The Use of a Process Simulator to Model Aeration Control Valve Position and System Pressure

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ABSTRACT
The design of the aeration system has become one of the most important aspects of the design of the activated sludge process. Process engineers use commercially available process simulators with activated sludge and aeration models to calculate dynamic temporal and spatial oxygen requirements, but current simulators do not have the ability model the system pressure, blowers, and control valves of the aeration system. Incorporating pressure losses and valve positioning calculations into the process simulators allows the engineer to see the pressure and valve position changes as the influent process conditions change diurnally and seasonally so equipment can be sized accordingly. The paper will describe the aeration system model and show the applications of using the combined models for control valve sizing, estimating the pressure requirement for the blower, and comparing three types of aeration control methods.

KEYWORDS: Aeration, Aeration Control, Modeling, Control Valves, System Pressure, Most Open valve

INTRODUCTION

With the continuing increases in energy costs and the requirements of Biological Nutrient Removal (BNR), the design of the aeration system has become one of the most important aspects of the design of the activated sludge process.

With proper influent and operational data, process engineers can use a commercially available process simulator with activated sludge and aeration models to calculate temporal and spatial oxygen requirements. The calculated oxygen requirements can then be used to design the diffuser layout and calculate airflow requirements. The sizing of the air distribution piping, air control valves and blower are then based on the calculated airflows and a selected single point design pressure.

The single point design pressure is based on a single condition, but in reality, the actual pressure is dynamic, based on airflow and valve positioning. The large number of valve positions and influent conditions normally limits the engineer to only design for a single pressure, but the use of a single design pressure can lead to improperly sized equipment, which will promote operational difficulties and potential energy inefficiency.

Incorporating pressure losses and valve positioning calculations into the activated sludge model simulation allows the engineer to see the pressure and valve position changes as the influent process conditions change diurnally and seasonally so equipment can be sized accordingly.

This paper will demonstrate the process of calculating and incorporating pressure losses, blower speed and valve positioning into the activated sludge model simulation. The paper will also show applications of using the combined models for control valve sizing, estimating the pressure requirement of the blower, and comparing three different types of aeration control methods.

AERATION MODEL SYSTEM DESCRIPTION

The aeration system model is a combination of valve, blower and pressure models that are all linked by the aeration system pressure (P_{sys}). The models are solved through an iterative fashion until the actual airflow for each aeration zone is within the determined tolerance of the airflow set point, and the pressure model is balanced.

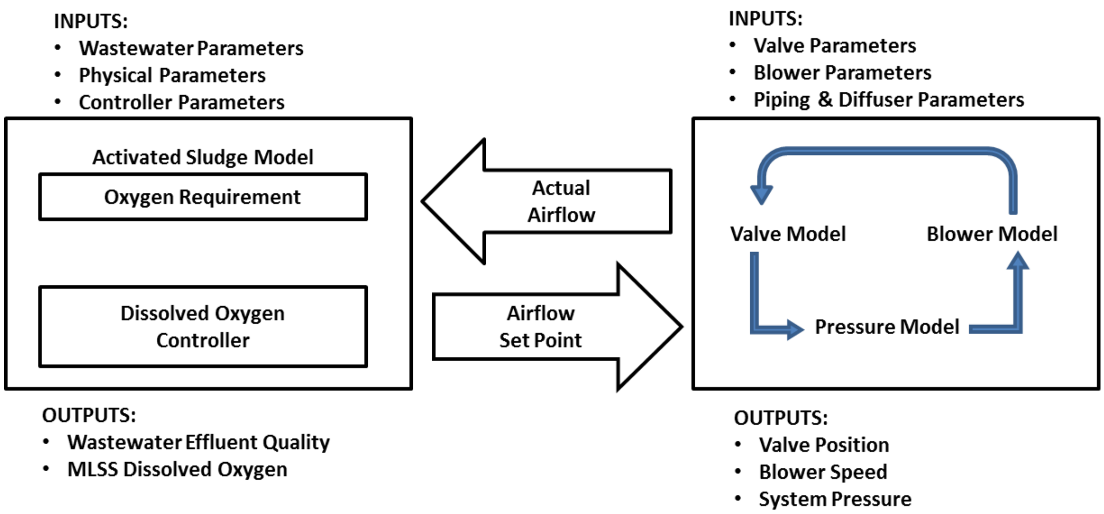


Figure 1: Activated sludge system and aeration system interaction

Valve Model

Within the aeration system the control valves are used to balance the airflow into the aeration zones. The most common control valves used for aeration control are butterfly valves. Control valves can be modeled by using flow coefficient (C_v) characterization curves. The C_v curve provides the relationship between the valve position and C_v. The curves are based on empirical data derived from laboratory testing done by the valve manufacturers. Figure 3 is an example of a C_v curve, and Equation 1 is used to describe the CV curve.

Equal Percentage Valve: $$\frac{C_V}{C_{V,max}} = V_R^{(V_P-1)}$$ (Equation 1)

Vp :Valve Percent Open *V_R : Valve Factor* *Cv,max: Cv at Open Position*

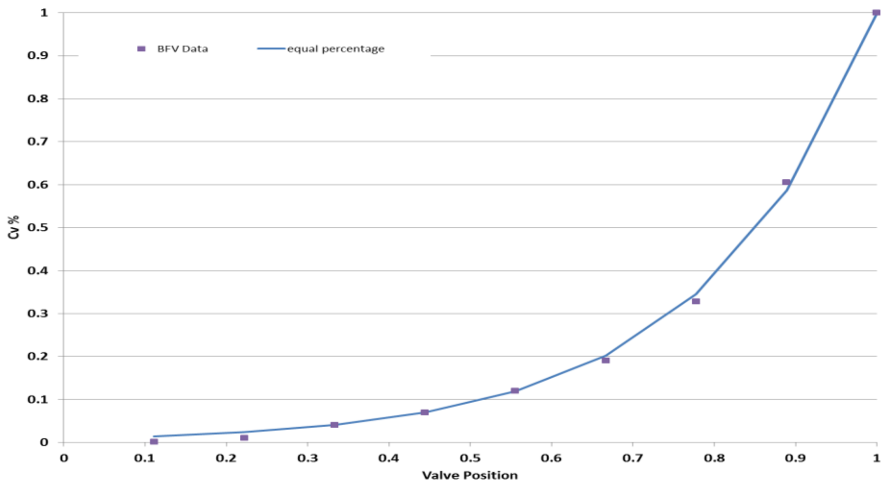


Figure 2: Butterfly Valve C_v Curve

The flow coefficient (C_v) was originally based on water pressure loss testing. The definition of C_v is the amount of flow per unit pressure loss in units of gpm/psi. In regards to airflow, Equation 2 calculates C_v based upon the airflow and pressure on either side of the valve. Equation 2 can also be rearranged to calculate the pressure loss across the valve ($P_i - P_o$) at a specified airflow and valve position. The equation requires that the pressure loss across the valves is less than 10% of the inlet pressure (P_i) (Crane, 1991).

Flow Coefficient for Gases: $$C_V = \frac{Q}{962}\sqrt{\frac{S_g(T+460)}{{P_i}^2 - {P_o}^2}}$$ (Equation 2)

Q :Airflow, scfm *Sg: Specific Gravity* *T: Temperature, F*
P_i: Inlet Pressure, psia *P_o: Outlet Pressure psia*

Blower Model

Blowers generate the airflow for the aeration system. Depending upon the type of blower, the airflow output is dependent upon the system pressure (P_{sys}), blower speed, or inlet valve position and discharge vanes positions. For this paper only the positive displacement type blower was modeled, so only blower speed is needed to model the blower. Equation 3 was used to calculate the blower output based on percent of maximum speed (N). Depending on the control method of the blowers, the blower speed is modified until the control variable, airflow or system pressure, is within the control system dead band.

Positive Displacement Blower: $$Q = N(Q_{max})$$ (Equation 3)

Q :Airflow, scfm *Qmax: Capacity of blower, scfm* *N: Blower Speed %*

Pressure Model

To model the system pressure within the aeration system, pressure loss calculations are required for aeration piping, diffusers, and control valves. In regards to the control valves, the C_v Equation 1 is used to calculate pressure loss across the valve. The diffuser pressure losses are highly dependent upon the diffuser flux (scfm/ft^2). Manufacturers will provide diffuser pressure loss versus diffuser flux curves. Data fitting analysis is used to generate a simple model equation. Calculating the pressure loss for the aeration piping can be fairly complex, because of multiple individual minor and pipe length losses required for the standard Darcy-Weisbach formula, but can be simplified by calculating pressure loss for one flow condition, then calculating a pressure loss coefficient that can be used for other flow conditions (WEF 2010). Equation 4 explains the simplified method.

$$K_L = P/Q^2 \qquad \text{(Equation 4)}$$

Equation 4 can be rearranged to calculate new pressure losses at different airflows.

$$P = Q^2(K_L)$$

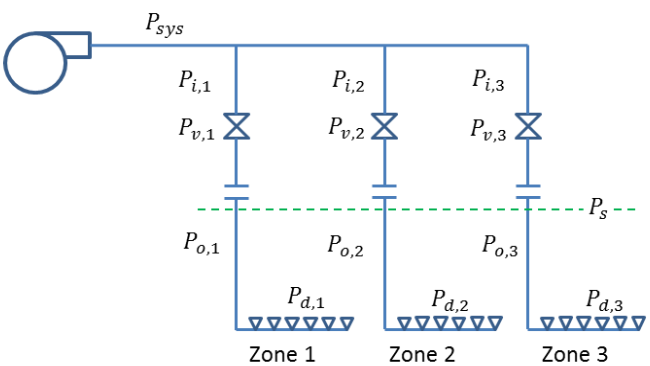
Q :Airflow, scfm *K_L: Pressure Loss Coefficient, psi/scfm^2* *P:Pressure loss, psi*

The sum of the minor pressure losses plus the static pressure becomes the system pressure (P_{sys}) as shown in Equation 5. The sum of the minor pressure losses for each aeration control zone must all be equal for the system to be considered balanced. Figure 3 is a depiction of all the minor pressure losses within a three zone aeration system.

System Pressure Calculation: $$P_n = P_{i,n} + P_{v,n} + P_{o,n} + P_{d,n} + P_s = P_{sys} \qquad \text{Equation (5)}$$

when the system is balanced

$$P_1 = P_2 = P_3 \ldots = P_n = P_{sys}$$



P_{sys}: System Pressure, psig
P_i: Upstream Pressure Loss, psi
P_v: Valve Pressure Loss, psi
P_o: Downstream Pressure Loss, psi
P_d: Diffuser Pressure Loss, psi
P_s: Static Pressure, psi

Figure 3: Aeration system minor pressure losses

MODEL CONFIGURATION

A BNR wastewater treatment plant (WWTP) was upgrading the activated sludge aeration system to increase the capacity of the facility from 15,000 to 19,000 m3/d (4 to 5 million gallons a day). As part of the upgrade process, air distribution piping, control valves, blowers, and an aeration control system were installed. The aeration system had four aeration control zones, with the ability to turn off the diffusers of half of zones 1 and 4 to create anoxic swing zones.

The commercially available software GPS-X by Hydromantis ESS, Inc. was used to perform the process simulation and pressure loss calculations. The aeration system model calculations were programmed into the GPS-X User File using Advanced Continuous Simulation Language (ACSL) statements; further information about GPS-X User Files and ACSL can be found in GPS-X and ACSL Reference manuals.

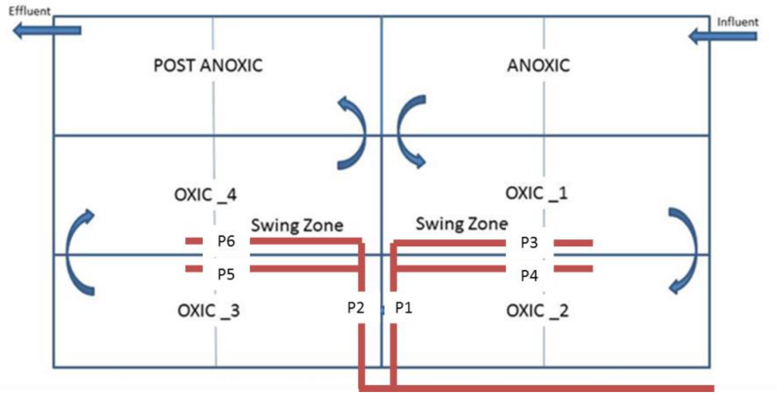


Figure 4: Aeration basin layout

The aeration tank was modeled as a plug flow reactor (PFR); this model allows the reactor to be divided into numerous continuously stirred tank reactors (CSTR) in series. This, in turn, allows a great deal of operational flexibility in the model so that various conditions can be simulated. The PFR for this model was divided into eight (8) CSTRs in series. Table 1 is a summary of the tank configuration. The dynamic inputs for the simulation were from a sampling of influent flow, diurnal peaking factor, cBOD, TKN, and TSS data. The influent fractions were considered to be constant. The analysis was run for 259 days at a 15 minute time interval.

Table 1: Activated sludge model aeration tank configuration

Stage	Anoxic	Aerobic						Post Anoxic
Control Zone		OX-1		OX-2	OX-3	OX-4		
CSTR	1	2	3	4	5	6	7	8
Vol. (mgd)	0.32	0.16	0.16	0.32	0.32	0.16	0.16	0.32
DO (mg/l)	0.0	2.0	2.0	1.5	1.0	0.5	0.5	0.0

The butterfly valve used was modeled as an equal percentage valve with a valve factor (V_R) of 110. The upstream aeration piping pressure loss coefficients were calculated based on the average airflows. The pressure loss coefficient for the downstream piping and diffusers is based on pressure loss data from the diffuser manufacturer. Both the diffuser and downstream pipe pressure losses are based on the airflow per diffuser ratio. Table 2 is a summary of the air piping and valve sizes and corresponding pressure loss coefficient factors.

Table 2:Pressure Loss Coefficients Summary

Pipe Section	Size	$K_{l,Pi}$	Aeration Zone	Valve Size	Cv Max	Diffuser Count	$K_{l,Po}$
-	in	psi/scfm^2	-	inch	-	-	psi/(scfm/dif)^2
P1	16	5.84E-10	-	-	-	-	-
P2	16	5.84E-10	-	-	-	-	-
P3	10	4.54E-09	1	8	5208	420	0.0086
P4	6	6.26E-08	2	6	2708	240	0.0086
P5	4	7.50E-07	3	4	1314	120	0.0086
P6	4	7.50E-07	4	4	1314	80	0.0086
Diffuser Pressure Loss: 0.0243(scfm/dif)^2+0.43632							
Static pressure: 15 ft							

DISCUSSION

Air Control Valve Sizing

Airflow control valves should typically operate in the 20-90% open range to prevent excess pressure losses and provide controllability. The swing zones located in zones one and four can make it difficult to size the air control valves. Whether the swing zone is aerated or not can cause a large shift in airflow per diffuser because the treatment dynamics change. The use of the simulation helped determine the valve positioning with swing zones on and off by running the simulation once in both operational modes. The valve positioning results are shown below in Figure 5. It was determined that the 8” and 4” valves in zones one and four, respectively, were able to stay in the linear range requirement during both scenarios.

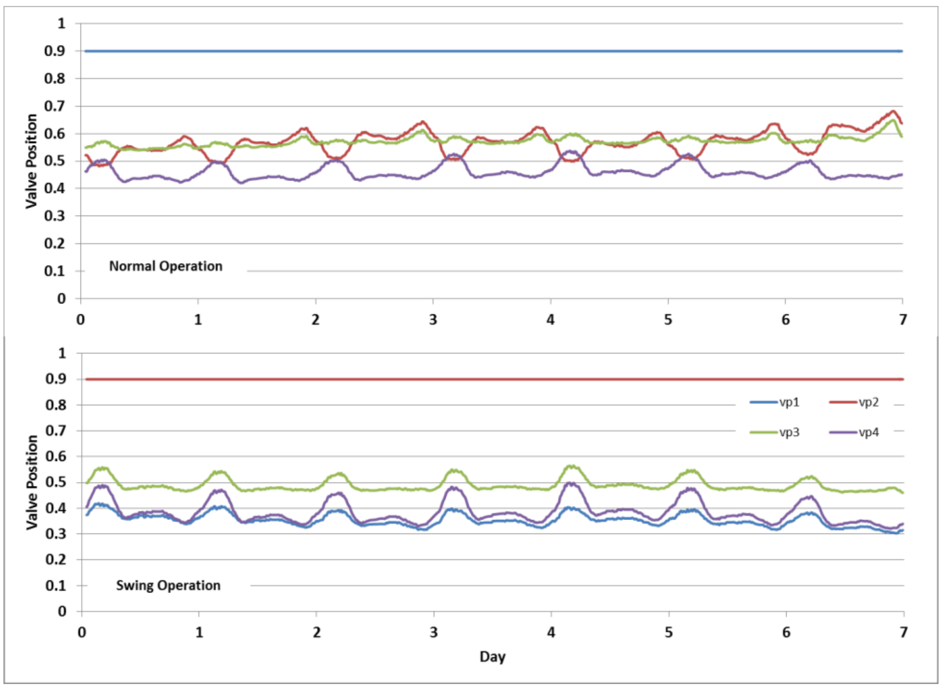


Figure 5: Valve positioning during normal and swing operation

Blower Sizing

Once the valve sizing was completed, the simulation was used to quantify the blower system pressure range by running the simulation for an extended period of 260 days with dynamic inputs. Figure 6 shows the blower system pressure results from the simulation. The simulation determined that the system pressure will fluctuate between 7.0 and 7.5 psig.

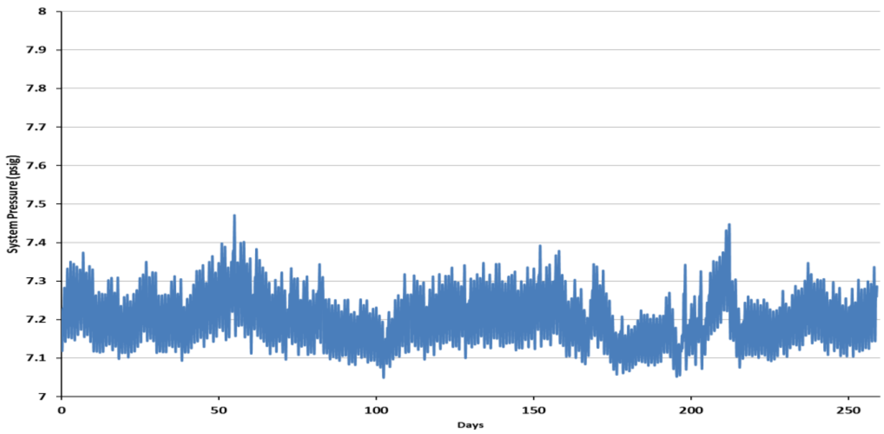


Figure 6: Calculated system pressure

Aeration Control Selections

The goal of aeration control is to provide enough airflow to meet the current oxygen demand at each aeration zone while keeping the system pressure as low as possible. For this to happen, the blower control and the distribution control need to work efficiently together.

There are two methods for the distribution control to communicate to the blower control that a change in total airflow is required. The first is airflow control, where the actual total airflow requirement is sent as a set point to the blower control. The other is pressure control, where the blower control is given a pressure set point requirement, which can be constant or dynamically calculated based on valve positions.

Constant Pressure Blower Control

At regular intervals, the aeration control system positions the air control valves to distribute the air to each aeration zone based upon the calculated airflow set point for each zone. At the same time blower control is changing the output of the blowers to keep the system pressure within the specified dead band of the constant pressure set point. As the control valves open as airflow demand increases, the system pressure will drop and the blower control will then increase airflow output to increase system pressure. The same control applies with the valves closing as airflow demand decreases, just in the opposite direction.

Dynamic Pressure Blower Control

At regular intervals, the aeration control system positions the air control valves to distribute the air to each aeration zone based upon the calculated airflow set point for each zone. At the same time, the blower control is changing the output of the blowers to keep the system pressure within the specified dead band of the constant pressure set point.

Dynamic pressure control includes most open valve logic to promote lower system pressure by having the position of the most open valve (MOV) determine the system pressure set point. The MOV is controlled between two predetermined valve position set points (Jenkins, 2013). If the MOV is opened higher than the high set point, the system pressure set point is increased, if the MOV is closed below the low set point, the system pressure set point is decreased.

Flow Based Blower 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 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 90% 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.

Control system comparisons

A simulation was run for each of the three aeration control logic concepts mentioned above, all simulations used the same airflow piping, and valve sizes and airflow amounts. The simulations were run for seven days with a 15 minute control step interval. The constant pressure simulation had a system pressure set point of 7.6 psig, with a 0.05 psig dead band on the blower control. The dynamic pressure simulation had the MOV set points at 60% and 45% open with a system pressure set point change of 0.05 psi with a 0.05 psi dead band on the blower control. The flow based simulation had the MOV at 90% and the blower control had a 30 scfm or about 1 % of the blower capacity dead band. Figure 7 shows the valve positions and system pressure of the simulations.

The flow based control valve positions were the most open, showing aeration zone 1 as the MOV at 90%, while the other three control valves were between 40 to 70% open. Next, the dynamic pressure control showed valve positions between 30 and 60% open. Last, the constant pressure valve positions were between 30 and 50%. The system pressure is dependent upon the valve positions, which is seen in the system pressure comparison figure. The constant pressure control is the highest at 7.6, moving within the dead band of the set point, while the flow based control is lowest between 7.1 and 7.4 psig without the operational noise of the system pressure dead band. Using the extended time period simulation data, the system pressure and airflow results were used to calculate blower power requirements. Compared to constant pressure control, dynamic pressure saved 3% in aeration power, while flow based control saved 5%.

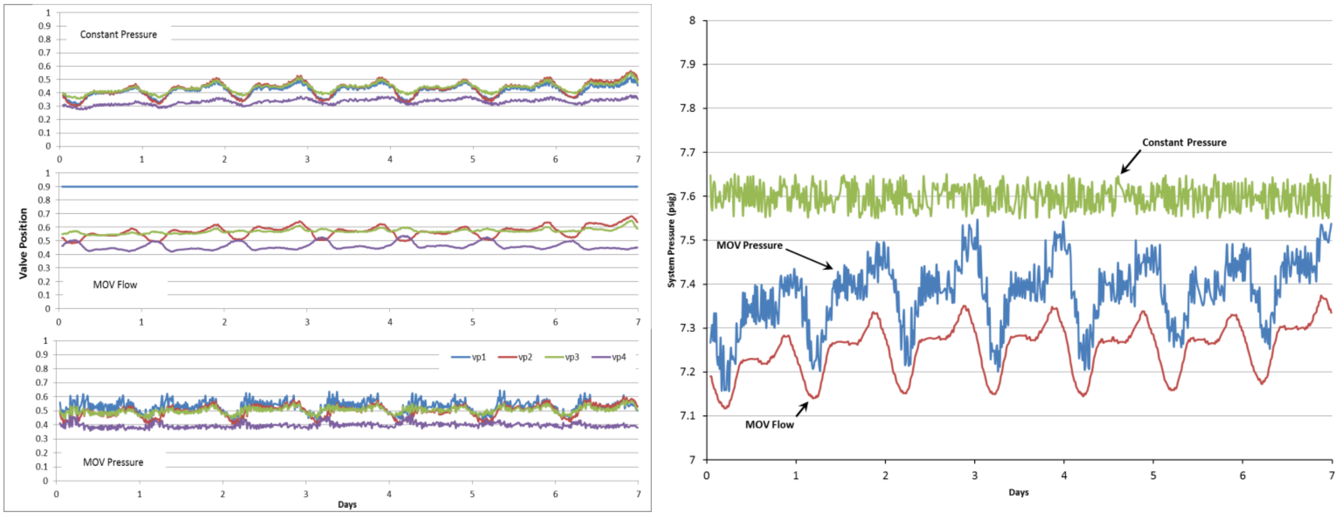


Figure 7: Valve positions and system pressure for different aeration control methods

Several simulations were run at different MOV position set points to try to optimize system pressure for the dynamic pressure control. At first the MOV set points were increased to drop the system pressure but control became unstable with the MOV bouncing between the set points due to the sensitivity of the valves to pressure changes at high open ranges. Then the MOV set points were spread apart, but that resulted in performance similar to a constant system pressure set point.

CONCLUSIONS

The design of the aeration system has become one of the most important aspects of the design of the activated sludge process, but process engineers only have commercially available process simulator with activated sludge and aeration models to calculate dynamical process requirements, not the actual equipment requirements for an aeration system.

It was demonstrated that the process of calculating and incorporating pressure losses, blower speed and valve positioning into the activated sludge model allows the engineer to see them change as the influent process conditions change diurnally and seasonally, so equipment can be sized accordingly.

Using the combined models for control valve sizing, estimating the pressure requirement for the blower, and comparing the dynamics of three different types of aeration control methods was also demonstrated.

At this point, the aeration system model could not be compared to actual operational data. A comparison would be valuable, and should be done to determine the overall accuracy of the model. However, the valve, blower and pressure models were developed using methods already used in design, which gives confidence that the models as used in the paper would provide an accurate design tool.

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