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Process Design and Application of Aerobic Hybrid Bioreactor in the Treatment of Municipal Wastewater

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***Abstract*—**Hybrid bioreactor having both suspended-growth and attached-growth bacteria is found a novel and excellent bioreactor system for treating the municipal wastewater containing inhibitory substrates too. In this reactor a fraction of substrate is used by suspended biomass and the remaining by attached biomass resulting in the competition between the two growths for the substrate. The combination of suspended and attached growth provides the system with enhanced biomass concentration and sludge age more than those in ASP. Similar to attached growth system, the hybrid bioreactor ensures considerable efficiency for treating toxic and refractory substances in wastewater. For the process design of hybrid bioreactor a suitable mathematical model is required. Although various mathematical models were developed on hybrid bioreactor in due course of time in earlier research works, none of them was found having a specific simplified solution of the corresponding models and without having any drawback. To overcome this drawback authors already developed a simplified mathematical model for process design of a hybrid bioreactor. The present paper briefly highlights on the various aspects of process design of an aerobic hybrid bioreactor for the treatment of municipal wastewater.

***Keywords*—**Hybrid bioreactor, mathematical model, process design, application, municipal wastewater.

I. Introduction

HYBRID bioreactor is the biological system where both suspended and attached growth biomass occur simultaneously. Suspended sludge-biofilm process is an aerobic hybrid process which combine suspended sludge with attached growth process by the incorporation of biofilm media into aeration tank of activated sludge process [7], [1], [9], [15]. The aeration tank was made hybrid bioreactor also by providing plastic nets vertically inside the tank [4], [6]. In this reactor competition for substrates exist between two different growths of bacteria. However, a suitable mathematical model is needed in the process design that considers two growths for a single substrate in a completely mixed system.

Slowly biodegradable substances in the wastewater are generally the aliphatic and aromatic organic compounds, inorganic salts, organic solvents etc which pose unique problems in wastewater treatment, due to their resistance to biodegradation and potential toxicity to the environment and human health. Those compounds are difficult to treat in conventional biological treatment process and are termed as refractory or recalcitrant. It is the hybrid bioreactor which takes up challenges for stabilizing those slowly biodegradable substances. Rational analysis for the appropriate process design for predictions pertinent to the performance of the said reactor is extremely needed.

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II. Role of Hybrid Bioreactor in Wastewater Treatment

The combination of suspended and attached biomass improved effluent quality, solids settling and promoted nitrification. The hybrid bioreactor system can eliminate recirculation of biomass by omitting the secondary clarifier and thereby economizing the entire process. Further the process reduces the volume of the tank thereby making optimization in reactor design and also imparts stability to the treatment system. In the past there was a problem in increase in biomass in a conventional activated sludge reactor due to difficulty in separation of large quantity of biomass in the secondary clarifier. These problems are eliminated in the hybrid bioreactor because of the attachment of a portion of biomass to the support medium. It has been established that two to five fold increase in biomass concentration is possible in hybrid bioreactor compared to that in a conventional activated sludge process [4]. Hybrid bioreactor has been satisfactorily used for the treatment of wastewater containing slowly biodegradable /recalcitrant substances. Solid retention time is higher for the adhered biomass than for the biomass flocs in suspension thereby making compatible for growth of nitrifying microorganisms preferentially onto the support [1].

III. Problem Scenario

So far, a few numbers of model expressions for the hybrid bioreactor was developed and almost none of them considered the concurrent growth of both suspended and attached biomass except the model proposed by [10]. However, the numerical solution obtained by *Regular Falsi* method in that case was an approximate one. In other cases, model expression for hybrid bioreactor was developed using either a set of dimensionless algebraic equation [8] or some graphical tools [2], which lead to an approximate solution. Earlier the numerical analysis method like *regular falsi technique*, *pseudo analytical tool* [10], [11], *normalized loading curve* were used to calculate the effluent substrate concentration in a hybrid bioreactor and no satisfactory result was obtained. Out of all, pseudo analytical appeared to be effective, because it simplified the analysis of biofilm segment in as hybrid bioreactor. However, it also could not provide an accurate solution and ultimately it was difficult to predict the performance of the hybrid bioreactor.

Therefore a proper process design for hybrid bioreactor finds its relevance for predicting its performance.

IV. Selection of Mathematical Model for Process Design

Chi-Yuan Lee (1992) has developed following model equation for the process design of hybrid bioreactor [10].

$$S_0\text{-}S_w - \frac{kSw\theta YaJ\,\frac{bs}{bt}}{(K+Sw)(\frac{1}{\theta c}+bd-\frac{YkSw}{K+Sw})} - aJ\theta=0 \qquad (1)$$

in which, J=substrate flux into the biofilm (mg/cm^2/day), S_0=entering substrate concentration (mg/cm^3), S_w=Exiting substrate concentration in bulk liquid (mg/cm^3), k=maximum specific rate of substrate use (per day), Ə=empty bed hydraulic detention time (hr), Əc=solid retention time (hr), K=half velocity coefficient (mg/cm^3), a=specific surface area of supporting media (cm^{-1}). b_s=biomass loss rate due to shearing from biofilm, day^{-1}, b_t=total biomass loss rate from biofilm, day-1, b_d= biomass decay coefficient, day^{-1} and Y=bacteria yield coefficient.

The drawback of this model was that no explicit relationship between exiting substrate concentration (S_w) and Substrate flux (J) was established. Therefore, it was difficult to determine the flux (J) because S_w and J are interdependent. Moreover, the substrate flux mentioned above should be the average substrate flux in the biofilm. In addition, the methodology for determining the average substrate flux was very complex. Furthermore, in the above model, there is no provision for calculating the effective biofilm thickness (Le) for ascertaining the type of biodegradation like aerobic, facultative, anaerobic etc. Regular falsi technique, traditionally applied for the numerical solution of the said model was also inconvenient and found approximate.

A computer program was developed for integrated fixed film activated sludge system for removing soluble COD and nutrients [14]. However, that model too was found very complicated and it did not consider the simultaneous growth of both suspended and attached biomass.

Later, modelling of hybrid bioreactor was accomplished assuming the reactor comprised of two units in series. The first reactor unit was modeled applying biofilm principle and the second one was modeled with the concept of activated sludge process [6], [5]. The limitation of those models was that suspended and attached growth systems were not considered simultaneously instead initially attached growth and subsequently suspended growth was simulated.

A simplified mathematical model was developed for a biofilm activated sludge reactor to calculate the substrate flux in the biofilm under substrate limiting condition [5]. The drawback of this model is that the analysis can be made for the targeted effluent concentration i.e. when the effluent substrate concentration is known priori. Another model of hybrid bioreactor reactor was proposed by [3]. In this model also the concurrent growth of both suspended and attached growth was not considered. However, in true sense the hybrid bioreactor is of completely mixed in nature. In this model the partial mixing condition was assumed. Again, no specific analytical solution of the same was developed, instead the special case like zero order and 1st order kinetics were simulated separately in the mass balance equation. Weighted average of the flux was derived by means of first and zero order kinetics without dividing the biofilm in small divisions in the said model.

Thus all the existing mathematical models which were developed for process design of a hybrid bioreactor suffer from a common drawback in determining the average substrate flux within biofilm and the effective biofilm thickness. In most of the existing models there is no specific analytical solution, which is simple in nature.

In view of all such limitations and drawbacks, a simplified model for hybrid bioreactor was developed by [12], [13] for easily determining the output parameters like exiting substrate concentration in bulk liquid, average substrate flux in the biofilm and effective as well as total biofilm thickness. The conceptual diagram of aerobic hybrid bioreactor considered in developing the model is shown in Fig. 1. Typical substrate profile assumed within the biofilm for model development is also shown in Fig. 2.

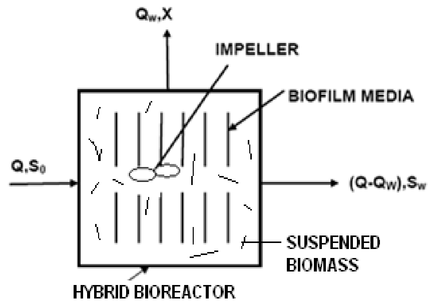

Fig. 1 Conceptual diagram of Aerobic Hybrid Bioreactor

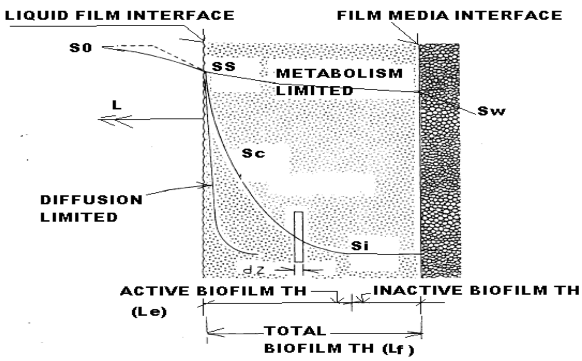

Fig. 2 Typical substrate profile within the Biofilm

A. Analytical Validation of the Selected Model

The performance of this model was examined with a set of representative input variables and standard kinetic data. The results were compared with similar outputs available in standard literatures as shown in Table I.

From Table I, it is evident that the selected model perfectly corroborates with the available ones. It is much simpler than all the existing models and involves no tedious calculation. In view of that the proposed model is considered to be validated with analytical data.

TABLE I
COMPARISON OF OUTPUT PARAMETERS (S W AND J) USING VARIOUS HYBRID MODELS

S_0 mg/cc	θ hr	$θ_c$ hr	a cm^{-1}	X_f mg/cc	S_w(mg/cc)		J(mg/cm^2/day)	
					Case 1	Case2	Case1	Case2
0.43	24	12	0.9	25	0.004	0.0039	0.271	0.2785
					Case1	Case3	Case1	Case3
0.43	12	12	1.8	25	0.004	0.004	0.27	0.28
					Case1	Case4	Case1	Case4
0.16	12	12	0.154	54.63	0.08	0.07	0.79	***

*'***' indicates non-availability of data.*
Case 1: By the model developed by authors
Case 2: By the model developed by [10]
Case 3: By the model developed by [5]
Case 4: By the model developed by [6]

B. Experimental Validation of the Selected Model

The Environmental Engineering Cell, Civil Engineering Department, IIEST, Shibpur has been carrying out studies on Hybrid bioreactor for treating municipal wastewater. The schematic diagram of aerobic Hybrid bioreactor system used is shown in Fig. 3. In this study, the hybrid bioreactor is operated under *with* and *without* any recirculation of biomass. After the analytical validation is over, it was decided to conduct the experimental run under semi-batch mode, so that the results could be compared with the model predictions. Hence, the reactor was operated with varying influent substrate concentration and batch periods, but with a constant density of attached biomass. The effluent substrate concentration was measured and thereby the substrate flux was calculated for each batch operation. Those parameters were also calculated using the proposed mathematical model and compared with respective experimental results. The comparison of such output parameters (S_w and J) with their experimental values is shown in Table II.

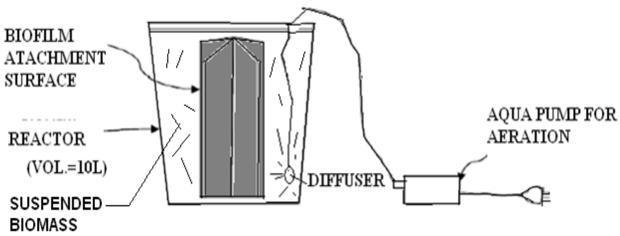

Fig. 3 Schematic Diagram of Aerobic Hybrid Bioreactor used in batch study

Table II clearly demonstrates that the effluent substrate concentrations are satisfactorily tallying with the values, predicted from the model. It is also established that the values of substrate flux derived from experimental observations and the model are close to each other depicting a nominal variation. Hence, the proposed model for the hybrid bioreactor is subsequently considered for Process Design.

TABLE II
COMPARISON OF OUTPUT PARAMETERS (SW AND J) WITH THE EXPERIMENTAL DATA OBTAINED FROM SEMI-BATCH STUDIES

S_0 mg/cc	θ	a	X_f	S_w (mg/cc)		J(mg/cm^2/day)	
				As per model by author	As per semi batch study	As per model by author	As per semi batch study
0.12	3	0.402	10	0..064	0.06	0.94	1.03
0.12	6	0.402	10	0.0349	0.036	0.6	0.587
0.12	9	0.402	10	0.0207	0.023	0.41	0.4
0.13	3	0.402	10	0.0705	0.068	1.0	1.06
0.13	6	0.402	10	0.0582	0.036	0.65	0.678
0.13	9	0.402	10	0.022	0.025	0.434	0.413
0.14	3	0.402	10	0.077	0.07	1.06	1.2
0.14	6	0.402	10	0.0415	0.038	0.69	0.73
0.14	9	0.402	10	0.024	0.027	0.458	0.433

V. PROCESS DESIGN

The process design of hybrid bioreactor is aimed to find out its volume, physical dimension and other operational requirements including oxygen for any targeted effluent substrate concentration. Besides this, it is also possible to calculate the solid retention time ($θ_c$), average substrate flux into the biofilm (J_{av}) and effective as well as total biofilm thickness. There must have certain design criteria, which can be checked accordingly for any physical configuration adopted for the reactor. The process design has been performed considering steady-state condition for biomass and substrate. Monod kinetics is assumed rational for the aerobic hybrid bioreactor treating municipal wastewater. Transport of the dissolved substrate in the liquid phase and biomass was considered due to molecular diffusion as described by Fick's law.

The rational design of the above hybrid bioreactor is contemplated employing Monod's growth pattern and associated kinetic coefficients. The values of kinetic coefficients, i.e. K, k, Y, b_t, b_s and b_d are determined experimentally. The items for the design of an aerobic hybrid bioreactor are aeration tank capacity and dimensions, aeration facilities, porosity of the reactor, optimum hydraulic retention time, solid retention time, biofilm thickness and specific surface area of the biofilm. It is observed that economical volume of the reactor can be achieved by adopting a large value of suspended biomass X and a thick biofilm in the attached surface. A common range of X between 3000 and 4000 mg/L may be considered in the design of the hybrid bioreactor for the sake of good settleability. The biomass concentration in waste sludge is denoted as X_r, which may be considered between 10000 and 12000 mg/L, in case of hybrid bioreactor with recirculation.

A. Determination of Aeration Basin Volume

The volume of the Aeration Basin (reactor) V is calculated as per the following steps:

For case 1: Hybrid bioreactor without recirculation

Step 1. Assuming rational values of MLSS concentration, X and hydraulic retention time θ for any particular value of porosity p, aJ_{avg} may be calculated as per

$$(S_0-S_w)-\frac{pkXS_w\theta}{(K+S_w)}-aJ_{avg}\theta=0$$

i.e.

$$aJ_{avg(calculated)}=\frac{S_o-S_w}{\theta}-\frac{pkXS_w}{(K+S_w)}=0$$

Step 2.

$$\theta_c=p*\theta \quad (2)$$

Step 3. MLSS, X can now be calculated as:

$$X_{calculated}=\frac{YaJ_{avg}\frac{b_s}{p*b_t}}{\frac{1}{\theta c}+bd-\frac{YkS_w}{K+S_w}} \quad (3)$$

Step 4. If $X_{calculated}=X_{assumed}$, then V=Q*θ

Otherwise, changing the value of p with the earlier value of aJ_{avg}, revised θ value can be obtained from (2) and revised calculated value of X can be obtained from (4). This trial process by changing the value of p will be continued till $X_{calculated}=X_{assumed}$ and the volume of the reactor $V=Q*\theta_{revised}$.

For case 2: Hybrid bioreactor with recirculation

Step 1. This step is same as case 1.

Step 2.

$$\theta_c=\frac{p\ \theta}{\frac{Qw}{Q}\frac{Xr}{X}} \quad (4)$$

Q_w= Waste sludge flow rate, m^3/hr; X_r=Biomass concentration in waste sludge (mg/cc). The fraction Q_w/Q should be in the range of (0.1-0.5). X_r may be considered between 10000 and 12000 mg/L.

Step 3. From the biomass balance for the suspended growth at steady state.

$$\frac{YaJ_{avg}}{pX}\frac{b_s}{b_t}-\frac{1}{\theta c}+\frac{YkSw}{K+Sw}-b_d=0$$

i.e.

$$aJ_{avg(calculated)}=\frac{X(\frac{1}{\theta_c}+bd-\frac{YkS_w}{K+S_w})}{(Yb_s/pb_t)} \quad (5)$$

Step 4. If "aJ_{avg} calculated from (2)" equals to "aJ_{avg} calculated from (5)", then V=Q*θ

Otherwise, changing the value of p with the earlier value of aJ_{avg}, revised θ value can be obtained from (2) and revised calculated value of aJ_{avg} can be obtained from (5). This trial process by changing the value of p will be continued till $aJ_{avg(calculated)}$ from (2)= $aJ_{avg(calculated)}$ from (5). The volume of the reactor $V=Q*\theta_{revised}$..

*B. The Surface Area to Be Provided =(1-p)V*a*

$$p=\frac{V-V_d}{V} \quad (6)$$

V = bioreactor empty bed liquid volume (m^3), V_d = liquid volume displaced by the media (m^3); p as calculated above has to be checked with the assumed value of p and the volume of the reactor again has to be recalculated and will be finalized till the trial process is over i.e. when calculated value of p equals to its assumed value.

C. Oxygen Requirements

Oxygen is required in the aerobic hybrid bioreactor for the endogenous respiration of the biomass in the system.

The oxygen requirement O_2 is given by,

$$O_2=\frac{Q(S_0-S_w)}{f}-1.42Q_wX_r \quad (7)$$

f=ratio of BOD_5 to ultimate BOD.1.42 = oxygen demand of biomass (g/g).

In this case, we have considered the removal of carbonaceous organic matter only.

D. Aeration Facility

The aeration facility should be provided in the reactor with air compressor along with controlled air flow through air flow-meter with an average air flow of 20-30 l/m. The airflow may be uniformly distributed through air nozzles to different slots of attached media .i.e. through eight (8) nos slots in octagonal attachment (one typical configuration) media. Mixing with aeration facility maintains proper agitation in order to make uniform suspended biomass in the aeration tank. A DO concentration more than 2.0 mg/L needs to be maintained in the reactor.

VI. Conclusion

There was no research work done earlier on the process design of an aerobic hybrid bioreactor without of which it is difficult to build up such a reactor system for the treatment of wastewater In order to go for a suitable process design a simplistic mathematical model is required for determining the outputs rationally. Obviously all the outputs are finally required for finalizing the design of an aerobic hybrid bioreactor. Although some mathematical models were developed as a preliminary step of process design there was no specific analytical simplified solutions of those models were developed which could determine all the necessary output parameters required for a process design of an aerobic hybrid bioreactor integrating the biofilm model and the classical suspended growth model simultaneously. A simplified approach for modeling of an aerobic hybrid bioreactor was already developed by the author and the present efforts were put on the process design of the hybrid bioreactor to make its successful application in the field. The development of the kinetic coefficients for the hybrid bioreactor for the treatment of municipal wastewater was also developed by the author, which have a significant role in the process design of the reactor.

For the municipal wastewater in the medium and small town the strength of wastewater varies due to disintegrated sewerage systems. For the low strength to medium strength municipal wastewater main problem for treatment is the sustaining of the biomass in the reactor. Presently adequate biomass is maintained through extended aeration and with high recirculation ratio thereby increasing the pumping cost of the treatment. For the low strength municipal wastewater which is highly biodegradable the suspended biomass is subjected to wash out. Thus the concept of attached biomass into the suspended growth system can be reasonably thought for ensuring sufficient biomass in the reactor. The footprint area of the proposed hybrid bioreactor is very small compared to the conventional reactor thereby making the economy of the treatment system.

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