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Applying Quality Engineering Technique to Improve Wastewater Treatment

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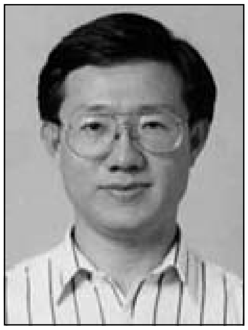

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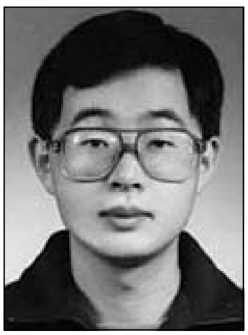

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Abstract

Wastewater treatment is a continuous effort for environmental protection. Many industrial plants employ the activated sludge process as a model for wastewater purification. The Chinese Petroleum Corporation holds a plant for wastewater treatment, where the sequencing batch reactor (SBR) process is employed. The SBR is an activated sludge system operating on a fill-and-draw basis. There are several quantitative indicators to measure the quality of the SBR effluent water. One of these indicators is the value of COD, chemical oxygen demand, in the SBR effluent. Historical data show that the COD value in the SBR effluent is too high and does not meet its designed value, which indicates the effluent water does not reach the desired quality standard. In this article, the quality engineering technique is briefly reviewed and the parameter design approach is applied to improve the SBR process by determining the nominal values of the process parameters. Three significant controllable factors (or parameters) have been identified in the experiment and their nominal values are: filling height 1.2 meters, reaction time 330 minutes, and concentration of MLSS 4000 ppm. By setting these parameter values, the COD value in the SBR effluent can be well controlled below its designed upper limit (125 ppm) and, consequently, the quality of the effluent water from the SBR process can be improved.

Introduction

Quality improvement of wastewater is an important field of environmental protection. Many industrial plants employ the activated sludge process as a model for wastewater purification. In the activated sludge process, wastewater is mixed with highly concentrated activated sludge in aeration tanks and exposed in the air such that the aerobic bacteria and microorganisms grow and the organic compounds are consumed. Then, the clean water is separated and effluented from the settled activated sludge which can be reused in aeration tanks.

The Chinese Petroleum Corporation holds a plant for wastewater treatment, where the sequencing batch reactor (SBR) process is employed. The SBR is an activated sludge system operating on a fill-and-draw basis (Orhon and Artan, 1994). The SBR process is essentially composed of a single tank or a number of tanks in parallel. The process consists of its semi-batch operation and the biological conversion and settling take place in the same reactor. Figure 1 shows the cyclic operations flow chart for the SBR process. In the process, wastewater is fed into the tank and mixed with the already present biomass. Sufficient time is allotted for biological conversion, then microorganisms are separated from the treated wastewater and the reactor is left idle after discharging and before refilling.

While the biochemical aspect of the SBR process is of much interest, most engineers and technicians are concerned more with the completeness of the process (Rozich and Gaudy, 1992). In the wastewater treatment plant under study, there are several quantitative indicators to measure the water quality of the SBR effluent. These indicators, as well as the corresponding designed values and the collected data for six days, are shown in Table 1. From the numerical data in Table 1, for current process, the indicator COD, chemical oxygen demand, in the SBR effluent is obviously out of the designed value,

	Indicator	pH	COD	Oil	S.S.	S^{2-}	$N(NO_3^-)$
	Unit		ppm	ppm	ppm	ppm	ppm
	Designed Value	6-9	<125	<10	<50	<1.0	<50
Date	***Time***						
97/6/09	8:30am	7.4	152	7.5	52	0.06	1.27
	3:30pm	7.6	144	6.4	28	0.08	<1.0
97/6/10	8:30am	7.5	163	9.7	30	0.07	<1.0
	3:30pm	7.6	148	8.9	40	0.08	<1.0
97/6/11	8:30am	7.6	142	11.2	43	0.07	<1.0
	3:30pm	7.4	126	3.6	28	0.05	<1.0
97/6/12	8:30am	7.5	98	10.2	10	0.05	<1.0
	3:30pm	7.4	107	7.1	21	0.03	<1.0
97/6/13	8:30am	7.5	149	9.7	20	0.07	<1.0
	3:30pm	7.5	103	9.4	17	0.06	<1.0
97/6/14	8:30am	7.6	129	7.3	26	0.07	2.78
	3:30pm	7.5	115	6.6	10	0.05	2.26

Table 1. Indicators for Quality of SBR Process and Collected Data

Fill → React → Settle → Draw → Idle

Figure 1. Flow Chart of the SBR Process

which indicates the effluent water does not reach the desired quality level. The objective of this article is to apply the quality engineering technique to improve the current process, that is, to reduce the COD value in the SBR effluent to its designed value.

Quality Engineering Technique

Quality is a continuous demand in our society. The purpose of quality control is to produce the products whose quality is designed and maintained at lowest possible cost, while providing full customer satisfaction. Quality control activities at the product planning, design, and production engineering phases are usually referred to as off-line quality control or quality engineering, whereas the quality control activities during actual production are referred to as on-line quality control (Taguchi, et. al., 1989). During the quality engineering phase, three steps should be followed:

1. System design. This step depends on the product phase during a life cycle. For example, during the research and development phase, system design involves the development of a prototype design and determination of materials, parts, components, and assembly system. In the production engineering phase, the determination of the manufacturing process is involved.
2. Parameter design. In this step, the levels (values) of controllable factors (design parameters) are selected to minimize the effect of noise factors on the functional characteristics of the product. Controllable factors are the process or product parameters that can be set by the experimenters or designers, whereas noise factors are those over which the experimenters or designers have no direct control but which vary with outer environment. Parameter design is a low-cost approach and thus should be applied to improve the quality first.
3. Tolerance design. This step applies if the reduction in variation of the functional characteristic achieved by parameter design is insufficient. Narrow tolerances are then specified for the deviations of design parameters in relation to the levels determined by the parameter design. Tolerance design is a high-cost approach and should not be applied unless parameter design can not improve the quality significantly.

Parameter design, introduced by Dr. Genichi Taguchi, is based on the concept of fractional factorial experimental design (Montgomery, 1997). Two major goals of parameter design are to minimize the process or product variation and to design processes or products so that they are robust to environmental conditions. “Robust” means that the process or product performs consistently and is relatively insensitive to factors that are difficult to control. In general, parameter design is to specify the nominal parameter values such that the variability transmitted from uncontrollable (or noise) factors is minimized (Barker, 1986).

Two important tools used in parameter design are orthogonal arrays and signal-to-noise (S/N) ratio (Phadke, 1989). Orthogonal arrays allow the experimenters or designers to study many design parameters simultaneously so that the information about the design parameters can be obtained with minimum time and resources. The signal-to-noise ratio is simply a quality indicator by which the experimenters or designers can evaluate the effect of changing a particular design parameter on the performance of the process or product.

The procedure to conduct the parameter design involves the following eight steps:

1. State the problem(s) of concern and the objective(s) of the experiment.
2. Select the quality indicator(s) or characteristic(s).
3. Select the parameters (or factors) that may influence the selected indicator(s), and then, identify controllable and noise factors.
4. Plan the levels for each factor.
5. Select the appropriate orthogonal arrays (OAs), and then assign the controllable factors to the columns of the inner OA and the noise factors to the columns of the outer OA. If the interaction(s) between the controllable factors may influence the indicator(s), the interaction(s) should be also assigned to the columns of the inner OA.
6. Conduct the experimental tests described by trials in OAs.
7. Analyze the results of the experimental trials and obtain the expected optimal combination of factor levels.
8. Conduct the confirmation experiment.

The planning phase includes steps 1 through 5, the conducting phase is step 6, and the analysis phase includes steps 7 and 8. Taguchi has tabulated 18 basic OAs that we call standard OAs. These arrays are two-level, three-level, or mixed. The two-level OAs are especially useful in screening experiments that determine whether each of controllable factors should be considered in parameter design. The confirmation experiment is very important in parameter design, particularly when screening or small fractional factorial experiments are utilized. The purpose of the confirmation experiment is to validate that the optimal conditions suggested by the experiment do indeed give the projected improvement. If the outcome of confirmation experiment is consistent with the experimental objective(s), the experimental process may stop for all practical purposes, since a satisfactory solution to the problem has been obtained. If the result does not meet the objective, then there is an evidence of failure for the parameter design. There can be many possible reasons for the failure, and thus, the experimenters or designers should reexamine each steps in whole design. Usually in this case, some more experimental trials would be conducted to obtain more information on the parameters.

Parameter design has been successfully applied in various fields of engineering and business for process or product improvement (Anand, 1991; Lulu and Rao, 1990; Shina, 1991). In this article, we will mainly use parameter design procedure to reduce the COD value in the SBR effluent and, consequently to improve the quality of wastewater treatment.

Screening Experiment and its Result

In the wastewater treatment plant under study, the current COD value in the SBR effluent is too high and can't meet its designed value. Apparently this affects the quality of the effluent water. Therefore, the experimental objective is to reduce the COD value in the SBR effluent to its designed value such that the water quality can be maintained, and

CONTROLLABLE FACTOR	***Code***	***Level 1***	***Level 2***
Filling Height	A	1.2 meters	1.8 meters
Reaction Time	B	240 minutes	300 minutes
Settling Time	C	60 minutes	80 minutes
pH Value	D	6.5	8.0
Temperature	E	32 °C	35 °C
Amount of PAC*	F	10 ppm	30 ppm
Concentration of MLSS**	G	6000 ppm	10000 ppm
NOISE FACTOR	***Code***	***Level 1***	***Level 2***
Amount of Oil	N1	< 50 ppm	> 50 ppm
Influent COD Value	N2	< 1000 ppm	> 1000 ppm
Amount of S^{2-}	N3	< 50 ppm	> 50 ppm

* Powder Activated Carbon
** Mixed Liquor Suspended Solids

Table 2. Controllable and Noise Factors and Levels for Screening Experiment

Trial No.	Inner Array (L8) Column 1 (A)	2 (B)	3 (C)	4 (D)	5 (E)	6 (F)	7 (G)	Outer Array (L4) Column					S/N
								3 (N3)	1	2	2	1	
								2 (N2)	1	2	1	2	
								1 (N1)	1	1	2	2	
1	1	1	1	1	1	1	1						
2	1	1	1	2	2	2	2						
3	1	2	2	1	1	2	2						
4	1	2	2	2	2	1	1						
5	2	1	2	1	2	1	2						
6	2	1	2	2	1	2	1						
7	2	2	1	1	2	2	1						
8	2	2	1	2	1	1	2						

Figure 2. Layout for the Screening Experiment

the quality indicator in the experiment is the COD value in the SBR effluent. Several brainstorming sessions were held by the engineers and technicians in the plant to determine the controllable and noise factors and their levels. Since the screening experiment is decided to be conducted first, all factors are set to be two-level. These factors and levels are listed in Table 2. The interactions between controllable factors are decided to be ignored. Since there are seven controllable factors and three noise factors with each 2 levels, the L_8 OA is used as the inner array and the L_4 OA is used as the outer array. The experimental layout for the screening experiment is shown in Figure 2.

The experimental results are recorded and the corresponding signal-to-noise ratios are calculated and listed in Table 3. Since we want to reduce the COD value, i.e., we want to make the value of the quality indicator as small as possible, the signal-to-noise ratio is computed according to the following formula (Ross, 1996):

$$S/N = -10 \log \left(\frac{1}{r} \sum_{i=1}^{r} y_i^2 \right)$$

where r is the number of measurements in a trial/row and y_i is the i^{th} measured value in a trial/row. Note that the signal-to-noise ratio is always to be maximized no matter what type of the quality indicator is. Based on the signal-to-noise ratios in Table 3, a response table can be made to evaluate the effect of each controllable factor and to obtain the optimal factor level combination. The response table is shown in Table 4. From the response table, it can be seen that factors A, B and G have strong effects on the COD value and the optimal factor level combination is $A_1B_2C_1D_1E_2F_1G_1$, where the notation A_i represents the i^{th} level of the factor A. This combination does not appear in the L_8 OA. Therefore, the confirmation experiment is necessary to be conducted. The expected signal-to-noise ratio for the optimal combination is (Ross, 1996)

Expected S/N = (-41.933)+(-41.819)+ (-42.596)+(-42.684)+(-42.664)+ (-42.743) +(-40.982) - 6(-42.784) = -38.717

In the confirmation experiment, the outer OA is still L_4 array. The COD values in the SBR effluent from the confirmation experiment are 80, 74, 92 and 88 ppm which results in the signal-to-noise ratio equal to -38.464. This outcome is even better than its expected value and, consequently, the conclusion can be drawn that $A_1B_2C_1D_1E_2F_1G_1$ is the optimal combination for the screening experiment.

Further Experiment and its Result

From the screening experiment, factors A, B and G are concluded to have strong effect on the COD value. Therefore, the three factors will be studied in the further experiment. First of all, the levels of these factors are replanned and shown in Table 5. For example of factor A, the optimal level of filling height obtained from the screening experiment is 1.2 meters. Therefore, in the further experiment, if factor A is decided to be three-level, then 1.2 meters would be the second (middle) level. That is, 1.2 meters is the center point for factor A in the further experiment. The values for the first and third levels of factor A are extended from this center point to the left and to the right by an equal-space size. In our case, this size is determined to be 0.2 meter and thus, the first level is 1.0 meter and the third level is 1.4 meters. The level planning for the other factors are proceeded in the same way. Since there are three 3-level controllable factors, the L_9 array is used as the inner OA, and the outer OA remains unchanged. The resulting experimental layout is shown in Figure 3.

The experimental results are recorded and the signal-to-noise ratios are calculated and listed in Table 6. From Table 6, a response table, shown in Table 7, is made to determine the optimal factor level combination. Based on the observation from Table 7, the optimal combination should be $A_2B_3G_1$. Again, this combination does not appear in the L_9 array and, consequently, the confirmation experiment will be conducted. The expected signal-to-noise ratio for the combination $A_2B_3G_1$ is

Expected S/N = (-42.380)+ (-41.975)+(-40.827) - 2(-42.608) = -38.823

Trial No.	*COD in ppm (4 values in each trial)*	*S/N*
1	102, 115, 105, 120	-40.886
2	163, 170, 170, 171	-44.534
3	137, 148, 136, 145	-43.021
4	72, 88, 98, 107	-39.292
5	192, 236, 204, 194	-46.330
6	126, 163, 142, 148	-43.249
7	98, 115, 103, 107	-40.501
8	133, 197, 150, 181	-44.462
	Average	-42.784

Table 3. Resulting COD Values and Signal-to-noise Ratios for Screening Experiment

Factor	A	B	C	D	E	F	G
Level 1	-41.933	-43.750	-42.596	-42.684	-42.904	-42.743	-40.982
Level 2	-43.635	-41.819	-42.973	-42.884	-42.664	-42.826	-44.587
Max-Min	1.702	1.931	0.377	0.200	0.240	0.083	3.605
Rank	3	2	4	6	5	7	1

Table 4. Response Table for Screening Experiment

Factor Code	*Level 1*	*Level 2*	*Level 3*
A	1.0 meter	1.2 meters	1.4 meters
B	270 minutes	300 minutes	330 minutes
G	4000 ppm	6000 ppm	8000 ppm

Table 5. Controllable Factors and Levels for the Further Experiment

```
                                      •••••••••••••••••••••••
                                      •   Outer Array (L4)  •
•••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••
•       •  Inner Array (L9)       •Column•                  •
•       •       Column            •3 (N3)•  1  2  2  1      •
•Trial  •   1     2     3     4   •2 (N2)•  1  2  1  2      •••••
• No.   •   A     B           G   •1 (N1)•  1  1  2  2      •S/N•
•••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••
•   1   •   1     1     1     1   •                         •   •
•   2   •   1     2     2     2   •                         •   •
•   3   •   1     3     3     3   •                         •   •
•   4   •   2     1     2     3   •                         •   •
•   5   •   2     2     3     1   •                         •   •
•   6   •   2     3     1     2   •                         •   •
•   7   •   3     1     3     2   •                         •   •
•   8   •   3     2     1     3   •                         •   •
•   9   •   3     3     2     1   •                         •   •
•••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••
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Figure 3. Layout for the Further Experiment

Trial No.	*COD in ppm (4 values in each trial)*	*S/N*
1	111, 127, 109, 172	-42.425
2	137, 145, 142, 167	-43.417
3	130, 155, 148, 201	-44.117
4	134, 150, 141, 224	-44.414
5	116, 119, 89, 96	-40.488
6	114, 134, 127, 141	-42.238
7	148, 150, 127, 150	-43.172
8	198, 150, 265, 229	-46.636
9	89, 116, 75, 96	-39.569
	Average	-42.608

Table 6. Resulting COD Values and Signal-to-noise Ratios for the Further Experiment

Factor	A	B	G
Level 1	-43.320	-43.337	-40.827
Level 2	-42.380	-43.514	-42.942
Level 3	-43.126	-41.975	-45.056
Max-Min	0.94	1.539	4.229

Table 7. Response Table for the Further Experiment

The COD values from the confirmation experiment are 78, 75, 90 and 84 ppm and the resulting signal-to-noise ratio is equal to -38.271, which is better than its expected value. Therefore, it can be concluded that $A_2B_3G_1$ is the optimal combination for the experiment. That is, for the SBR process in the wastewater treatment plant under study, the parameter values should be set as follows:

Filling height: 1.2 meters
Reaction time: 330 minutes
Concentration of MLSS: 4000 ppm

The values for the other parameters (i.e., settling time, pH value, temperature, and amount of PAC) should follow the results from the screening experiment; i.e.,

Settling time: 60 minutes
pH value: 6.5
Temperature: 35 °C
Amount of PAC: 10 ppm

Conclusions

The SBR process is employed to purify wastewater in the wastewater treatment plant of the Chinese Petroleum Corporation. Collected data show that the COD value in the SBR effluent is too high and does not meet its designed value. In this article, the parameter design method is briefly reviewed and is applied to improve the SBR process by determining the nominal values of the process parameters. Three significant controllable factors have been identified in the experiment and their nominal values are: filling height 1.2 meters, reaction time 330 minutes, and concentration of MLSS 4000 ppm. By setting these parameter values, the COD value in the SBR effluent can be well controlled below its designed upper limit (125 ppm) and, consequently, the quality of the effluent water from the SBR process is significantly improved.

Parameter design is an effective and systematic approach for experimental design and has been successfully applied in various fields for process or product improvement. However, it should be noted that the planning phase is particularly critical in parameter design. Failing to appropriately identify the controllable and noise factors and to plan their levels will yield erroneous conclusions and thus increase experimental and operations costs.

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