Improved Hybrid Biological Reactor Design Under Mixed-Growth Conditions

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Abstract

Wastewater treatment and disposal is a pillar for safeguarding public health and sustaining socioeconomic development. The cost and design efficiency of various wastewater treatment technologies are key factors in the economic value of treated wastewater. However, biological treatment processes are among the most valuable among a vast array of treatment technologies. Biological reactors conventional design procedures are normally sufficient to achieve desired treatment efficiencies while assuming suspended-growth only and attached growth only. The ASP and RBC are typical examples. This assumption of one dominant state of microorganisms has come under increased scrutiny in recent years due to advances in biological processes. For instance, in a fluidized bed biofilm reactor or an integrated film activated sludge reactor, high fluid shear can dislodge attached cells in high quantity and increases the amount of suspended cells. These biofilm reactor, intended by design, may actually be operating like a suspended growth reactor. As such, these reactors have become a bona fide "hybrid" biological reactors. In hybrid biofilm reactors neither suspended nor biofilm kinetics are dominant. Procedures incorporating both suspended and attached growth kinetics must be used. This paper addresses possible improvement in the design procedure for hybrid reactors using a mathematical model and preliminary results of experimental testing of a hybrid reactor using petrochemical wastewater. The model takes into consideration parameters which were not considered in conventional design procedures such as biofilm diffusional resistance, suspended versus attached microorganisms substrate utilization ratio (biomass ratio in conventional design procedures), hydraulic retention time, and shear loss.

Keywords: wastewater treatment, industrial wastewater, hybrid biological reactors, mixed growth biological processes, kinetic modeling

Introduction

In most biological reactors conventional design procedures are normally sufficient to do a good job. The activated sludge process (ASP) and the rotating biological contactor (RBC are) examples of the suspended-growth and attached growth (Metcalf and Eddy, 2014). However, in innovative biological reactors neither suspended nor biofilm kinetics is sufficient (Chang et al., 2005; Rittman and McCarty, 2001). Hybrid model incorporating both suspended and attached growth kinetics must be used including provision for shear losses.

The conventional approach for the design of biological reactors assumes that microorganisms either in a suspended or attached state, but not both, are responsible for the utilization of organic substrate (Metcalf and Eddy, 2014; Sarkar and Mazumdar, 2015). This approach works well for conventional biological reactors, which strongly favor suspended or attached biomass. For example, an activated sludge process has a large aeration basin containing cells in suspension for the degradation of organic compounds. Although attached cells, or biofilm, exist on basin wall and diffusers, they are in small amounts and contribute very little to the degradation of organic substrate.

The assumption of one dominant state of microorganisms has come under increased scrutiny in recent years due to advances in biological processes (Sarkar and Mazumdar, 2015; Metcalf and Eddy, 2014). For instance, in a fluidized bed biofilm reactor high fluid shear can dislodge attached cells in high quantity and increases the amount of suspended cells and, in this case, the biofilm reactor, intended by design, may actually be operating like a suspended growth reactor. Another example is the modification of the activated process to cope with an increasing organic loading arising from population growth. Packing materials for biofilm growth have been added to existing aeration basins to increase the total biomass in the basins. As a result, these reactors have become a bona fide “hybrid” biological reactors.

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 (Sarkar and Mazumdar, 2015).

In hybrid reactors usually two questions are raised: Are suspended cells, attached cells, or both, dominating the removal of substrate in biological reactor? What is the design procedure for a hybrid biological reactor? 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 implified solution of the corresponding models and without having any drawback. To overcome this drawback a mathematical model for process design of a hybrid bioreactor needs to be developed.

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 (Chang et al., 2005).

However, the numerical solution obtained by Regular Falsi method (lee, 1992, Sez and Rittman, 1991) in that case was for a chemostat. In other cases, model expression for hybrid bioreactor was developed using either a set of dimensionless algebraic equation (Kim and Suidan, 1989) or some graphical tools (Fouad and Bhargava, 2005), which lead to an approximate solution. 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.

This study addresses these questions by using a mathematical model to quantify the rate of organic degradation by suspended and attached cells co-existing in a "hybrid community." The system modeled was a completely mixed flow (CMF) reactor containing pure culture microorganisms degrading a single substrate. The utilization of substrate by suspended cells was described by Monod equation (Metcalf and Eddy, 2014); and for attached cells by simultaneous diffusion and degradation equation. The simple CMF system allowed the modeling study to focus on the interplay between suspended and attached cells.

The objectives of this study are first to develop a hybrid model for a completely mixed flow (CMF) reactor, i.e., a chemostat. The model will be used to determine the conditions under which one of the two states, or both, will become responsible for the removal of majority of contaminants. Dominant regions for the cells will be delineated in a multi-dimensional space of process parameters. The selection of a simplistic chemostat model will allow this study to focus on interactions, rather than the effects of hydrodynamics.

The present paper briefly highlights on the various aspects of process design of an aerobic hybrid bioreactor for the treatment of municipal wastewater.

Hybrid biological reactors non-steady-state model

Kinetics of suspended cells

A schematic diagram of a hybrid biological reactor is shown in Figure 1a. the total volume $V_T\left(L^3\right)$ can be divided into void volume $V_v\left(L^3\right)$and the volume occupied by the solid material of packing media $V_s\left(L^3\right)$.

$$V_T = V_S + V_V \left(= V_S + nV_T\right) \qquad (1)$$

The void volume is where suspended cells can grow and the volume occupied by the packing solid material is not useful for treatment. Biofilm also occupies a small volume, but it is usually negligible when compared to the total volume.

The specific area for the packing media is defined as the total surface area of the packing media divided by the reactor volume $a = \frac{A}{V_T}$.

The utilization of substrate by suspended cells can generally be described by the Monod equation. The amount of pollutants removed by suspended cells per day, $r_s\left({}^{M_s}\!/_{T}\right)$, can therefore be calculated by the following equation:

$$r_s = \frac{kS_b}{K_s + S_b} X_s V_v \qquad (2)$$

Where k is the maximum specific rate constant for substrate utilization $\left({}^{M_s}\!/_{M_x.T}\right)$; K_s is the half rate concentration $\left({}^{M_s}\!/_{L^3}\right)$; S_b is the organic concentration in bulk liquid $\left({}^{M_s}\!/_{L^3}\right)$; and X_s is the concentration of suspended cells $\left({}^{M_x}\!/_{L^3}\right)$.

The concentration of suspended cells in a hybrid reactor changes due to growth from substrate utilization, endogenous decay, shear-off from biofilm, and wash-out in the effluent. These four mechanisms can be described as follows, assuming there are no cells in the influent:

$$\frac{dX_S}{dt} = -\frac{Q}{V_V} X_S + \left(\frac{YkS_b}{K_{S+}S_b} - b\right) X_S + \frac{A}{V_V} b_S L_f X_f \qquad (3)$$

Where Q is the wastewater flow rate $\left({}^{L^3}\!/_{T}\right)$; Y is the yield $\left(T^{-1}\right)$ and b is the decay $\left(T^{-1}\right)$coefficient for cells; b_s is the shear loss coefficient for attached cells $\left(T^{-1}\right)$; A is the biofilm surface area $\left(L^2\right)$; L_f is the biofilm thickness $\left(L\right)$; X_f is the cell density in biofilm $\left({}^{M_x}\!/_{L^3}\right)$; and t is the time $\left(T\right)$. The last term in the equation assumed that sheared-off attached cells become suspended cells.

$\frac{\partial X_S}{\partial t}$ =change in suspended bacteria with time

$\frac{Q}{V_V} * X_S$=suspended biomass washes out

$\left(\frac{Y * K * S_b}{K_S + S_b}\right) * X_S$=net rate of growth

$\frac{A}{V_S}$=shear loss

Biofilm kinetics

Biofilm is a layer-like aggregate of microorganisms attached on a soild surface. The thickness of the biofilm poses a diffusional resistance to the transport of substrate in the biofilm resulting in concentration profile. The cells near the exterior (i.e. liquid side) “encounter” a higher substrate concentration than those in the interior near the solid wall. The profile of substarte concentration in the biofilm (Figure 1b) can be described by the following diffusion with reaction equation:

$$\frac{\partial S_f}{\partial t} = D_f \frac{\partial^2 S_f}{\partial z^2} - \frac{kS_f}{K_S + S_f} * X_f \qquad (4)$$

Where S_f is the substrate concentration in the biofilm $\left({M_s}/{L^3} \right)$; D_f is the diffusivity of substrate in the biofilm $\left({L^2T}/{} \right)$; and z is the distance in biofilm (L).

$\frac{\partial S_f}{\partial t}$=Change in substrate concentration within biofilm

$D_f \frac{\partial^2 S_f}{\partial z^2}$=Diffusion flux term (fick’s 2nd law of diffusion)

$\frac{K * S_f}{K_S + S_f} X_f$ =Substrate degradation by the attached biomass (Monod reaction or Michellis-Menten model)

Two boundary conditions are required for the above governing equation, one at the exterior $(z = L_f)$ and another at the interior $(z = 0)$ of the biofilm:

1. Amount of water exist from bulk solution equal to that enter to bio film

   $D_f \frac{dS_f}{dz} = k_f [S_b - S_f|_{z=L_f}]$ at $z = L_f$

   (5)

   $D_f \frac{\partial S_f}{\partial z}$ = Substrate flux entering the bio film

   $K_f \lfloor S_b - S_f \rfloor$=Substrate flux leaving the bulk solution

2. The tangent is horizontal at $z = 0$

   $\frac{\partial S_f}{\partial z} = 0$

   (6)

Where k_f is the film transfer coefficient across the boundary layer $\left({L}/{T} \right)$. Microbial cells in the biofilm grow due to substrate utilization, decay due to death, and can be sheared off by the wastewater flowing in the reactor. Biofilm thickness changes as a result of these mechanisms. Because the substrate concentration varies in the biofilm, the growth rate must be integrated to obtain the time-evolution of biofilm thickness:

$$\frac{dL_f}{dt} = \int_0^{L_f} [\frac{YkS_f}{K_S + S_f} - b - b_s]dz$$

(7)

$\frac{\partial L_f}{\partial t}$=Change in bio film thickness with time

$\frac{Y*K*S_f}{K_S + S_f} - b - b_S$=Total amount of substrate consumed by the attached microorganism

Hybrid reactor model

The change in substrate concentration in the bulk phase of hybrid chemostat is caused by: 1) Substrate inflow in the influent; 2)Substrate outflow from the effluent; 3) Substrate utilized by suspended cells; and 4) Substrate utilized by the biofilm. The equations for the four mechanisms are assembled as presented in the following equation:

$$\frac{\partial S_b}{\partial t} = \frac{Q}{V_v}(S_o - S_b) - \frac{kS_b}{K_S + S_b} X_S - k_f \frac{A}{V_V} \left(S_b - S_f \big|_{z=L_F} \right)$$

(8)

Where S_o is the substrate concentration in the influent $\left(M/_{L^3} \right)$. In a chemostat, the substrate concentration in the effluent is the same as that in the reactor. Equation 3 to 8 constitute the nonsteady state model for a hybrid biological reactor in which both suspended and attached cells are responsible for the removal of organic pollutants. The solution to the model yields the time-evolution of substrate concentration, suspended cells concentration, and biofilm thickness.

The nonsteady state hybrid model consists of four governing equations describing the time-evolution of four dependent variables: bulk substrate concentration(S_b), substrate concentration in the biofilm(S_f), biofilm thickness(L_f), and the concentration of suspended cells(X_s).

Model Solution

The equations were solved using numerical integration vis Gear's method for stiff systems coded in a subroutine DISODE (Hindmarch, 1980). A FORTRAN program to solve the above differential equation from (2) to (8) was developed.

The program must provided with the some important parameters such as substrate diffusivity in bio film (cm2/day), film transfer coefficient (cm/day), max substrate specific utilization rate (1/day), half rate concentration (mg/ml), yield coefficient (mg vss/mg sub), decay coefficient (1/day), shear loss coefficient (1/day),total bio film loss coefficient (1/day) bio film density (mg vss/ml), initial bio film thickness (cm), influent substrate concentration (mg/ml), influent flow rate (ml/day), reactor volume for suspended growth (ml),surface area for biofilm growth (cm2), substrate flux into bio film (mg/day) and substrate utilization by suspended cells (mg/day)

The important parameters are listed in Table 1. It is important to know that some of these parameters were estimated in a previous study (Ahmed et al., 2017), as discussed in section 4.1, and the others are obtained from Chang et al. (2005).

Table 1. Kinetic Parameters Used in the Model Solution (Ahmed et al., 2017)

Parameter	Unit	Value
Y	1/d	4.59
$1/k$	mg-substrate/mg-VSS/d	0.12
K_s	mg/l	20
b	1/d	1.61
b_s	1/d	0.1
D_f	cm^2/d	0.67
k_f	cm/d	250
X_f	g-VSS/l	400

VSS: Volatile suspended solids.

Results and Discussions

Metcalf and eddy (2014) presented solutions for a trickling filter with different types of packing material. For example the general they presented general guidance for selection of suitable type of trickling filter out of which high surface area plastic packing parameters are shown in Table 2.

Table 2. Trickling filter design parameters for plastic packing treating primary effluent [Metcalf and eddy, 2014]

Design parameter	Units	Partial BOD removal
BOD removal efficiency	%	40-70
Ventilation	Type	Forced air
Organic loading	Kg. BOD/m3.d	1.6-3.5
Hydraulic loading	M3/m3.d	40-100
Recirculation ratio	QR/Q	0-2
Depth	M	0.9-6
Effluent quality	BOD, mg/l	>30

Additionally, the water environment federation (WEF) (Metcalf and Eddy, 2014) provided empirical solution for high surface area plastic packing media. WEF solution is used as means of illustrating the use of the model developed in this paper and as a comparison between the experimental results obtained (Ahmed et al., 2017, Ahmed et al., 2018) and the model results. The comparison is shown in Table 3 and Figure 1.

Table 3. Using the WEF (2011) (Metcalf and Eddy, 2014) formulation for plastic packing to compare with model and experimental results

Type of wastewater	Flow (ml/min)	So (mg/l)	Se (mg/l)	% Removal	Se WEF (mg/l)	Se Model (mg/l)
Domestic	50	18	8	55	8.5	9
Petrochemical	50	92	38	58	43	39
petrochemical	100	83	39	53	77.5	40

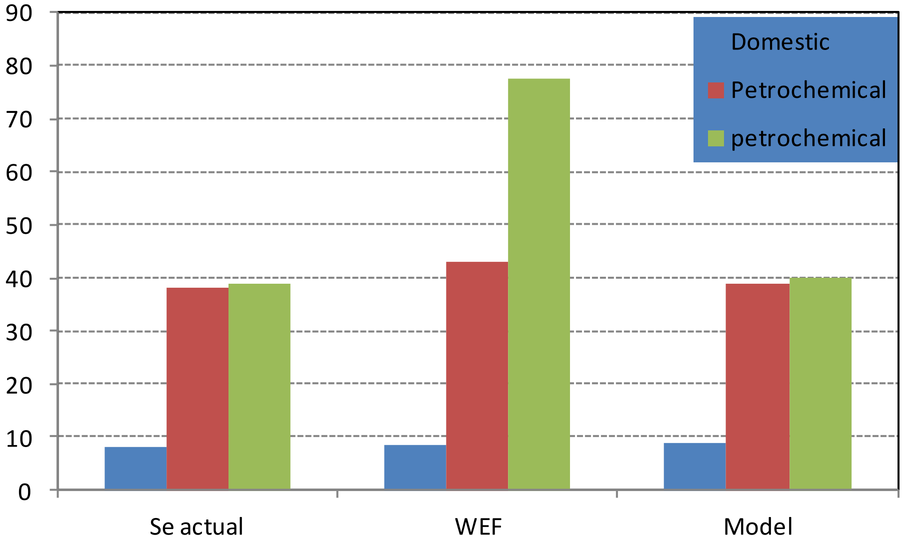

Figure 1. Comparison of Model vs. WEF Solution.

It is clear that the model is able to predict the performance in a better way than the WEF solution especially at higher flow rates. Additionally, the model is able to give a better understanding and knowledge of the controlling and limiting steps. The model results indicated that biomass measurement, which has been used alone by previous researchers, is inadequate to determine the dominant microorganisms responsible for substrate utilization (Ahmed et al., 2017). Diffusional resistance in the biofilm can decrease the rate of substrate removed by the biofilm. A thick biofilm with low substrate diffusivity may not degrade a greater amount of substrate than suspended cells.

These results indicate that care must be taken when designing and operating a biological reactor to ensure that cells responsible for the removal of organic substrate are dominant as intended.

Conclusions

In this paper, model simulations illustrating the flexibility in operation for a hybrid reactor are discussed. Potential benefits which may be exploited in a multi-species hybrid reactor will also be discussed.

The main conclusion of this study is that the conventional design procedure of biofilm reactors has drawbacks which could be overcome by the use of a more detailed mathematical model. The mathematical model is very is advantageous in its output than the empirical formulation to study and design biofilm wastewater treatment processes. More specifically:

- The mathematical model can reasonably predict the process performance especially at higher flow rates where , e.g. WEF 2011 formulation, over estimate process parameters.
- The mathematical model help obtaining better estimates for process parameters can be used to scale up the process.

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References

Ahmed M., Mydlarczyk A., and Abusam A. 2017. Kinetic modeling of GAC - IFAS chemostat for petrochemical wastewater treatment. *Journal of Water Resources and Hydraulic Engineering*. 6(**2**): 27-33.

Ahmed M., Al-Dhafeeri A., Mydlarczyk A. 2018. Predominance of attached versus suspended growth in a mixed-growth, continuous-flow biological reactor treating primary-treated petrochemical wastewater. *Arabian Journal for Science and Engineering*. Accepted 17 May 2018.

Chang, H. T., S. J. Parulekar and M. Ahmed. 2005. A dual-growth kinetic model for biological wastewater reactors. *Biotechnology Progress* **21**(2):423–31.

Fouad, M and Bhargava. R 2005. Mathematical model for the biofilm-activated sludge Reactor. *Journal of Environmental Engineering*, 131(4), pp 557- 562.

Hindmarsh, A. C. (1980) “LSODE and LSODI, two initial value ordinary differential equation solvers,” ACM-SIGNUM Newsletter, 15(4), 10-11.

Kim. R. and Suidan. T. 1989. Approximate algebraic solution for a biofilm model with the monod kinetic expression. *Water Research*, 23(12), pp. 1491-1498

Lee, Chi-Yuan. 1992. Model for Biological Reactors Having Suspended and Attached Growths. *Journal of Environmental Engineering*, 118(6), pp. 982-987.

Metcalf and Eddy. 2014. *Wastewater Engineering: Treatment and Resource Recovery*. NY: McGraw-Hill.

Rittman, B., and P. McCarty. 2001. *Environmental Biotechnology: Principles and Applications*. New York: McGraw-Hill Science Engineering.

Saez. P. and Rittmann. B. 1991. Accurate Pseudo analytical solutions for steady state biofilm. *Biotechnology and Bioengineering*. 39, pp. 790-793.

Sarkar, S. and Mazumder, D. 2015. Process Design and Application of Aerobic Hybrid Bioreactor in the Treatment of Municipal Wastewater. *International Journal of Chemical and Molecular Engineering*. 9(3), 500-504.

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