Heterogeneous Modeling, Identification and Simulation of Activated Sludge Processes

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Abstract: Problem statement: The activated sludge system is a complex dynamic process and must account for a large number of reactions between large numbers of components. There is necessity for simulation models which describe the dynamic behavior of the activated sludge process. The application of the models in most treatment plants is limited due to lack of appropriate data acquisition and parameters identification studies. To realize this, an improvement of the operating strategies of Waste-Water Treatment Plants (WWTP) is required. The objectives of this study were to: (i) To build a process model considering mass transfer limitations and simulate an existing plant (Helwan WWTP) and validate the results using data from another existing plant with (Zenine WWTP). (ii) To adjust the model kinetic parameters of the biochemical reactions under the effect of mass transfer conditions to be prepared for simulation purposes. (iii) Study the effect of the operating conditions on the removal efficiency of both substrate and ammonia. **Approach:** A process model of the process was built considering mass transfer limitations and the three growth processes: Carbon oxidation, nitrification and denitrification. Helwan WWTP was used in order to extract the suitable stoichiometric and kinetic parameters to be used for the simulation. Helwan WWTP was used through the simulation results of the substrate (BOD) and ammonia. Egyptian Zenine WWTP was used for the testing and validation of the process model through predicting the response of substrate. **Results:** The average error of the removal efficiency in Helwan WWTP reached 3.3% for the substrate and 12.5% for the ammonia while the average error of the removal efficiency in Zenine WWTP of substrate reached 4.6%. The effects of recycle ratio, flow rate and influent substrate concentrations on the removal efficiency of the aeration tank were studied. It was found that the removal efficiency of substrate and ammonia was increased by increasing the recycle ratio, influent substrate concentrations and also increased by decreasing influent flow rates. It was found also that the sludge age increased by increasing the recycle ratio and decreased by decreasing the influent flow rates. **Conclusion:** The heterogeneous process model was able to describe the characteristics and reflects the real phenomena existing in activated sludge processes.

Key words: Activated sludge, mass transfer, carbon oxidation, nitrification, gentrification, removal, efficiency, recycle ratio, flow rate, aeration tank, sludge age

INTRODUCTION

Activated sludge is a complex dynamic process and simulation of such systems must necessarily account for a large number of reactions between a large numbers of components. There is a need for simulation models that describe the dynamic behavior of such important process process. Simulation models of the activated sludge process are believed to be useful tools for research, process, optimization and troubleshooting at full-scale treatment plants, in addition to serving a teaching and design assistance tools. However, the application of the models in most treatment plants is limited due to a lack of advanced input parameters values required by the models. To improve the operating efficiencies of current wastewater treatment plants, both municipal and industrial engineers have looked at automatic process control. This work is an extension of our previous work Ibrahim Mustafa et al.[1].

Figure 1 shows a schematic diagram of the activated sludge process where aeration basins (reactors) are typically open tanks containing equipment to provide aeration and to provide sufficient mixing energy to keep the MLSS in suspension.

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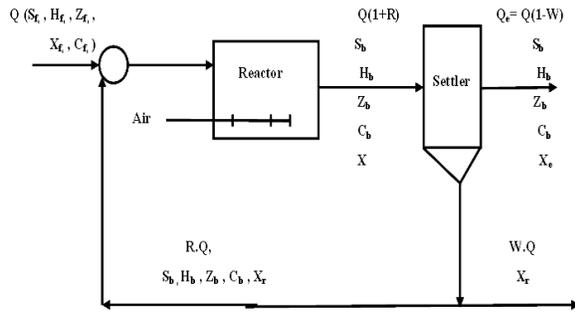
Fig. 1: Schematic diagram of the activated sludge process

The depth is mainly determined by energy transfer/mixing characteristics and usually ranges from 3-7.5 m[2]. A single piece of equipment such as diffused air, mechanical surface aerator, or jet aerator is used in many cases to provide aeration and keep the solids in suspension. Auxiliary mechanical mixers are used when the aeration does not provide sufficient mixing energy.

The secondary clarifier performs two functions in the activated sludge process. The first function, clarification, is the separation of MLSS from the treated wastewater to produce a clarified effluent that meets the effluent suspended solids goal. The other is the thickening of sludge to be recycled to the bioreactor. Since both functions are affected by clarifier depth, the design depth must be selected to provide an adequate volume for both functions [1,3]. For instance, the volume must be sufficient to store the solids during periods of high flow.

The objectives of this study are:

- To build a process model considering mass transfer limitations and simulates an Egyptian plant: Helwan wastewater treatment plant that exists in the south of Cairo and has a capacity of 350,000 m^3 day^{-1} and average removal efficiency of 85% for substrate and 62% for ammonia. To be more sure of the simulation results, the model validation was performed for Zenine wastewater treatment plant that exists in the west of Cairo and has a capacity of 330000 m^3 day^{-1} and average removal efficiency of 87.6% for substrate
- To adjust the model kinetic parameters of the biochemical reactions of the three growth processes: Carbon oxidation, nitrification and denitrification under the effect of mass transfer conditions to be prepared for the simulation purpose
- To Study the effect of the operating conditions such as flow rate, recycle ratio and feed substrate concentrations on the removal efficiency of both substrate and ammonia

Activated sludge process model development: The key to successful modeling of the activated sludge process is the appropriate assumptions to achieve a compromise between complexity and utility. The present study is concerned with the general derivation of a dynamic model of the activated sludge process in the bioreactor. The bioreactor (aeration basin) model describes the removal of organic matter, nitrification and denitrification. The bioreactor model is based on the previous biofloc model which depends on activated sludge model number one, ASM1, by considering both the mass transfer limitations and biochemical process reactions[3]. The simulation model considers the four main components: BOD readily biodegradable Substrate (S), ammonia (H), Nitrate (Z) and oxygen (C). The assumptions in the biofloc model are considered here in the process model in addition to the following assumptions:

- The power input used in the bioreactor is assumed to be 80% of the maximum value to realize complete mixing in the reactor
- The effluent biomass concentration is be neglected,
- The consumption of substrate, ammonia and oxygen in the settler is neglected
- Constant average volumetric flow rate of the influent is considered
- Constant average recycle ratio and wastage ratio is considered
- The details of the process model developed appear in the schematic diagram shown in Fig. 1

Derivation of the process model: The derivation of mass balances on the settler and the bioreactor is considered. The derivation of mass balance equations of substrate is considered by applying mass balance on the settler in order to get the biomass concentration exiting which is recycled to the bioreactor; then mass balance equations of the bioreactor will be derived.

Applying a component mass balance on biomass for the settler gives:

$$Q(1+R)X = Q(R+W)X_r + Q_e X_e \qquad (1)$$

Hence, the effluent biomass concentration is neglected, $X_e = 0.0$.

Then:

$$X_r = \left(\frac{1+R}{R+W}\right)X \qquad (2)$$

By performing mass balance on the reactor, the following equations are obtained:

Mass balance on substrate (S): If substrate consumption in the settling tank is neglected and there is substantial decrease in the water content of the settled sludge related to that measured so that:

$$S_{before\ settler} = S_{after\ settler}$$

Applying a component mass balance on substrate for the bioreactor gives:

Substrate Inflow = Outflow + Net growth + Accumulation:

$$Q\ S_f + RQ\ S_b = Q(1+R)\ S_b + K_{gs}A_{tf}\left(S_b - S_S\right) + V\frac{dS_b}{dt} \quad (3)$$

$$\frac{V}{Q}\frac{dS_b}{dt} = S_f - S_b - \frac{K_{gs}A_{tf}}{Q}\left(S_b - S_s\right) \quad (4)$$

Mass balance on ammonia (H): Ammonia nitrogen can be removed from wastewater by volatilization of gaseous ammonia. Gas stripping is most effective when contaminated wastewater is exposed to free air. Hence, this process is considered by adding a factor of ammonia stripping (G_f) to the first order differential equation of ammonia.

Applying a component mass balance on ammonia for the bioreactor gives:

$$NH_3\ accumulated = NH_3\ Inflow\text{-}NH_3\ Outflow\text{-}NH_3$$
Volatilized by air stripping:

$$\frac{V}{Q}\frac{dH_b}{dt} = H_f - H_b - G_f\frac{K_{gh}A_{tf}}{Q}\left(H_b - H_s\right) \quad (5)$$

Mass balance on nitrate (Z): Applying a component mass balance on nitrate for the bioreactor gives:

$$Nitrate\ Inflow = Nitrate\ Outflow + Net\ growth\ of$$
Nitrate + Nitrate Accumulation

$$\frac{V}{Q}\frac{dZ_b}{dt} = Z_f - Z_b - \frac{K_{gz}A_{tf}}{Q}\left(Z_b - Z_s\right) \quad (6)$$

Mass balance on oxygen (C): Applying a component mass balance on oxygen for the bioreactor gives:

$$Oxygen\ Inflow = Oxygen\ Outflow + Net\ growth\ of$$
Oxygen + Oxygen Accumulation

$$\frac{V}{Q}\frac{dC_b}{dt} = C_f + \frac{V}{Q}K_la\left(C^* - C_b\right) - C_b - \frac{K_{gc}A_{tf}}{Q}\left(C_b - C_s\right) \quad (7)$$

Mass balance on biomass (X): Applying a component mass balance on biomass for the bioreactor gives:

Input = Output + Rate of Reaction + Accumulation

Hence:

$$QX_f + RQ\left(\frac{1+R}{R+W}\right)X = Q(1+R)X - r_xV + V\frac{dX}{dt} \quad (8)$$

Hence:

$$\frac{V}{Q}\frac{dX}{dt} = X_f + \frac{V}{Q}r_x + \frac{W(1+R)}{(W+R)}X \quad (9)$$

From task group[4] the rate of reaction of heterotrophic and autotrophic biomass can be obtained as follows:

$$\begin{aligned}
r_x &= \mu_H\left(\frac{S_b}{K_s + S_b}\right)\left(\frac{C_b}{K_{oH} + C_b}\right) \\
&+ \eta_g\mu_H\left(\frac{S_b}{K_s + S_b}\right)\left(\frac{K_c}{K_c + C_b}\right)\left(\frac{Z_b}{K_z + Z_b}\right) \\
&+ \mu_A\left(\frac{H_b}{K_h + H_b}\right)\left(\frac{C_b}{K_{cA} + C_b}\right) - b_H - b_A
\end{aligned} \quad (10)$$

These dynamic model equations are first order differential equations and can be solved by the following technique.

Solution technique: The initial value problems given by the above equations are solved by Gear's method for multiple ordinary differential equations (1985). A computer program was written for this purpose. A large number of data points have been taken to improve the accuracy of the results when the parameters in the model were being estimated.

Results and Discussion: Selecting suitable kinetic and stoichiometric parameters is considered by using Helwan WWTP data. It covers also the model testing by carrying out the simulation on Helwan WWTP on substrate BOD and ammonia concentrations. Zenine WWTP was used for the testing and validation of the process model through predicting the response of substrate only as will be shown.

Parameters Evaluation: Shieh and Mulcahy[5] used an experimental procedure for the determination of intrinsic kinetic coefficients. The experimental apparatus (rotating disk biofilm reactor) provides a relatively simple, yet rigorous means for examination of

both intrinsic and mass transfer limited kinetics. It allows for direct measurement of intrinsic kinetic coefficients and biological parameters relevant to a given reaction. The intrinsic kinetic coefficient of biological denitrification measured in their study is $K_z = 2.875$ mg NO3-N_2 day^{-1} and nitrate-nitrogen effective diffusivity is De = 0.815×10^{-5} cm^2 sec^{-1}.

Alison *et al.*[6] measured the maximum specific growth rate μ_{max} and the half saturation coefficient (K_s). A simple respirometric technique was used where different volumes of concentrated wastewater were contacted with biomass and the response measured as a change in oxygen uptake rate ΔOUR. The ΔOUR was then related to the growth rate and a series of substrate concentration/growth rate relationships determined from which μ_{max} and K_s were calculated. Typical μ_{max} and K_s values published for municipal sewage are in the range μ_{max} = 1-5 day^{-1}, with typical values of 2.5 day$^{-1[7]}$. The range K_s = 6-19 mg L^{-1}, with a typical value of 12 mg L^{-1}.

Here, the component mass balance equations on the substrate, ammonia, nitrate, oxygen, autotrophic and heterotrophic biomass derived above are considered in order to extract the best values of parameters to simulate Helwan WWT plant performance. Hence, different measurements were taken from Helwan wastewater treatment plant data and an appropriate sequential quadratic programming scheme was performed to obtain the optimum set of parameters at which the theoretical predictions (the output of the simulation model program) are very close to the measured results (the output from Helwan WWTP). The data shown in Table 1 are used as input for the model program. The suitable parameters in turn will be used during the validation stage when we consider simulation of Zenine WWTP. Table 1 shows the average measured values of process parameters for Helwan WWTP.

Using the kinetic and stoichiometric parameters in the literature in ASMI we can now perform a complete simulation. However, in order to get acceptable agreements between the real and theoretical concentrations, numerical estimation of some parameters is necessary. To simplify this procedure, the relations between the effluent concentrations of the components and the kinetic and stoichiometric coefficients used in the model should be known. It was found that the effluent concentration of substrate, ammonia are directly proportional to the values of some parameters such as saturation coefficients such as K_s, K_A, K_{CA}, ... and yield coefficients such as Y_H and Y_A.

Table 1: Average values of process parameters for Helwan WWTP.

Parameter	Value
Q_o (m^3 day^{-1}) (inlet flow)	43.750
R (%)	60.000
W (%)	3.500
S_F (mg L^{-1}) (BOD)	83.000
H_f (mg L^{-1}) (ammonia)	1.030
Z_f (mg L^{-1}) (nitrate)	11.000
SVI (mL g^{-1})	57.000
(P/V) (W m^{-3})	109.700
V (m^3) (reactor volume)	3000.000
X_f (mg L^{-1}) (biomass)	50.000

Table 2: The parameter values extracted from the floc model

Symbol	Value	Explanation
Y_A	0.55	Yield for autotrophic biomass
Y_H	0.7	Yield for heterotrophic biomass
μ_A	0.42 day^{-1}	Maximum specific growth rate for autotrophic biomass
μ_H	4.35 day^{-1}	Maximum specific growth rate for heterotrophic biomass
K_s	220 mg L^{-1}	half saturation coefficient for heterotrophic biomass
K_{c1}	0.05 mg O_2 L^{-1}	Oxygen half saturation coefficient for heterotrophic biomass
K_z	0.15 mg NO$_3$-N L^{-1}	Nitrate half saturation coefficient denitrifying heterotrophic biomass
K_A	250 g NH 3-N L^{-1}	Ammonium half saturation coefficient for autotrophic biomass
K_{c2}	2 mg O_2 L^{-1}	Oxygen half saturation coefficient for autotrophic biomass
b_A	0.08 day^{-1}	Decay rate coefficient for autotrophic biomass
b_H	0.62 day^{-1}	Decay rate coefficient for heterotrophic biomass
η_g	0.8	Correction factor for μ_H under anoxic conditions
C^*	9.8 mg L^{-1}	Saturated oxygen concentration

Also, it was found that they are inversely proportional to growth rates such as μ_H, μ_A. These relations are very useful to reach the best values of kinetic and soichiometric coefficients that make the theoretical results comparatively much closer to those of the real systems.

The values given in Table 2 are considered typical for neutral pH and domestic wastewater. The selected values of the kinetic and stoichiometric coefficients shown in Table 2 represent a set of values that result in a good fit of the experimental data and the model predictions.

The following are some observations on the values shown in Table 2:

- Some parameters such as C (saturated) = 9.8 mg L^{-1}, density, diffusivities, viscosity, are adopted from the literature
- Diffusivity inside flocs is assumed to be 80% of that in pure water

- Some parameter values such as μ_H, μ_A are within the same range of activated sludge model number one, ASM1[4]
- Some parameters values such as K_S, K_A, K_{CH}…are out of the range of ASMI by Henze *et al.*[4] considering the mass transfer limitations
- The study of parametric sensitivity of the model has shown that the influence of the parameters of Y_A and K_A is not large on the effluent concentration of ammonia. It can be explained that the fraction of the autotrophs that oxidize ammonia in the aerobic growth process to the heterotrophs is very small, so the effluent ammonia is more sensitive to μ_H and b_H than μ_A and b_A for the same reason
- The assumed values for ammonia stripping factor $G_F = 0.075$ is attributed to multaneously losing of ammonia loss due to practical conditions such as agitation, temperature, exposed surface area plus non-adding any chemicals such as lime inside the aeration basin
- The value for μ_g agrees with the literature
- The average experimental value for the ratio of active biomass in flocs is nearly 0.8. This makes the effluent biomass falls in the range 2.2-3 g L^{-1}, this is in agreement with literature[8].

Model testing: Zhang *et al.*[9] performed some trials for coke wastewater treatment plant by fixed biofilm system for COD and NH_3-N removal. The experimental results showed that this system was efficient and stable in COD and NH_3-N_2 reductions. The effluent COD and NH_3-N_2 were 114 and 3.1 mg L^{-1} with removal efficiency of 92.4 and 98.8 % respectively.

In order to test the accuracy of the values obtained for the parameters, numerical runs of the model have been carried out for the simulation model that uses the parameters obtained for the model and the constants which define the characteristics of the system.

The model proposed in this study was tested in a similar manner. Helwan WWTP data, which were used for the extraction of kinetic and stoichiometric coefficient as shown in Table 2, are used in order to test the model. The theoretical results (or the model predictions) in terms of the effluent concentrations were compared against the field results of Helwan Waste-Water Treatment Plant (WWTP).

Operating data for Helwan WWTP aeration basin:

The aeration basin volume	= 3,200 m³
Cross sectional area	= 806.88 m²
Volumetric flow rate	= 43,750 m³ day⁻¹
Percentage of average Recycle ratio	= 30-120% of the feed

Percentage of average wastage ratio	= 0.1-5.0% of the feed

The power input in (W m⁻³):

For the aeration basin	= 200 kW on the basis of 80

Percentage of the available maximum power input

The technique of aeration: The technique of aeration used in the plant is mechanical surface aeration where the wastewater is agitated at the surface to promote the transfer of oxygen to the water from the atmosphere above the liquid. The surface aerators also throw water into the air to increase contact area. The agitator type used is in a cone turbine with 16 blades

Available volumetric flow rate of air = 1246.36 m³ h⁻¹. Evaluation of K_{la} according to the following correlation, K_{la} is a function of power input m⁻³ of liquid volume (P/V) in the aeration basin:

$$K_{la} = \frac{K_{la\,max}\,(P/V)}{(P/V) + k} \qquad (11)$$

Where:

V (occupied reactor volume)	= 1822.91 m³
P	= 200 kW
Hence:	
P/V	= 109.71 W m⁻³
By fitting:	
$K_{la\,max}$	= 500 day⁻¹
K	= 450
Hence:	
K_{la}	= 98.01 day⁻¹

Simulation results for Helwan WWTP: It is important to note that the effluent BOD and ammonia field data can only serve as a rough guide for evaluating the model behavior because they are very noisy[10].

Considering the previous operating data for the northern aeration basin for Helwan WWTP in the simulation model for readily biodegradable substrate BOD (S) and ammonia (H), the results shown in Table 3 and 4 were obtained.

Percentage of average removal efficiency relative error:

$$= \left| \frac{S_{out\,real} - S_{out\,theo}}{S_f} \right| * 100 \qquad (12)$$

The average removal error between the theoretical and real values of ammonia (H) comes from the air stripping operation where the assumed value of the air stripping operation where the assumed value of the air stripping factor may not be accurate enough to express the real amount which was lost when exposed to free air.

Table 3: Simulation results for Helwan WWTP, in Feb. 2002

Date	Feed			S_{out}		H_{out}		Percentage of average removal error	
	S_f(mg L^{-1})	H_f(mg L^{-1})	SVI (mL g^{-1})	Real	Theo.	Real	Theo.	S (%)	H (%)
3/2/96	83	11.0	57	12	12.075	5.3	5.593	0.010	2.67
10/2	83	12.5	56	14	12.076	3.0	6.300	2.320	26.40
13/2	90	13.1	56	20	12.700	11.0	6.670	8.110	33.10
16/2	88	12.3	57	14	12.526	4.5	6.250	1.700	14.23
21/2	69	12.0	47	17	11.000	5.3	6.800	8.750	12.50
26/2	69	11.3	53	10	10.680	3.0	5.800	12.000	4.78
Average error								3.650	18.95

Table 4: Simulation results for Helwan WWTP, in March 2002

Date	Feed			S_{out}		H_{out}		Percentage of average removal error	
	S_f(mg L^{-1})	H_f(mg L^{-1})	SVI (mL g^{-1})	Real	Theo.	Real	Theo.	S (%)	H (%)
2/3	221	18.8	57	31	20.460	10.6	11.15	4.770	4.700
6/3	427	20.6	56	39	47.000	11.9	13.47	2.820	7.620
11/3	266	20.3	56	34	41.900	15.6	13.23	2.970	11.400
23/3	280	15.4	57	48	54.330	10.2	10.10	2.300	0.650
30/3	248	23.3	47	28	23.348	12.5	13.90	2.000	6.000
Average error								2.972	6.074

In fact, for a real plant the stripping factor is not constant but depends on the practical situations. The average removal error between the theoretical and real error is as shown in the range of (6-19%).

Model validation: Helwan WWTP is used for the manipulation of kinetic parameters and stoichiometric coefficient as shown in Table 2 and used also for testing the model. However, Zenine WWTP is used for the validation of the model using the same kinetic and stoichiometric coefficients. Zenine WWTP exists in the west of Cairo. It treats wastewater in a capacity of 330,000 m^3 day^{-1}. It consists of 3 modules; each one contains 22 aeration basins. They have the same volume and the same method of aeration and different conditions. It is noted that the volumes of the aeration basins in Zenine WWTP are smaller than those of Helwan WWTP but their numbers in Zenine WWTP are greater.

Operating data for Zenine WWTP aeration basin:

- The aeration basin volume = 537 m^3
- Cross sectional area = 50 m^2
- Volumetric flow rate = 5,000 m^3 day^{-1}
- Percentage of average recycle ratio = 90% of the feed
- Percentage of Average wastage ratio = 0.5-5.0% of the feed
- The power input in (W m^{-3}): For the aeration basin = 40.33 kW on the basis of 75 % of the available maximum power input
- The technique of aeration: The technique of the aeration method used in the plant is the diffused air technique, where the air is introduced below the

surface through diffusers or nozzles, the rise has been found that $K_{la\ max}$ = 500 day^{-1}, K = 450, hence, K_{la} = 150.41 day^{-1}

Simulation results for Zenine WWTP: The previous operating data of aeration basin in module 3 for Zenine WWTP and stoichiometric and kinetic parameters shown in Table 2 are used in order to validate the simulation model. Readily biodegradable substrate BOD (S) only is used for the purpose of validation because of unavailable data for the other components such as ammonia. The simulation model was applied for a period 12 months for BOD. Table 5-10 show some simulation results for Zenine WWTP. Velocity of the bubbles creates a circulating mixing pattern in the liquid. The available volumetric flow rate of air = 1227.3 m^3 h^{-1}. Evaluation of K_{la} was done in the same way as above, using the same correlation 6 Where V (occupied reactor volume) = 208.33 m^3 and P = 40.33 kW, hence, P/V = 193.6 W m^{-1}, by fitting it from Table 5-10 it can be showed that the % average removal error of the removal efficiency of substrate (BOD) between the real and theoretical results of Zenine WWTP equals 4.634%. The results show that the theoretical and the real values of substrate (BOD) are in good agreement. These results give a good indication that the model is able to predict the output of the aeration tank in a wastewater treatment plant.

Parametric study of activated sludge process: The parametric study is expected to play an important role in the evaluation of the performance of the aeration basin in activated sludge plants. Hence, it is very important to study the performance of the aeration basin.

Table 5: Simulation results for Zenine WWTP in Jan. 2001

			S_{out}		Percentage of average removal
Date	S_f	SVI	Real	Theo.	Eff. Error S (%)
1/1	119	130	16	17.4	1.20
5/1	146	129	15	19.4	3.01
9/1	133	141	16	18.5	1.90
15/1	124	152	16	17.8	1.45
21/1	138	132	16	18.9	2.20
26/1	132	120	17	18.4	1.00
Average error					2.15

Table 6: Simulation results for Zenine WWTP in Mar. 2001

			S_{out}		Percentage of average removal
Date	S_f	SVI	Real	Theo.	error S (%)
1/3	127	128	20	17.72	1.80
5/3	160	144	23	18.90	2.50
13/3	174	164	24	20.60	2.00
17/3	166	144	22	20.20	1.10
22/3	110	101	14	16.30	2.10
31/3	135	122	30	18.30	8.67
Average error					3.03

Table 7: Simulation results for Zenine WWTP in May 2001

			S_{out}		Percentage of average removal
Date	S_f	SVI	Real	Theo.	Eff. error S (%)
2/5	130	91	15	18.30	2.54
4/5	137	95	20	18.80	1.00
6/5	111	96	13	16.70	3.33
10/5	112	111	18	16.89	1.00
15/5	117	119	18	17.30	1.50
20/5	141	143	29	19.10	7.02
26/5	160	119	27	20.31	4.20
31/5	103	150	11	16.10	4.95
Average error					3.20

Table 8: Simulation results for Zenine WWTP in July 2001

			S_{out}		Percentage of average removal
Date	S_f	SVI	Real	Theo.	Eff. error S (%)
1/7	147	141	44	18.20	17.55
4/7	95	133	11	14.80	4.00
7/7	121	116	5	16.50	9.50
10/7	101	106	10	14.50	4.45
13/7	93	91	35	14.90	21.60
19/7	127	142	20	16.94	2.90
25/7	109	175	16	15.60	0.36
31/7	140	231	8	17.80	7.00
Average error					8.42

Table 9: Simulation results for Zenine WWTP in Sept. 2001

			S_{out}		Percentage of average removal
Date	S_f	SVI	Real	Theo.	Eff. error S (%)
1/9	131	98	20	18.10	1.53
5/9	109	122	19	16.30	2.50
8/9	110	133	14	16.64	2.40
15/9	119	138	11	17.20	5.21
22/9	99	193	9	15.50	5.57
25/9	102	217	10	15.50	5.24
30/9	133	203	10	18.20	6.20
Average error					4.05

Table 10: Simulation results for Zenine WWTP in Dec. 2001

			S_{out}		Percentage of average removal
Date	S_f	SVI	Real	Theo.	Eff. error S (%)
1/12	144.0	95	24	15.8	5.70
5/12	119.0	98	13	15.4	2.00
11/12	105.0	97	11	14.8	3.62
17/12	121.7	89	28	21.0	5.75
25/12	104.0	122	29	14.7	13.75
31/12	130.0	190	10	15.0	3.85
Average error					5.78

They found that more than 97% of the organic carbon was removed and only small concentrations of the NH_4-N_2 were found in the effluent.

The data shown in Table 1 and the kinetic and stoichiometric coefficients shown in Table 2 will be considered. When one parameter is concerned with under study, the others are maintained as constants. Sludge age, θ_c, is defined as the ratio of biomass in the reactor to the net rate of biomass. It is often called solids retention time in the reacting system. It has a principal effect on the performance and capabilities of an activated sludge system. It is important in activated sludge systems because it is an operational parameter that can be physically controlled to maintain treatment performance. David *et al.*[12] landmark study linked the sludge age to the treatment efficiency thereby providing means of maintaining treatment performance by manipulating physical attributes such as wastage rate.

At steady state conditions, the net rate of biomass generation is equal to the rate at which biomass flows out of the system. If biomass is removed through the recycle line and by losses in the clarifier overflow, the sludge age, as shown in Fig. 1, is given by:

$$\theta_c(d) = \frac{VX}{QWX_r + Q_eX_e} = \frac{V(R+W)}{QW(1+R)} \tag{15}$$

where, $X_e = 0.0$.

The sludge age can be controlled either by the sludge wastage rate from the bottom of the clarifier or by the rate of sludge recycle. Through experience,

This is performed by studying the effect of operating parameters: influent flow rate, recycle ratio, wastage ratio, power input and influent composition of substrate and biomass on removal efficiency of the substrate (BOD) and ammonia.

Suwa *et al.*[11] studied the effect of the operational performance on percentage nitrogen removal efficiency by a single-stage, single-sludge activated sludge process.

operators of conventional activated sludge reactors have found that θ_c should usually lie between 3-14 days in order to produce a biological floc which can be handled easily. For θ_c less than 3 days, the biomass is not dense enough to settle easily, producing "bulking sludge". For θ_c greater than 14 days, the floc particles are too small to settle rapidly and the fraction of living cells in the biomass is low. Good sludge settling properties are essential for an efficient gravity settler operation and a stable activated sludge process. Since the sludge age largely governs how well a floc will settle, a value is chosen based upon experience and the type of sludge generated in the process.

The sludge age can be controlled by the wastage rate from the bottom of the settler or by the rate of sludge recycle. By decreasing the sludge wastage rate, the sludge age is increased. The same result can be obtained when R, the rate of recycle ratio is increased. Perdrieux and Therien[13] and Hashimoto *et al.*[14] showed that the higher the sludge age the better assimilation of the substrate by the cell and the more the rate of utilization of the stored carbon for energetic requirements.

Effect of recycle ratio: The purpose of the recycle of sludge is to maintain a sufficient concentration of activated sludge and increase the concentration of the biomass in the aeration basin. The addition of a recycle stream also dilutes the concentration of entering substrate and decreases the residence time of fluid elements in the aeration basin. So the required degree of treatment can be obtained in the time interval desired. The return of activated sludge from the clarifier to the inlet of the aeration tank is the essential feature of the process.

The recycle ratio (R (%)) is defined as the ratio between the recycle flow rate to the aeration tank influent flow rate. Figure 2 shows the effect of changing recycle ratio on the percentage removal efficiency of the substrate and ammonia at certain conditions such as S_f, H_f, C_f and (P/V). It is noted at these conditions that as R increases, the removal efficiency of substrate increases from a very small value at very low values of R (%) till it reaches 84% at R (%) = 40%, then it reaches 86% at R (%) = 80%. Finally, it becomes almost constant with further increase in R (%) where it appears that the substrate removal efficiency is not enhanced by a recycle ratio larger than 80%.

With respect to ammonia, the percentage removal efficiency increases from 33.991 at very small values of recycle ratio and reaches 52% at R (%) equal to 80% then becomes constant as R (%) increases. It is the case here also that appeared that ammonia removal efficiency is not enhanced by a recycle ratio larger than 80%. This can be explained in the first stage where removal efficiency of substrate and ammonia increases continuously when R (%) in the range increases (0-80%), the rate of biomass production increases. This produced biomass can degrade the organic substrate (BOD) and ammonia efficiently. This explains why the percentage removal efficiency increases till it reaches nearly 80%. However, in the second stage, the percentage removal efficiency becomes constant because aeration is unable to supply the excess biomass by the necessary oxygen. Also, the rate of increasing biomass concentration will be reduced as %R increases as shown in Fig. 3. When the operating conditions change, the curves in Fig. 2, will have the same shape but they may be shifted to the right or the left according to the available conditions. Figure 3 shows that the effluent biomass concentration (X_{out}) will always increase as R (%) increases due to the biomass resulting from the degradation of the substrate and ammonia.
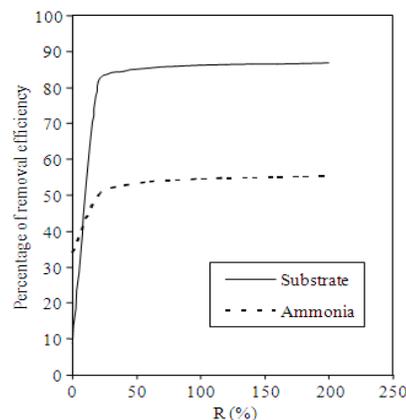

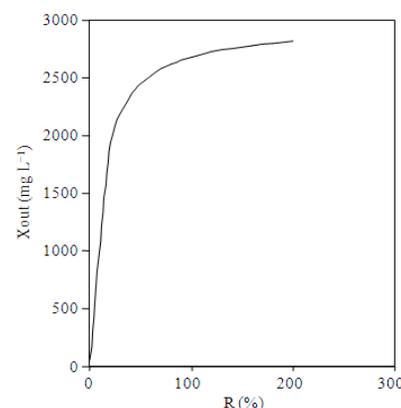Fig. 2: Effect of recycle ratio on removal efficiency
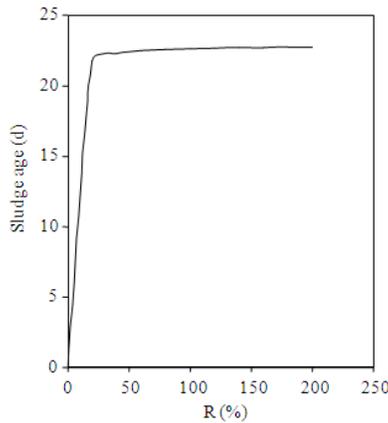

Fig. 3: Effect of recycle ratio on biomass effluent

Fig. 4: Effect of recycle ratio on sludge age

Fig. 5: Effect of flow on removal efficiency

Fig. 6: Effect of flow on effluent biomass

Yuichi Suwa *et al*.[10] showed that the higher the concentration of sludge biomass in an aeration basin, the larger the number of microorganisms and the number of flocs which possess aerobic and anoxic micro-sites inside the flocs. Thus the oxidation and denitrification rate in the aeration basin will be enhanced by higher volumetric BOD loading. Since organic matter is essential for oxidation and denitrification as the electron donor. Tashiro *et al*.[14] showed that it might be difficult to carry out simultaneous carbon-nitrogen removal when the influent is applied to this process.

Since the sludge age largely governs how well a floc will settle, it is important to study the effect of recycle ratio on sludge age. Figure 4 shows the effect of changing R (%) on the sludge age, θ_c, in the aeration tank. It is shown that θ_c increases continuously as R (%) increases. It is noted that an increasing in R (%) will increase the biomass concentration and consequently a better assimilation of the substrate by the cell can be obtained and the rate of utilization of the substrate for energetic requirements can be increased.

Hence, the sludge age can be controlled by the sludge recycle from the bottom of the clarifier.

Effect of influent flow rate: It is very important to study the effect of influent flow rate on the % removal efficiency because it is an external factor and is very difficult to control. Logically, increasing the flow rate will cause high loading on the performance of the plant. Figure 5 shows the effect of increasing the flow rate on the removal efficiency of substrate and ammonia. It is shown that the removal efficiency of substrate decreased from 100% at very small values of flow rate to 36.5% at $q = 100,000$ m^3 day^{-1}. The same pattern is repeated for ammonia but the removal efficiency of ammonia is less than that of the substrate.

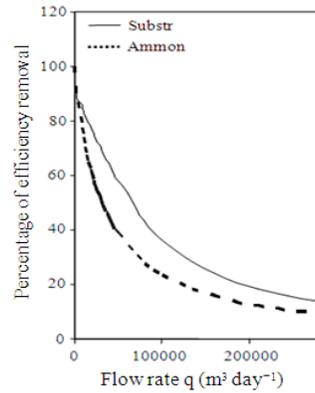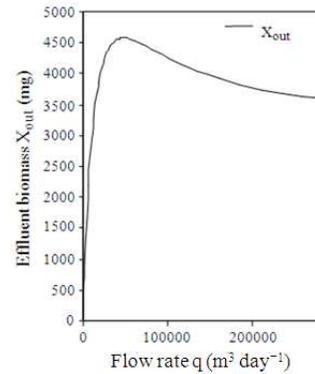Figure 6 shows that X_{out} increases from 25 mg L^{-1} till the highest value of 4577 mg L^{-1} at 50,000 m^3 day^{-1} then decreases as the flow rate increases till it becomes constant. The highest value of X_{out} (the optimum value) corresponds to critical flow rate. The microorganisms after this critical rate are washed out of the reactor faster than they are generated by the reaction under washout conditions; the concentration of biomass in the reactor decreases and the conversion of substrate decreases.

In fact, optimizing the different flow rates in the plant is an important factor in wastewater plant operation. An industrial plant should operate in a range of flow rate close to the critical to fulfill the highest effluent biomass such as Helwan WWTP which has flow rate of 43,750 m^3 day^{-1}. Maintaining a high concentration of biomass is a tempting strategy to improve plant performance, since a large biomass can degrade more organic material. However other forms of microorganisms may adapt to the high concentration of biomass which in turn makes the activated sludge process less efficient. These results agree with
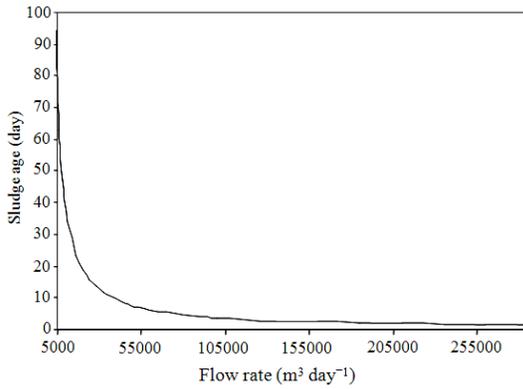
Fig. 7: Effect of flow rate on sludge age

those of Muller *et al.*[16] who showed that a very low biomass production could be achieved when a very high influent flow rate is applied.

Figure 7 shows that increasing the flow rate will decrease the sludge age in the reactor, hence, the removal efficiency of the aeration basin decreases. The microorganisms will not have enough time to oxidize the substrates and ammonia. It is required to control the influent flow rate to maintain a high conversion. The sludge age can be calculated at the critical flow rate according to Eq. 14. It equals 8.6 days; it is a good value for the sludge age that gives sufficient time to perform different biodegradations.

Effect of influent substrate concentration: The influent composition is important for the design and control of a WWTP. The concentration of influent substrate concentration determines the performance of the plant. Benefield and Molz[17] showed that although substrate treatment would not likely be affected until a very low DO was reached, a distinction between excess and low DO was made since nitrification can be limiting at DO concentrations less than 2 mg L^{-1}.

In Fig. 8, the behavior of percentage removal efficiency can be classified into two stages. In the first, the conversion of substrate increases with increasing S_f from 77.7% at small values of S_f to reach 96.5% at $S_f = 700$ mg L^{-1}. Then it becomes constant as S_f increases. It means that the output substrate concentration remains constant, but in the second stage, the effluent substrate concentration remains constant and it does not depend upon the entering substrate concentration. It appeared that the removal efficiency was not enhanced by S_f larger than 700 mg L^{-1}.

This response represents an inherent "self control" by the reactor since changes in feed concentration do not affect the output substrate concentration[13].

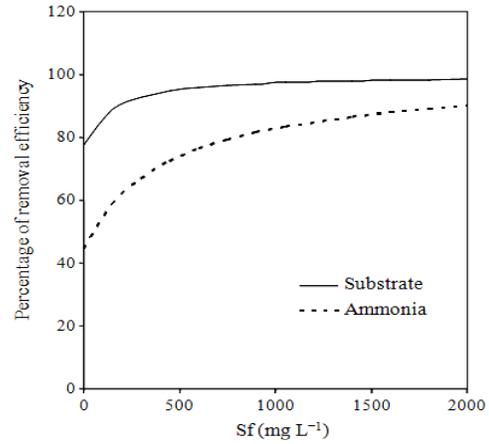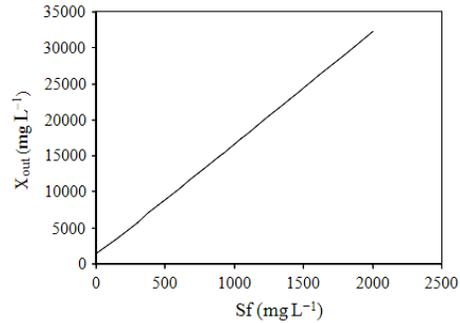Fig. 8: Effect of feed concentration on percentage of removal efficiency

Fig. 9: Effect of Feed substrate concentrations on effluent biomass (X_{out})

This can be understood by Fig. 9 where the effluent biomass (biological solids) concentration is increasing linearly as S_f increases sufficiently to handle the higher loading of the substrate. The percentage removal efficiency of ammonia increases from 44.3% at very small value of S_f then it increases continuously till it reaches 86.6% at $S_f = 1409$ mg L^{-1}.

CONCLUSION

A mathematical process model was developed for the aeration tank of the activated sludge process for four main components in addition to biomass. Identification of kinetic and stoichiometric parameters was undertaken in order to obtain suitable values of parameters (as shown in Table 2) to prepare the model for the simulation purpose and to obtain results compatible with existing activated sludge plants. It was found that some parameter values such as half saturation coefficients were found out of the range of

the activated sludge model number 1 ASM1[4] due to considering the mass transfer limitations in the floc model. Some other parameter values were assumed like the ammonia stripping factor and the other parameters like saturated concentration of oxygen were taken from ranges given in the literature.

In this study two Egyptian WWTPs were used: Helwan WWTP and Zenine WWTP. The two plants are different in some conditions such as aeration tank volume, flow rates and the aeration technique. Helwan WWTP uses the surface aeration with mechanical agitation technique but Zenine WWTP uses the diffused air technique.

Helwan WWTP data was used through the simulation of the response of different components of substrate (BOD) and ammonia. Zenine WWTP was used for testing and validation of the process model through the prediction of the substrate only. The average relative errors of the removal efficiency between the real measurements in the plant and the theoretical results of the process model were calculated. The average error of the removal efficiency in Helwan WWTP reached 3.3% for the substrate and 12.5% for the ammonia. However, in Zenine WWTP it reached 4.6% for the substrate. These results emphasize the model validation and the kinetic parameter accuracy.

A parametric sensitivity of the activated sludge process also was performed. The effects of recycle ratio, flow rate, influent substrate concentrations on the removal efficiency of the aeration tank were studied. It has been found that the removal efficiency of substrate and ammonia was increased by increasing the recycle ratio, influent substrate concentrations and also increased by decreasing the influent flow rates. It has been found that the sludge age increased by increasing the recycle ratio and decreased by decreasing the influent flow rates.

The highest value of X_{out} was determined as well as the corresponding flow (the critical flow rate). The microorganisms after the critical flow rate are washed out of the reactor faster than they are generated by the reaction under washout conditions; so the concentration of biomass in the reactor decreases and the was calculated at the critical flow rate according to 8.6 days; this is a good value for the sludge age and gives sufficient time to perform different biodegradations.

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