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Modeling of Activated Sludge Bioreactor for BOD degradation in Industrial Wastewater

Dagde, Kenneth, K., Nwokoma, Darlington, B.M.
Department of Chemical Engineering, Rivers State University of Science and Technology, Port Harcourt, Nigeria
Department of Chemical Engineering, Federal University of Technology, Owerri, Nigeria

ABSTRACT

A model for an activated sludge bioreactor, which describes the dynamic behavior of the substrate-Biological Oxygen Demand (BOD) utilization and biomass growth, is developed. The activated sludge was modeled as system of Continuous stirred tank bioreactor (CSTR) operating isothermally. The model was solved numerically by employing the fourth order Runge-Kutta algorithm and simulated using Matlab program. The model prediction of BOD degradation (31.35mg/l) as compared to plant data (30.0mg/l) showed a deviation of 4.5%. The model simulations reveal 16h as the optimum hydraulic retention time and a recycle ratio of 1.0 for an industrial wastewater treatment plant with MLVSS of 2400mg/l and BOD concentration of 250mg/l. These results, which are in good agreement with the plant design parameters, imply that the WWT plant could be described using system of CSTR configuration.

Keywords: *modelling, activated sludge, cstr in series, substrate utilization, biomass recycling, petrochemical wastewater treatment.*

1. INTRODUCTION

Several toxic substances are released into the ecosystem through wastewater generated from municipal and industrial plants. This poses serious threat to human health and the environment, since most of these substances are mutagenic or carcinogenic. The overwhelming needs to rid industrial wastewater of these toxic substances has not only led to strict environmental laws but also the inventing of new technologies that emphasize source reduction of pollutant and treating of unavoidable generated waste to non-toxic level prior to discharge to the receiving body. Amongst wastewater treatment options, biological treatment through activated sludge process is adjudged to possess not only the capability of plummeting organic pollutants to the stringent permissible level set by Environmental Protection Agencies, but probably the most cost effective method of destroying organics present in wastewater (Gouldar et al., 2000;Nweke et al., 2003).

The activated sludge process, developed since 1914, is a heterogenic compound, composed of microorganisms, colloidal matter, organic polymers, mineral particles and cations (Metcalf and Eddy, 2002; Ghanizadeh et al., 2001). Several vital parameters are predisposed by the hydraulic flow characteristics in the activated sludge reactor including organic matter removal and sludge settling properties (Horan, 1990). The two basic reactor types are plug flow and complete mix. The principle of a conventional activated sludge involves the aeration of the primary-treated wastewater and activated sludge, which are acclimated microorganisms in a tank or basin (Henze et al., 1995). After an ample aeration time the flocculent activated sludge solids are separated from the wastewater in a secondary clarifier. The clarified wastewater is further treated or discharged. A fraction of the sludge produced is recycled into the aeration tank to increase resident sludge concentration, while the excess sludge is wasted. The functional species responsible for the removal of soluble, readily biodegradable organic pollutant found in industrial wastewater are heterotrophic bacteria (Reardon et al., 2002; Okoh, 2003; Mendonca et al., 2004; Otenio et al., 2005).

The activated sludge reactor is a complex physical-chemical-biological system with internal interactions between process variables and dynamic changes in influent wastewater flowrate, concentration, and composition (Makinia et al., 2005). This informs the growing interest in developing and applying mathematical models for real-time wastewater treatment plant monitoring and control, trouble-shooting, operator training and optimising design of new plant (Andrew, 1992; Grady, 1998; Lee et al., 2002; Dagde et al., 2006). The purpose of this research is to develop a model for degradation of organic pollutants found in industrial wastewater using activated sludge configuration. To keep the topic convenient, consideration will only be limited to BOD reduction in the wastewater. The results from the developed model are compared with data obtained from full-scale industrial wastewater treatment (WWT) plant.

2. MODEL DEVELOPMENT

2.1 Bioreactor Model

The continuity equation from the mass balance in the systems of continuous stirred tank bioreactor as depicted in Figure 1, were used to develop the mathematical model to monitor the flow of the biomass and substrate concentrations in the bioreactor.

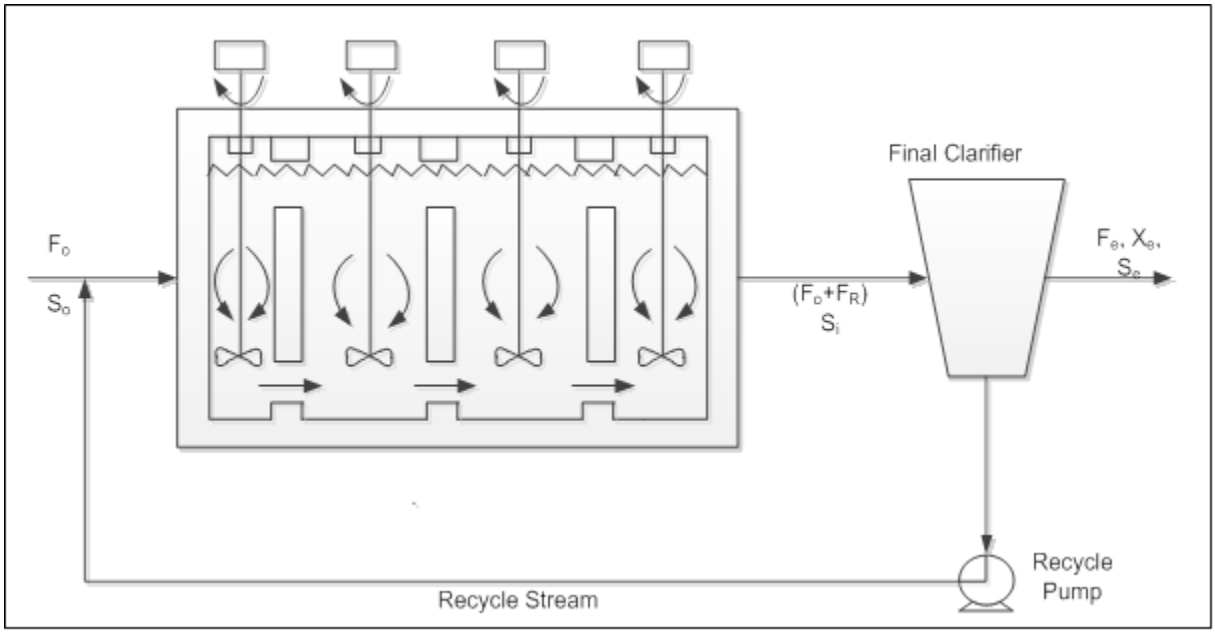

Figure 1: Hypothetical Representation of the n-Series of Complete Mix Activated Sludge Reactor

In developing this model the following assumptions were made:

a. Readily biodegradable substrate, which serves as source of carbon and energy, are present and accessible to the heterotropic bacteria.

b. The major reactions are oxidation of the carbonaceous substrates by/ endogenous decay of the heterotrophics

c. Sufficient aeration is maintained in the bioreactor, that is oxygen is sufficiently present, so as to achieve good mixing of the liquid phase.

d. The limiting substrates are consumed by all of the different heterotrophic bacteria.

e. The feed stream is sterile; the biomass is acclimated and introduced at exponential growth phase.

f. The clarifier is ideal: with assumed constant volume. No reaction at the clarifier.

g. All particles reside for the same amount of time in the bioreactor.

2.1.1 Mass Balance for Biomass

Under these assumptions, the component balance for the biomass concentration in the first compartment of the bioreactor is obtained

$$\frac{dX_1}{dt} = \frac{1}{\tau}\left[1+\varepsilon\right]\left(X_0 - X_1\right) + R_{X1} \quad (1)$$

where $\tau = \frac{V}{F}$ = Hydraulic retention time, $\varepsilon = \frac{F_0}{F_R}$ = Recycle ratio (-), V_1 = Volume of reactor 1 (l), X_0 = Inlet biomass concentration (mg/l), F_0 = Flow in (l/h), F_R = Recycled flow (l/h), R_X = Biomass growth rate (mg/l.h), t = time (h).

For the second, third and n-compartment of the bioreactor we obtain

$$\frac{dX_2}{dt} = \frac{1}{\tau}\left[1+\varepsilon\right]\left(X_1 - X_2\right) + R_{X_2} \quad (2)$$

$$\frac{dX_3}{dt} = \frac{1}{\tau}\left[1+\varepsilon\right]\left(X_2 - X_3\right) + R_{X_3} \quad (3)$$

$$\frac{dX_n}{dt} = \frac{1}{\tau}\left[1+\varepsilon\right]\left(X_{n-1} - X_n\right) + R_{X_n} \quad (4)$$

2.1.2 Biomass Kinetic Model

For mixed microbial consortia, as in activated sludge, the net growth rate accounting for both microbial explosion and endogenous death is expressed as (Michael, 1987):

$$R_X = (\mu - \varpi)X \quad (5)$$

whereμ = Specific microbial growth rate (h^{-1}), ϖ = Microbial decay rate (h^{-1}).

The specific growth rate for substrates is expressed as (Monod, 1945; Grady et al., 1999; Reardon et al., 2000; Polymenakou and Stephanou, 2005):

$$\mu = \mu_m \frac{S}{K_S + S} \quad (6)$$

where S = Substrate concentration (mg/l), μ_m = Maximum specific growth rate (h^{-1}), K_S = Half saturation constant (mg/l).

Substituting Equation (6) into (5) gives:

$$R_X = (\mu_m \frac{S}{K_S + S} - \varpi)X \quad (7)$$

Substituting Equation (7) into equations (1 - 4) and re-arranging gives:

$$\frac{dX_1}{dt} = \frac{1}{\tau}\left[\left(1+\varepsilon\right)\left(X_0 - X_1\right)\right] + \left[\mu_m \frac{S}{K_S + S} - \varpi\right]X_1 \quad (8)$$

$$\frac{dX_2}{dt} = \frac{1}{\tau}\left[\left(1+\varepsilon\right)\left(X_1 - X_2\right)\right] + \left[\mu_m \frac{S}{K_S + S} - \varpi\right]X_2 \quad (9)$$

$$\frac{dX_3}{dt} = \frac{1}{\tau}\left[\left(1+\varepsilon\right)\left(X_2 - X_3\right)\right] + \left[\mu_m \frac{S}{K_S + S} - \varpi\right]X_3 \quad (10)$$

$$\frac{dX_n}{dt} = \frac{1}{\tau}\left[\left(1+\varepsilon\right)\left(X_{n-1} - X_n\right)\right] + \left[\mu_m \frac{S}{K_S + S} - \varpi\right]X_n \quad (11)$$

2.2 Mass Balance for Substrate

As the substrate is degraded due to biochemical reactions, a negative sign is attached to the substrate utilization term. The component mass balance for the substrate concentration in the first compartment of the bioreactor is obtained as

$$\frac{dS_1}{dt} = \frac{1}{\tau}\left(1+\varepsilon\right)\left(S_0 - S_1\right) - R_{S_1} \quad (12)$$

Where S_0 = Inlet Substrate concentration (mg/l), R_S = Substrate utilization rate (mg/l.h),
For the second, third and n-compartment of the bioreactor we obtain

$$\frac{dS_2}{dt} = \frac{1}{\tau}\left(1+\varepsilon\right)\left(S_1 - S_2\right) - R_{S_2} \quad (13)$$

$$\frac{dS_3}{dt} = \frac{1}{\tau}\left(1+\varepsilon\right)\left(S_2 - S_3\right) - R_{S_3} \quad (14)$$

$$\frac{dS_n}{dt} = \frac{1}{\tau}\left(1+\varepsilon\right)\left(S_{n-1} - S_n\right) - R_{S_n} \quad (15)$$

2.2.1 Substrate Kinetic Model

The substrate utilization rate, R_S is expressed as

$$R_S = \frac{\mu X}{Y} \quad (16)$$

Substituting Equation (6) into Equation (16) yields:

$$R_S = \frac{\mu_m X}{Y}\left(\frac{S}{K_S + S}\right) \quad (17)$$

Substituting Equation (17) into Equations (12 - 15) gives:

$$\frac{dS_1}{dt} = \frac{1}{\tau}\left(1+\varepsilon\right)\left(S_0 - S_1\right) - \frac{\mu_m X}{Y}\left(\frac{S_1}{K_S + S_1}\right) \quad (18)$$

$$\frac{dS_2}{dt} = \frac{1}{\tau}\left(1+\varepsilon\right)\left(S_1 - S_2\right) - \frac{\mu_m X}{Y}\left(\frac{S_2}{K_S + S_2}\right) \quad (19)$$

$$\frac{dS_3}{dt} = \frac{1}{\tau}\left(1+\varepsilon\right)\left(S_2 - S_3\right) - \frac{\mu_m X}{Y}\left(\frac{S_3}{K_S + S_3}\right) \quad (20)$$

$$\frac{dS_n}{dt} = \frac{1}{\tau}(1+\varepsilon)(S_{n-1} - S_n) - \frac{\mu_m X}{Y}\left(\frac{S_n}{K_S + S_n}\right) \quad (21)$$

Equations (8 – 11) and (18 – 21) are the model equations for change of biomass and substrate concentrations in a system of continuous stirred tank bioreactors with recycle.

3. MATERIALS AND METHODS

The biomass and substrate concentrations from an industrial Activated Sludge Process of the wastewater treatment unit are given in Table 1. The operating parameters are given in Table 2.The kinetics parameters as shown in Table 3 were obtained from literatures. These values were used for this work because the experimental conditions for which the kinetics was obtained agree with operating conditions of the wastewater treatment plant studied in this work.

For simplification, a constant maximum specific growth rate that does not change when the identity of limiting resource changes is assumed for this work, though previous study showed that the physiological state of an organism changes as the identity of limiting resource changes (μ_{max}, Y and K_S change when the identity of limiting resource changes (Harder and Dijkhuizen, 1983). This assumption was based on previous work describing microbial growth on essential substrates using Liebig's law if minimum and assuming a constant maximum specific growth rate (Baltzis and Fredrickson, 1988; Huisman and Weissing, 1999).

Table 1 Biomass and Substrate Concentration from the biological Treatment Unit

Component	Concentration (mg/l)	
	Inlet	Outlet
Biomass (MLVSS*)	2400	8145.33
Substrate (BOD)	250	≤30.0

* MLVSS – Mixed Liquor Volatile Suspended Solids (mg/l)

Table 2 Process Parameters from the Biological Treatment Unit

Parameters	Values
Design Flow Rate (l/h)	75,000
Reactor Volume (l)	1200000
Hydraulic Retention Time, θ (h)	16.0
Recycle Ratio	1.0

Table 3: Kinetic Parameters (Schroder et al., 1997; Grady et al., 1999; Goudar et al., 2000, Metcalf and Eddy, 1991)

Parameters	Values
Half Saturation Coefficient, K_S ($mgBOD_5/l$)	60.0 mg/l
Maximum Specific Growth rate, μ_m ($mgBOD_5/mgVSS/h$)	$0.251h^{-1}$
Yield coefficient, Y_G ($mgVSS/mgBOD_5$)	0.6mg/mg BOD_5
Endogenous decay coefficient, ϖ	$2.4day^{-1}$ ($0.1h^{-1}$)

3.1 Solution Technique

3.1.1 Initial and Boundary Condition

Initially (i.e at t=0),the concentration of substrate (BOD) in the waste water inoculated with the biomass is uniform at 250mg/l, while the concentration of biomass introduced is 2400mg/l.

The initial and boundary conditions of Equations (8 – 11) and (18 – 21) may then be defined as

$$At \quad t = 0; X(0) = 2400 mg/l, S(0) = 250 mg/l \quad (22)$$

$$At \quad t = t, X = X(t), S = S(t) \quad (23)$$

Equations (8 – 11) and (18 – 21) were solved simultaneously using the above initial and boundary conditions, and the parameters in Tables 1 – 3 using fourth order Runge-Kutta algorithm implemented in MATLAB.

4. RESULTS AND DISCUSSION

The results for Biomass concentration and substrate (BOD mg/l) degradation in the series of CSTR are given in Tables 4 and 5, respectively. The comparison of the exit BOD concentration from the model prediction and Plant data is given in Table 6. It shows that the model prediction deviated from the Plant data by 4.5%, which implies that the model is reasonable.

Table 4: Biomass Concentration in the CSTR in Series

Time (-)	Reactor 1	Reactor 2	Reactor 3	Reactor 4	Reactor 5	Reactor 6
0	2400	13247.24	73120.55	80359.22	81234.38	81340.18
5	3562.19	19662.16	26900.83	27775.99	27881.8	27894.59
10	4600.302	25392.21	32630.88	33506.04	33611.84	33624.63
15	5527.582	30510.5	37749.17	38624.33	38730.13	38742.92
20	6355.863	35082.34	42321.02	43196.17	43301.98	43314.77
25	7095.714	39166.09	46404.76	47279.92	47385.72	47398.51
30	7756.576	42813.84	50052.51	50927.67	51033.47	51046.26
35	8346.883	46072.14	53310.82	54185.97	54291.78	54304.57
40	8874.167	48982.58	56221.26	57096.41	57202.22	57215.01
45	9345.156	51582.3	58820.97	59696.13	59801.93	59814.72
50	9765.862	53904.46	61143.13	62018.29	62124.09	62136.88

Table 5: BOD Concentration in the CSTR in Series

Time (-)	Reactor 1	Reactor 2	Reactor 3	Reactor 4	Reactor 5	Reactor 6
0	250	202.41214	157.712807	116.9241	81.385564	52.550222
5	227.106448	180.61581	137.3942	98.613545	65.757627	40.270401
10	215.18844	169.4013	127.137878	89.661957	58.513728	35.02726
15	209.000206	163.65534	121.99674	85.337275	55.220603	32.850481
20	205.791896	160.71841	119.430003	83.261816	53.738923	31.958866
25	204.129914	159.21925	118.15131	82.269219	53.075608	31.595808
30	203.269349	158.45453	117.515004	81.79532	52.779348	31.448338
35	202.823856	158.0646	117.198543	81.569254	52.647167	31.388499
40	202.593264	157.8658	117.041199	81.461456	52.588221	31.364227
45	202.473914	157.76446	116.962979	81.410063	52.561939	31.354384
50	202.412144	157.71281	116.924096	81.385564	52.550222	31.350393

Table 6: Comparison of Model Prediction and Plant Data

Parameter	Model Prediction	Plant Data	% Deviation
Exit BOD Concentration, mg/l	31.35	30.00	4.5

Figure 2 shows the profile of biomass in each stage of the biooxidation tank. It represents a typical microbial growth curve having the usual lag phase, followed by exponential growth (between stage n = 1 and n = 3), then stationary phase (between n = 3 and stage n = 6). It indicates that the concentration of the microorganisms along the stages to a point where it becomes stationary due to depletion/ shortage of food (substrate –BOD).

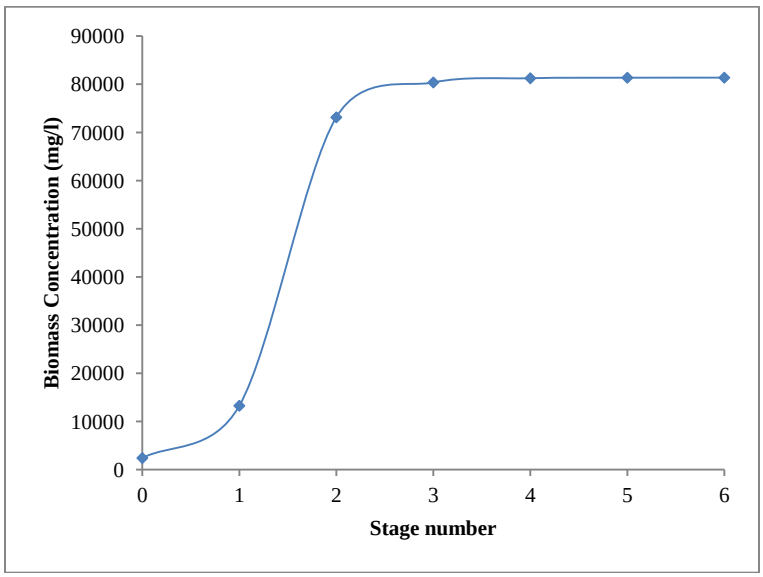

Figure 2: Profile of Biomass of each Bioreactor Stage

The BOD concentration profile with time for the n-staged Continuous stirred tank bioreactor is depicted in Figure 3. It indicates that the BOD concentration reduces with time from stage 1 to stage 6. The profile of exit BOD at each Bioreactor unit is illustrated in Figure 4. It shows that the BOD concentration reduced from 250mg/l in the 1st unit to 31.35mg/l in the 6th unit, which further divulges that the exit BOD concentration decreases along the units.

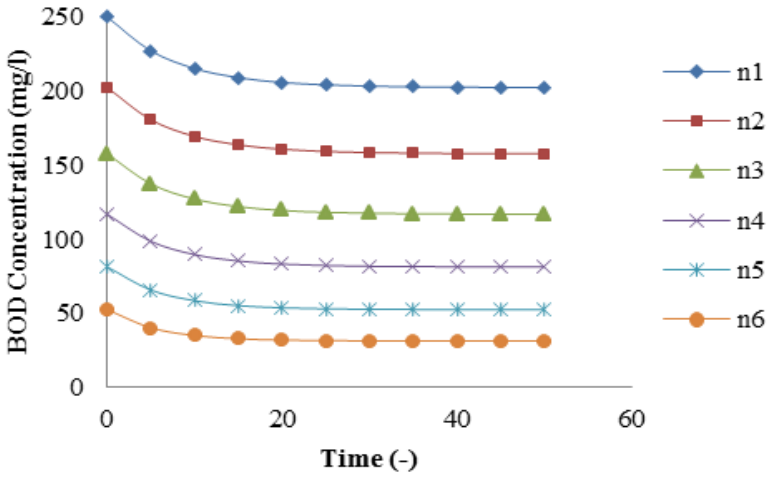

Figure 3: Profile of Exit BOD of each Bioreactor Stage

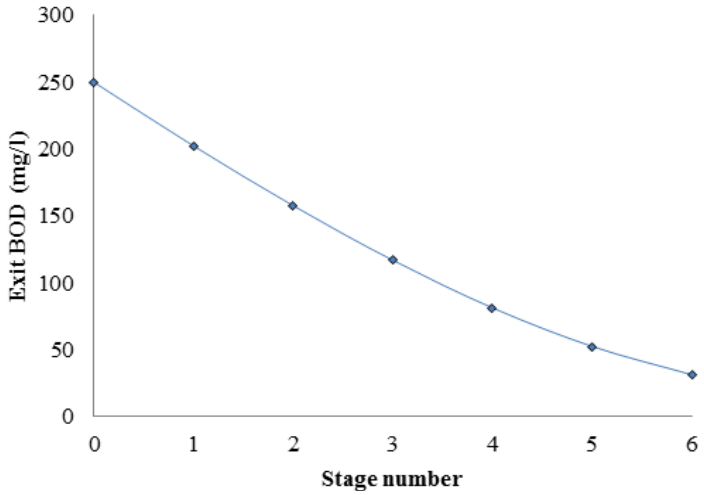

Figure 4: Profile of Exit BOD of each Bioreactor Stage

Effect of Hydraulic Retention Time on Exit BOD of each Bioreactor unit

Figure 5 shows the effects of hydraulic retention time τ on the exit BOD of the bio-oxidation tank. It illustrated that the exit BOD concentration decreases with increase in hydraulic retention time (for $\tau > 16h$). It also shows that bio-oxidation terminated at the 5th tank (for $\tau > 16h$), while for less than 16h hydraulic retention time ($\tau \leq 16$), the bio-oxidation proceeded to the 6th tank.

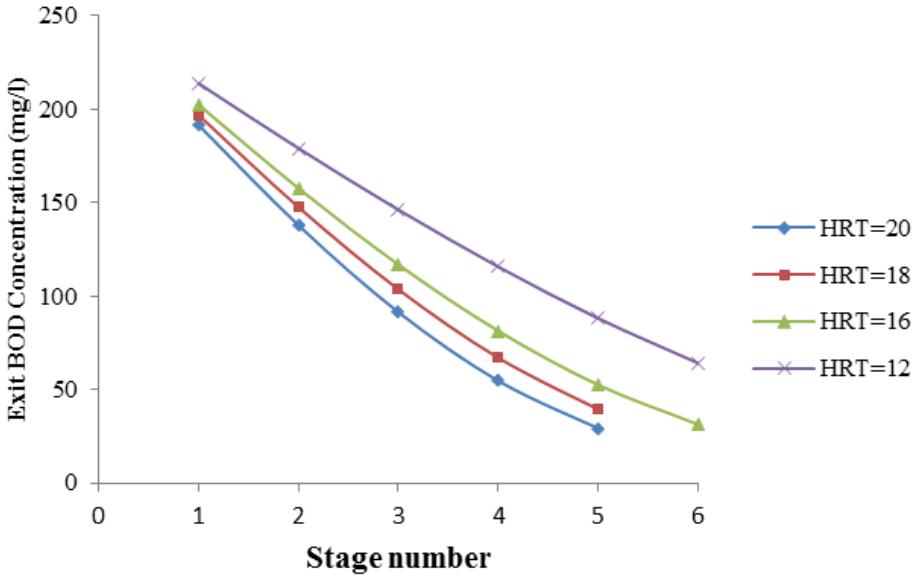

Figure 5: Effect of Hydraulic Retention Time on Exit BOD of each Bioreactor unit

Effect of Recycle ratio (Ɛ) on Reactor Performance

In activated sludge process, effort is made to increase the substrate utilization rate without increasing the specific substrate utilization rate. This is achieved by recycling the acclimatized biomass back to the bio-oxidation tank. Figure 6 shows the effect of recycle ratio on the exit concentration of the last unit of the series of Continuous stirred tank bioreactor. It divulges that as the recycle ratio increased from 0.25 to 1.0, the exit BOD concentration reduced from 250mg/l in the 1st unit to 31.35mg/l in the 6th unit, which implies that the exit BOD concentration reduces with increase in recycle ratio. Thus, it is favorable to operate at a 100% recycling, though it may increase the operating cost.

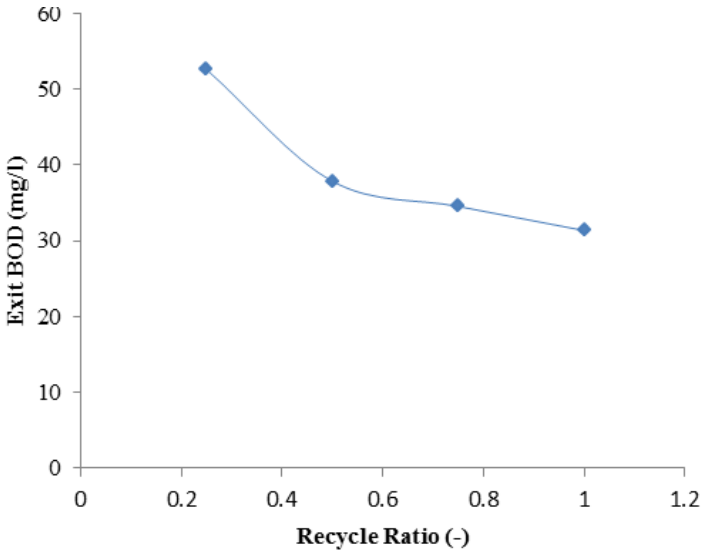

Figure 6: Effect of Recycle Ratio on Exit BOD of each Bioreactor unit

Effect of inlet BOD on Exit BOD of each Bioreactor unit

Figure 7 shows the effect on inlet BOD concentration on final effluent discharge. It illustrates that increase in inlet BOD concentration to 350mg/l led to an increase in exit BOD concentration of 80.68mg/l in the 6th unit, which is above FEPA standard of 30mg/l for BOD discharge. It is therefore advisable to maintain the inlet BOD concentration within the Plant design specification of 250mg/l.

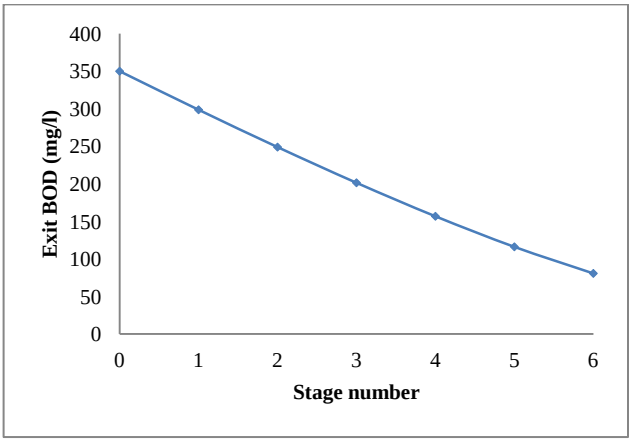

Figure 7: Effect of Inlet BOD Concentration on Exit BOD of each Bioreactor unit

5. CONCLUSION

A mathematical model for the Biological Oxygen Demand (BOD) biodegradation in system of Continuous stirred tank bioreactor is presented. The biodegradation kinetic parameters for the model were obtained from literature and the model was verified with data obtained from an industrial wastewater treatment facility. There was reasonable agreement between predicted effluent BOD concentration and that of the plant data. The effluent discharge value of 31.35 mg/l was predicted from the model as compared to 30.0 mg/l obtained from Plant data, which indicates a percentage deviation of 4.5. Model simulation of the hydraulic retention time showed an economic incentive in operating the system with moderate values of the residence time. The optimum hydraulic retention time and recycle ratio for the activated sludge system studied in this work were found to be 16h and 1.0, respectively, which are in agreement with the plant data. This suggests that the developed model can be used for process optimization, simulation and control.

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