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Effluent quality control in small Biological Process Treating Domestic Wastewater

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The problem of fluctuating influent flow and pollution concentration is a serious concern in small wastewater treatment plants. In this study, a simple mathematical simulation of an activated sludge process has been utilized to derive operational controls to stabilize process disturbance effects on effluent quality. The sensitivity of the model has been tested for several factors known to have significant variability with time and occasion. The variable factors were chosen from previous operational records of a small-scale process. The model was tested on a small process serving a university campus through extreme flow and pollutant conditions. Data collected during the applications of the controls was used to test the effectiveness of the model. The results were encouraging.

Small institutions, organization and towns very often use Activated Sludge Process (ASP) to treat wastewater, as the process is economical and easy to operate. Usually these biological systems operate as extended aeration process with treatment up to secondary level. Small treatment processes serving particularly university campuses, hospitals and oil fields are prone to shocks from large variations in influent flow rate and waste concentrations resulting from variations in number of users and organization activities (Shahalam and Abbassi, 1990). The effluent of many of such processes is very often used for irrigation purposes, which require reliable and steady quality of the effluent water. Traditionally experienced operators of plants control the rate of recycle flow to the aerator to dampen the effect of inflow shocks on the effluent quality (Shahalam and Angelbeck, 1978).

A built physical system has its limitations on microbial mass that it may effectively maintain in the aeration tank and the extent of solids compaction that it may achieve in the clarifier (Shahalam and Angelbeck, 1978). These limitations are mostly determined by the size of the aeration tank, aeration equipment, oxygen transfer capacity, pump capacity, and the size and shape of the clarifier. Solids compaction factor, which affects the amount of microorganism return to aerator by recycling, is directly a function of solids wastage rate and the rate of recycle flow from the bottom of the clarifier. In the process, the operators often face decision problems of determining proper recycle and sludge wastage rates. Among many controls available, the controls of sludge recycle and wastage appear to be the most practical and easy-to-apply (Shahalam and Angelbeck, 1978; Shahalam and Abbassi, 1990).

This paper deals with a methodology of determining the proper recycle and wastage rates when a system experiences inflow shocks.

System control functions

Figure 1 shows a conventional activated sludge process with sludge recycle and wastage from the bottom of the clarifier. Mathematical representation at steady state conditions were used to express the control factors of recycle and sludge wastage rate.

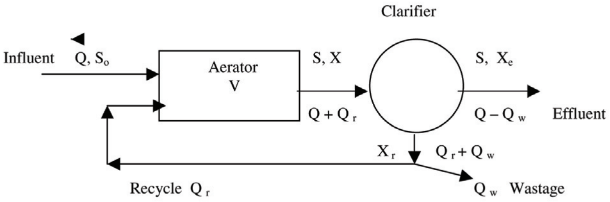

Figure 1. Extended Aeration Activated Sludge System

Substrate mass balance under steady state condition provides Equation 1.

$$S = [S_o / (1 + R)] / [1 + \{K\theta / K_s\} X] \qquad [1]$$

Equation [1] is derived with an assumption that the "S" is very small in comparison to K_s. For a desired value of S, the equation may be used to determine X (Equation 2).

$$X = [K_s \{(S_o /((1+R) S)) - 1\}] / K\theta \qquad [2]$$

where S_o = Influent substrate concentration, mg/l BOD_5, S = Effluent substrate concentration (mg/l BOD_5), K = Maximum substrate degradation rate constant (per day) in the degradation rate expression: $(KS)/(K_s + S)$, θ = Aerator hydraulic detention time $(V/ (Q + Q r))$, V = Volume of the aerator (m^3), Q = Influent flow rate (m^3/day), Q_r = Recycle flow rate (m^3/day), K_s = Substrate concentration (mg/l) at substrate degradation rate of "K/2"; and X = Mixed liquor volatile suspended solids (MLVSS) in the aerator (mg/l). Volatile solids balance in the aerator results in Equation 3. The equation used volatile solids growth rate as $(\mu_m S) / (K_s + S)$.

$$Q_r X_r + Q X_o - (Q + Q_r)X + V [\{(\mu_m X S) / (K_s + S)\} - K_d X] \qquad [3]$$

When S is very small and negligible in comparison to K_s, Equation 3 may be expressed as Equation 4.

$$R (C - 1) = 1 - C_o - \theta [(\mu m / K_s) S - K_d] \qquad [4]$$

where $R = Q_r / Q$, $C = X_r / X$, $C_o = X_o / X$, X_r = Volatile solids concentration in the clarifier underflow (mg/l), X_o = Volatile solids concentration in influent (mg/l), and π_m = Maximum volatile solids growth rate constant (per day) in growth rate expression: $(\pi_m S) / (K_s + S)$; and K_d = Endogenous decay rate constant (per day). A steady state volatile solids balance in the clarifier results in Equation 5.

$$(1 + R) = \{ R + (Q w / Q) \}C \qquad [5]$$

where Q_w = Wastage flow rate, m^3 / day. The term mean cell residence time (θ_c) is defined as Equation 6.

$$\theta_c = VX / (Q_w X_r) = V / (Q_w C) \qquad [6]$$

Mean cell residence time is related to aerator MLVSS (X) by Equation 7 (Metcalf and Eddy, 1981).

$$X = (\theta_c / \theta) \{ Y (S_o - S) \} / (1 + K_d \theta c) \qquad [7]$$

where Y = mg volatile suspended solids produced per mg of BOD_5. Equation 7 may be rearranged as:

$$\theta_c = 1 / [\{ Y (S_o - S) \} / (\theta X) - K_d] \qquad [8]$$

Equating Equations 6 and 8, the expression for C (Equation 9) is derived.

$$C = V [\{Y (S_o - S)\} / (\theta X) - K_d] / Q_w \qquad [9]$$

Inserting Equation 9 in Equation 4, Equation 10 is derived.

$$R = \frac{[1 - C_o - \theta \{ (\pi_m / K_s) S - K_d \}]}{[V \{ Y (S_o - S) / (\theta X) - K_d \} / Q_w] - 1} \qquad [10]$$

Equation 11 is derived including Equation 9 into Equation 5. The control variables (Equations 10, 11) that may be easily adjusted in the treatment plant are recycle flow rate (Qr) and Wastage flow rate Q_w. For a target effluent quality S, knowing the influent water quality and flow, desired level of MLVSS (X) is set by Equation 2. With known X, Equations 10 and 11 may be used to determine the control variables Q_r and Q_w. Equations 10 and 11 are solved by trial and error.

$$Q_w =(RQ) / [\{(1 + R) Q\} / \{V [\{Y (S_o - S) / (\theta X)\} - K_d \}-1] \qquad [11]$$

Monitored process

A small conventional activated sludge process operating as an extended aeration system serving a university campus in Muscat, Oman was chosen for monitoring and testing the effect of controls when the system is under shocks of hydraulic and organic loadings. The system serves the university having a student-strength of nearly 9,000. It also serves nearly 600 faculty and staff who reside with family within the campus. Students reside in dorms five days in a week. During two days of the weekend, most of the students leave the campus. This factor brings a significant flow variation every week. During every year, the faculty and staff are allowed two months vacation during vacation period during summer. Figure 2 depicted monthly average flows, which clearly demonstrated wide variations of flow during a typical year. The recorded variations were as high as ±25% of the annual average. The flow has annual recurrence of variations. Effluent water is used for irrigation of campus lawns, gardens and plantations and it requires effluent BOD_5 to be less than or equal to 10 mg/l. Under normal operation, the record showed cases of 100% change in the effluent BOD_5 during extreme flow disturbances.

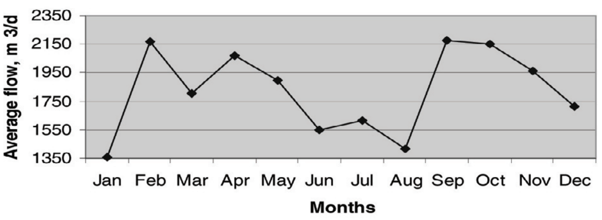

Figure 2. Variations in monthly flows

System operational data and applied controls

In the experimental phase, in a number of disturbance cases (Figures 3 and 4), the controls derived by Equations 10 and 11 were applied. The system was monitored to determine the efficiency of these controls. A disturbance case was defined when the hydraulic inflow or organics concentration in inflow or both recorded a change of ± 25 percent from respective previous daily records. Thirty-three individual cases of the state of the treatment process were monitored. Application of the model controls (Equations 10 and 11) needs kinetic parameters representing the process. Ten normal steady state operation data were utilized to determine the basic kinetic parameters of the process. The values estimated from operational data are K = 1.3 per day, Ks = 90 mg/l, Kd = 0.002 per day, Y = 0.77 mg VSS produced / mg of BOD_5 consumed, and μm = 1 per day.

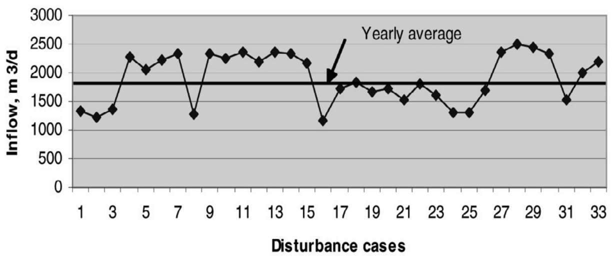

Figure 3. Inflow in selected disturbance cases

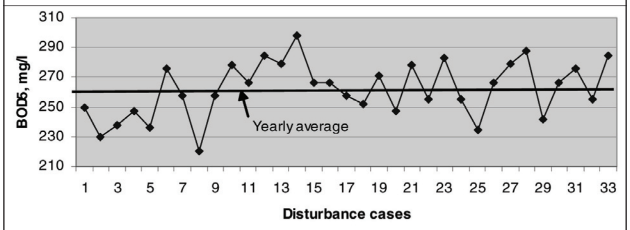

Figure 4. Inflow BOD_5 in selected disturbance cases

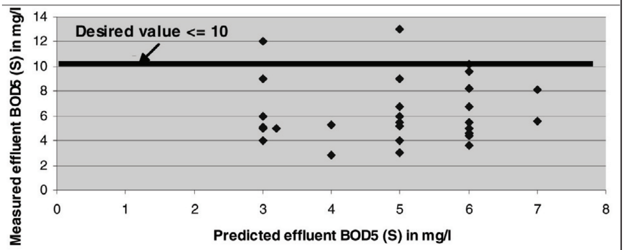

Figure 5. Predicted vs. Measured effluent BOD_5 (S)

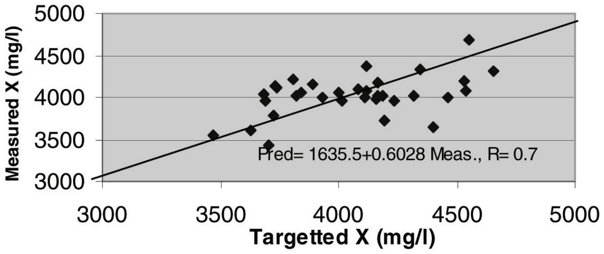

Figure 6. Targetted vs. measured

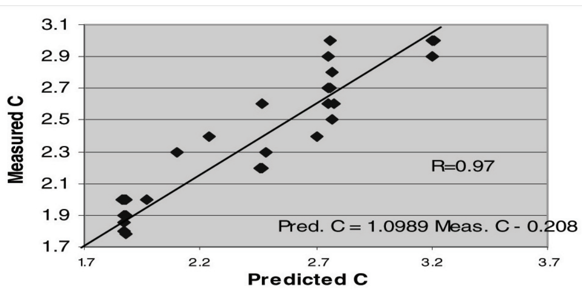

Figure 7. Predicted vs. Measured values of solids compaction factor in the clarifier, C=(Xr/X)

The aerator has a volume of 1654 cubic meter. One-year data of 2001 indicated an average hydraulic detention time of 0.55 days with the maximum of 0.973 day and minimum of 0.33 days. The standard deviation is 0.22 day. The recycle average was 75 percent of plant inflow while the maximum and minimum were 100 and 25 respectively. During a disturbance, influent flow and BOD_5 along with normal kinetic parameters were utilized in Equations 10 and 11 to determine appropriate controls of recycle and sludge wastage. Operators applied the controls adjusting the recycle and wastage pumping rates. Control effectiveness was measured comparing predicted and measured values of effluent BOD_5 (S), aerator biomass (X in Equation 7) and clarifier compaction factor (C in Equation 9). The predicted and observed values of S, X and C appeared in Figures 5, 6 and 7 respectively.

Discussion

Annual average inflow of past one year was 1823 m^3/day. The maximum and minimum of the disturbance cases were 2512 and 1161 m^3/day respectively. The variation cases cover one-year operation of the plant. Annual average inflow-BOD_5 of past one year was 262 mg/l. The maximum and minimum of the disturbance cases were 298 and 220 mg/l respectively.

Figure 8 contains the values of model predictions of control variable sludge-recycle for experimental cases. The return rate of pumping for each case was adjusted to the model prediction value and was maintained at that stage until at least a change of 25 percent of the initial inflow rate is recorded. A change of 25 percent in an existing flow within 24 hours prompts for calculating a new set of control variables. The "25 percent" was selected for this purpose somewhat arbitrarily with some rational of standard deviation and average inflow rate of past flow records. Standard deviation and the average of past year inflow were 431 and 1823 m^3/day respectively.

Maximum allowable value of recycle was 100 percent of the influent flow rate determined from the existing sludge pumping capacity. System functions predicted an increase in the recycle when the inflow increased. Due to the physical limitation of the concentration of mixed liquor suspended solids (X) in the aerator to be within a range of 4000-5000 mg/l, the values of control variables of sludge recycle and wastage were also constrained for satisfying the requirement. The range of X was determined from previous records of MLVSS level in the aerator. Air pump capacity and limitation of oxygen transfer constraint MLVSS level in the aerator.

An increase in the recycle flow tends to retain higher concentration of MLVSS in the aerator and total system

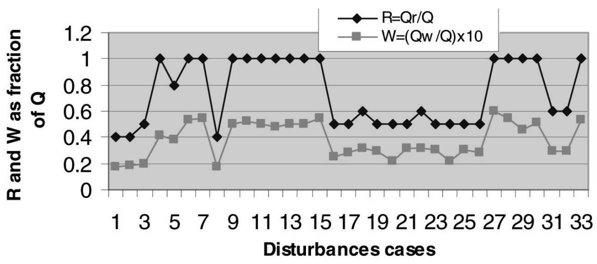

Figure 8. Model suggestions for recycle and sludge wastage rates

thus increasing the mean cell residence time of the system. Higher mean cell residence time improves the efficiency of the organics removal. An increase in MLVSS decreases the food to microorganisms ratio thus enhances the effective food utilization by microorganisms. However, as the recycle flow increases, the concentration of solids in the flow from clarifier bottom decreases. This particular factor has a tendency to keep on increasing the recycle flow. However, due to upper limitation, the recycle flow could be as high as 100 percent of inflow.

Second control variable applied to dampen the effect of shock flows was the sludge wastage rate. The model predictions of the variable for 33 experimental cases appear in Figure 8. It is observed that when a shock is due to higher inflow, the sludge recycle increases and the sludge concentration at the clarifier bottom decreases. Consequently, to maintain a favorable mean cell residence time (θc), hydraulic volume of sludge wastage needs to be increased. BOD_5 of the stream represented organic content (S) in the effluent. Measured and model predicted values for experiment cases appear in Figure 5. The model targets a desired level of organics (S) for estimating the control variables. The recommended upper limit in the experimental cases was set at 10 mg/l of BOD_5. From the measured data, it is apparent that the model prescribed controls were capable of keeping the effluent organics well below the desired upper limit of 10 mg/l. Only three cases out of 33, recorded BOD_5 above 10 mg/l. However, the superceded values were very close to 10 mg/l. It is noted that in the estimation of the control variables, the values of effluent quality (S) was conveniently selected to keep the value of X within a workable range when the recycle remains below or equal to the upper limit of 100 percent.

The desired and measured values of MLVSS in the aerator have a correlation coefficient of 0.7. It indicated that the application of the controls had significant effect in maintaining the MLVSS between 3500 and 5000 mg/l (Figure 6).

Figure 7 shows measured and predicted solid compaction factor at the bottom of the clarifier. The prediction based on steady state of the clarifier. The process operates as an extended aeration system with long hydraulic detention and means cell residence times. Longer detention time tends to turn the system to a pseudo-steady state within one or two hydraulic detention times. The correlation between the predicted and measured values of C was very good. The value of correlation coefficient value was 0.97.

It is noted that in model development, aeration system was treated individually resulting in expressions 1 and 2, which contain a hydraulic detention time (θ), which is determined by total hydraulic inflow (Q+Qr). Due to large detention time in the process, it appears that the calculation of the detention time considering recycle flow along with raw inflow and balancing the mass considering aeration tank separately is more appropriate than the conventional consideration of the total system and the raw inflow only.

Average detention time in the aeration tank, considering combined inflows of recycle and raw wastewater in the operating process was found to be 0.6 days. The minimum and maximum detentions were recorded to be 0.4 day and 0.9 day respectively. The usual mean cell residence for average flow is nearly 12 days. The maximum and minimum mean cell residence times were recorded to be 22 days and 8 days respectively. From the results, it appears that the assumption of steady state in balancing mass in aeration tank and clarifier were adequate to simulate the process under occasional disturbances of the system.

Conclusion

Based on the data and observations the following conclusions are drawn:

1. Small-activated sludge processes, which operate at extended aeration mode treating municipal wastewater when occasionally disturbed by hydraulic flow and organics loadings, can be effectively controlled by adjusting sludge recycle rate and sludge wastage rate.
2. A set of equations developed based on simple mass balances on aerator and clarifier units under steady state expressed the system adequately through occasional disturbances when proper controls were applied.

Acknowledgement

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