI controller will either over- or under-react to daily and seasonally changing conditions. The system is self-tuning and stabilizes quickly after process disturbances.

The flow control of the blowers (as opposed to pressure control) has additional advantages. The system is not required to restrict the flow to maintain a constant pressure, so the most-open-valve logic of the aeration control system ensures that the blower is always operating at the lowest possible system pressure. It also prevents the often observed cyclical hunting of blower and valves that is caused by the blower control and valve control loops responding to the control action of the other control loop, instead of process changes, leading to premature failure of the actuators.

RESULTS

The startup flow at Poinciana was at 2 mgd, sixty five percent less than design, which could have lead to wasted energy or process upset, but the designed flexibility of the system prevented any limitations due to low loading. The system has been able to meet the dissolved oxygen set-point requirements. The system is able to control the dissolved oxygen within 0.5 mg/l of the set point 94.5% of the time and within 1.0 mg/l of the set point 99.5% of the time. The estimated aeration power savings is 41 percent compared to constant speed operation.

The operational data of the WWTP's advanced aeration system including actual dissolved oxygen, air flow, and valve positions are shown in Figure 9.

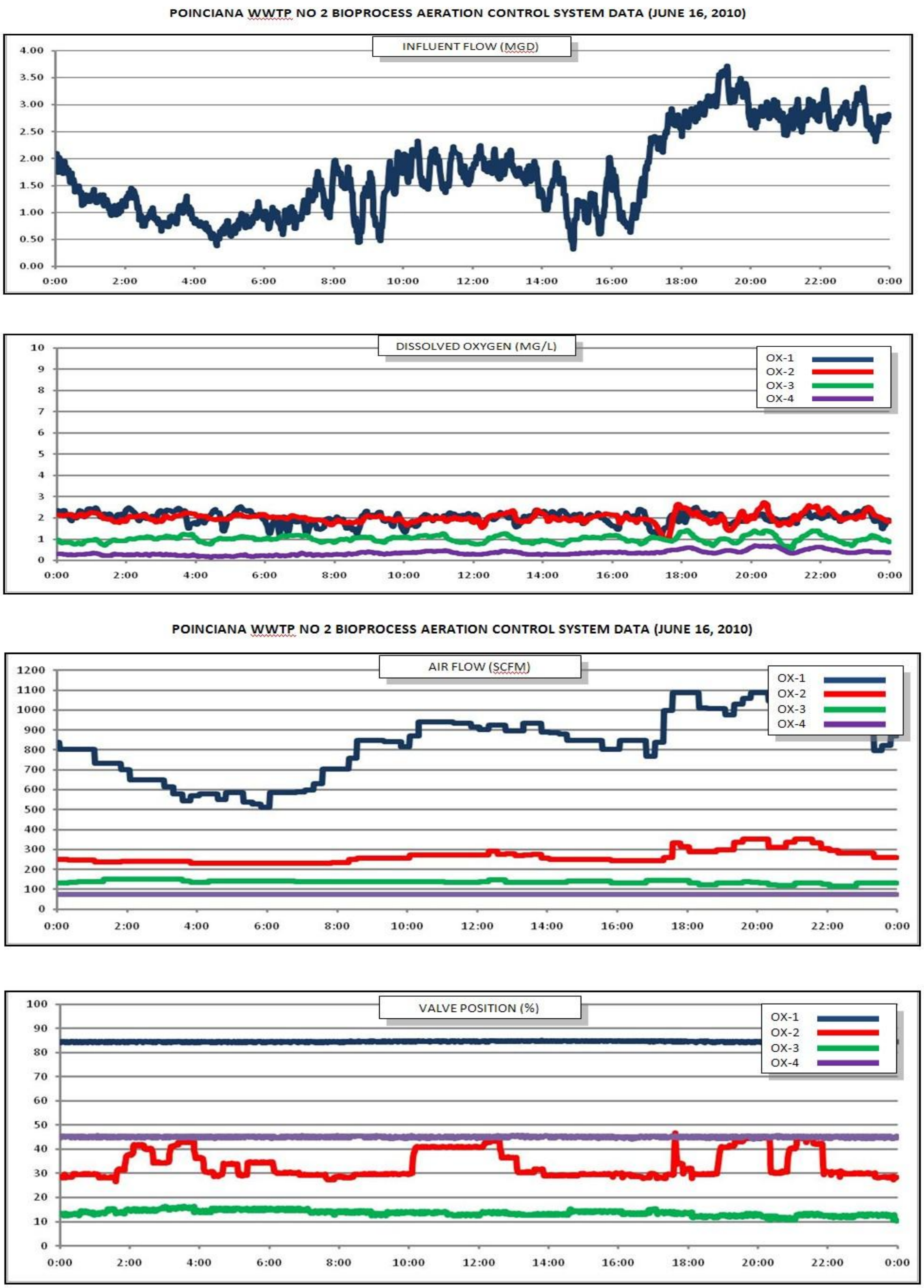


Figure 9: Poinciana Influent Flow, dissolved oxygen, air flow, and valve positions

CONCLUSION

The Poinciana aeration system installation confirms that a successful application of an aeration control system is dependent upon a successful operation of aeration system components. System components must be correctly sized and installed to insure successful operation. By following the design procedures described in the methodology of the paper the implementation of a properly designed aeration control system can reduce aeration energy by 25 to 40 % can be achieved.

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