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MODELING A SYSTEM OF ROTATING BIOLOGICAL CONTACTOR (RBC) FOR BIODEGRADATION OF PHENOL IN INDUSTRIAL WASTEWATER

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ABSTRACT

A model for a 4-stage Rotating Biological Contactor (RBC) for the biodegradation of phenol from industrial wastewater has been developed using the mass conservation principles. The kinetics for biodegradation of phenol and oxygen utilization were obtained from literature under the same operating conditions. The systems of non-linear differential ordinary differential equations obtained were integrated numerically using the fourth-order Runge-Kutta algorithm adapted to a Visual Basic 6.0 computer program. Model predictions of 0.0505mg/l obtained for effluent phenol concentration, compares favorably well with the plant data of 0.05mg/l with a maximum deviation of 1.0%. A biodegradation of approximately 70mg/l at residence time of approximately 10hours, 56mg/l at residence time of approximately 8.5hours, 57mg/l at residence time of approximately 7.5hours, and 68mg/l at residence time of approximately 6.0hours with a constant oxygen concentration utilization of 0.087mg/l, were obtained from the first, second, third and fourth-stage respectively. Functional parameters such as retention time, rotational speed, respiratory coefficient and biomass concentration were simulated to study its effect with a view to obtain optimum efficiency.

Keywords: Modeling, Rotating biological contactor, Substrate & oxygen utilization, Biomass recycling, Refinery wastewater treatment, Biodegradation, Simulation.

Contribution/ Originality

This study contributes in the existing literature by developing a model that can be adapted for simulation of industrial RBC unit, unlike other works on RBC which requires extensive experimental studies to obtain data. It improves on earlier work by presenting a four-stage model as against a lumped model.

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1. INTRODUCTION

Industrial wastewater is one of the important pollution sources in the pollution of the water environment. Industrial wastewater from industries like refineries, petrochemical plants, pharmaceuticals, paint industries, tanning and finishing of leather, coal gasification and phenol-based polymerization processes contain phenol which constitute serious threat to the flora and fauna, animals and human being because of its toxic and hazardous nature [1]. The toxic and hazardous nature of phenol has been extensively studied [2, 3]. The use of Rotating Biological Contactor (RBC) in aerobic treatment of industrial wastewater such as decolourization [4] nitrification [5] iron oxidation [6] and domestic sewage [7] has been overwhelmingly successful because of the advantages of RBC over other types of wastewater treatment facilities. RBC has high effluent quality, high contact time, high process stability, resistant to hydraulic shock or organic loading, low sludge production, no risk of channeling; the process is relatively silent compared to dosing pumps for aeration and large active surface area. It is easier to operate, low cost of maintenance and very effective [8-10]. An RBC consists of a series of closely spaced, circular, plastic disks that is attached to a rotating horizontal shaft. The bottom of about 40% of each disk is submerged in a tank containing the wastewater to be treated. The biomass film that grows on the surface of the disks moves into and out of the wastewater as the RBC rotate. While the microorganisms are submerged in the wastewater, they absorb organics (phenol); whereas when they are rotated out of the wastewater, they are supplied with needed oxygen.

In earlier works on RBC, most of the parameters used in their models cannot be easily obtained without extensive experimental studies, thus the model cannot be adapted for simulation of industrial RBC unit [11, 12]. Dagde, et al. [1] developed a model to predict phenol biodegradation in a RBC process but lumped the 4-stage RBC unit as a single stage. In the present paper, models of a typical four-stage Rotating Biological Contactor (RBC) for phenol bio-degradation in industrial wastewater is presented.

2. MODEL DEVELOPMENT

2.1. Enzyme and Biodegradation Kinetics

In wastewater treatment systems, it is more convenient to deal with biomass than bacterial numbers. Therefore, Monod developed an empirical expression for the specific growth rate based on the effect of a single limiting substrate as:

$$\mu = \frac{\mu_{\max}[S]}{K + [S]} \tag{1}$$

In biochemical process, a portion of the substrate is used for microbial growth. Hence for substrate balance, the yield is introduced. The yield Y is defined as:

$$Y = \frac{mass\ of\ \ cell\ \ \ formed}{mass\ of\ \ substrate\ consumed} \tag{2}$$

Therefore,

$$\frac{1}{Y}\mu = \frac{1}{Y}\frac{\mu_{\max}[S]}{K+[S]} \tag{3}$$

This implies that the Monod's equation relates the specific growth rate, based on essential component of growth to the concentration of substrate. where, Ks is the half – saturation constant, that is, the concentration S when $\mu = \frac{\mu_m}{2}\left(\frac{Kg}{m^3}\right)$, $\mu_{\max}$ is the maximum growth rate, and S is the concentration of limiting substrate.

The specific growth of biomass in a rotating biological contactor with simultaneously growth limiting concentrations of phenol and oxygen, the relationship is:

$$\mu = \mu_{\max}\left(\frac{S}{Ks+S}\right)\left(\frac{U}{Ku+U}\right) \tag{4}$$

2.1.1. Biodegradation and Substrate Utilization Kinetics

The rate of biomass increase is proportional to the initial biomass concentration and is represented by the first – order equation:

$$\frac{dX}{dt} = \mu X \tag{5}$$

where, $\frac{dX}{dt}$ is the growth rate of biomass $(kg/m^3.day)$, X = Concentration of biomass (kg/m^3), μ = Specific growth rate constant (day^{-1}).

Substituting equation (4) into Equation (5) yields

$$\frac{dX}{dt} = \mu_{\max}\left[\left(\frac{S}{Ks+S}\right)\left(\frac{U}{Ku+U}\right)\right]X \tag{6}$$

Substrate is converted to biomass as the biomass feeds on the substrate for cell growth and metabolism. If all substrate S could be converted to biomass X, then the rate of substrate utilization is:

$$-\frac{dS}{dt} = \frac{dX}{dt} \tag{7}$$

Equation (7) is similar to the energy conservation equation, which states that dissipation equals production. Equation (7) holds only for ideal solutions. But such idealization cannot occur due to inefficiencies in the conversion process and a yield coefficient $(Y<1)$ is introduced such that the rate of utilization is in excess of the rate of biomass generated. Therefore, in real situation,

$$-\frac{dS}{dt} = \frac{1}{Y}\frac{dX}{dt} \tag{8}$$

where Y is the fraction of substrate converted to biomass.

Substituting equations (6) into equation (8) yields:

$$-\frac{dS}{dt} = \frac{\mu_{max}}{Y}\left[\left(\frac{S}{Ks+S}\right)\left(\frac{U}{Ku+U}\right)\right]X \tag{9}$$

Thus, equation (6) for biomass production and equation (9) for substrate utilization are the fundamental biological design equations for different design configurations.

2.2. RBC Model Developments

Figure 1 shows a schematic sketch of a four-stage Rotating Biological Contactor (RBC). The influent enters through the first stage of the bio-reactor and is degraded in the four stages of the bio-reactor to an acceptable environmentally friendly level before it finally leaves to the sedimentation basin to the environment.

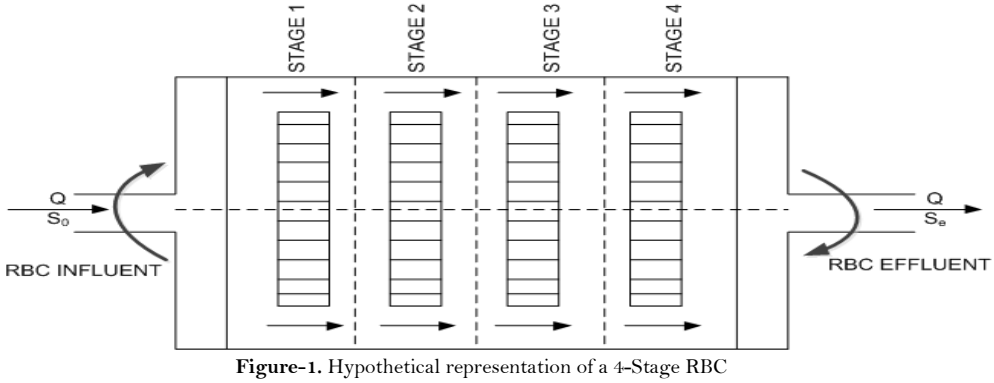

Figure-1. Hypothetical representation of a 4-Stage RBC

Where Q is the volumetric flow rate of the substrate and S_0 and S_e are the concentration of the substrate at the inlet and exit of the RBC respectively.

2.2.1. Model Assumptions

In developing the model the following assumptions were made:

i) Well-mixed conditions exist in the RBC due to aeration and mixing as the rotary disc rotates, hence we can assume uniform concentration in the radial direction.

ii) The enzymes are immobilized; hence substrate flow is due to both diffusive mass transfer and bulk flow.

iii) Reaction occurs at the same temperature hence the system is isothermal.

iv) Oxygen generated in the system due to surface renewal equals oxygen consumed in the system.

v) The mass of liquid adheres to the same bio-film throughout the disc rotation.

vi) Microorganism concentration is assumed constant throughout the biofilm.

vii) Diffusivity coefficients of substrate and oxygen are based on water as medium.

viii) Model is valid only for steady state condition, since the bio-film thickness is constant

2.2.2. Material Balance for the Substrate

Under these assumptions, applying the conservation principle to the substrate and incorporating the rate of its disintegration, we have

$$AD_S \frac{dS_n}{dl} = Q(S_n - S_{n+1}) - \frac{X\mu_{\max}}{Y}\left(\frac{S_n}{K_S + S_n}\right)\left(\frac{U_n}{K_U + U_n}\right)V \qquad (10)$$

Equation (10) can be written in dimensionless form by defining a dimensionless length in the reactor, Z , as:

$$dZ = \frac{dl}{L_R}, \qquad dl = dZL_R \qquad (11)$$

Where l is the axial length of the bio-reactor and L_R is the actual length of the bio-reactor.

Substituting equation (11) into equation (10) yields:

$$\frac{AD_S}{L_R}\frac{dS_n}{dZ} = Q(S_n - S_{n+1}) - \frac{X\mu_{\max}}{Y}\left(\frac{S_n}{K_S + S_n}\right)\left(\frac{U_n}{K_U + U_n}\right)V \qquad (12)$$

Multiplying equation (12) by L_R / AD_S gives:

$$\frac{dS_n}{dZ} = \frac{vL_R}{D_S}(S_n - S_{n+1}) - \frac{(L_R)^2 X\mu_{\max}}{D_S Y}\left(\frac{S_n}{K_S + S_n}\right)\left(\frac{U_n}{K_U + U_n}\right) \qquad (13)$$

$$where,\ v = \frac{Q}{A}(\text{Rotating Velocity}),\ l = length\ of\ reactor$$

$$But,\ v = \varpi r \quad (\text{since the velocity is angular})$$

Therefore equation (13) becomes:

$$\frac{dS_n}{dZ} = \frac{\omega r L_R}{D_S}(S_n - S_{n+1}) - \frac{(L_R)^2 X\mu_{\max}}{D_S Y}\left(\frac{S_n}{K_S + S_n}\right)\left(\frac{U_n}{K_U + U_n}\right) \qquad (14)$$

2.2.3. Material Balance for Oxygen Utilization

Oxygen is generated within the system and transferred in the system due to surface renewal of the exposed disc. It is assumed that all the oxygen generated in the system is used up by the biomass for cell maintenance and growth. Hence oxygen can be seen as a substrate (since the micro organisms also feed on it). Under these assumptions, applying the conservation principle to oxygen utilization and incorporating the rate of its utilization, we have

$$AD_U \frac{dU_n}{dl} = Q(U_n - U_{n+1}) - \left[\frac{Q_{O_2} X_n}{Y}\mu_{\max}\left(\frac{S_n}{K_S + S_n}\right)\left(\frac{U_n}{K_U + U_n}\right)\right]V_r \qquad (15)$$

Where, Q_{O_2} is the respiratory coefficient $\left(\frac{\text{kg oxygen}}{\text{kg organism}}\right)$

Similarly, by introducing dimensionless length, equation (15) gives:

$$\frac{AD_U}{L_R}\frac{dU_n}{dZ} = Q(U_n - U_{n+1}) - \left[\frac{Q_{O_2}X_n}{Y}\mu_{\max}\left(\frac{S_n}{K_S + S_n}\right)\left(\frac{U_n}{K_U + U_n}\right)\right]V_r \quad (16)$$

Multiplying equation (16) by L_R / AD_U gives:

$$\frac{dU_n}{dZ} = \frac{\nu L_R}{D_S}(U_n - U_{n+1}) - \frac{(L_R)^2 Q_{O_2} X_n \mu_{\max}}{D_S Y}\left(\frac{S_n}{K_S + S_n}\right)\left(\frac{U_n}{K_U + U_n}\right) \quad (17)$$

$$\textit{where, } \nu = \frac{Q}{A}\,(\text{Rotating Velocity})$$

$$\textit{But, } \quad \nu = \omega r \quad (\text{since the flow is rotational})$$

Therefore, equation (17) becomes:

$$\frac{dU_n}{dZ} = \frac{\omega r L_R}{D_S}(U_n - U_{n+1}) - \frac{(L_R)^2 Q_{O_2} X_n \mu_{\max}}{D_S Y}\left(\frac{S_n}{K_S + S_n}\right)\left(\frac{U_n}{K_U + U_n}\right) \quad (18)$$

2.2.4. Material Balance on the Biomass

Under the above assumptions, applying the law of conservation of mass to the biomass and assuming uniform concentration of biomass in all the stages of the bio-reactor, we obtain

$$0 = QX + V_r X\left(\mu_{\max}\left(\frac{S_n}{K_S + S_n}\right)\left(\frac{U_n}{K_U + S_n}\right) - K_d\right) \quad (19)$$

Dividing equation (19) through by V_r, gives:

$$\frac{X}{\tau} = -X\left(\mu_{\max}\left(\frac{S_n}{K_S + S_n}\right)\left(\frac{U_n}{K_U + S_n}\right) - K_d\right) \quad (20)$$

Where $\tau = Q/V_r$ is the retention time of biomass in the bio- reactor, K_d is the endogenous decay rate (to take care of die-off of micro-organism) and V_r = Volume of bio-reactor

Solving equation (20) for $X\mu_{\max}\left(\frac{s}{K_S + S}\right)\left(\frac{U}{K_U + U}\right)$ yields

$$\frac{X}{\tau} + K_d X = X_n \mu_{\max}\left(\frac{S_n}{K_S + S_n}\right)\left(\frac{U_n}{K_U + S_n}\right) \quad 21$$

Substituting Equation (21) into Equations (14) for substrate degradation and equation (18) for Oxygen utilization, yield

$$\frac{dS_n}{dZ} = \frac{\omega r L_R}{D_S}(S_n - S_{n-1}) - \frac{(L_R)^2}{D_S Y}\left(\frac{X}{\tau} + K_d X\right) \quad (22)$$

$$\frac{dU_n}{dZ} = \frac{\omega r L_R}{D_S}(U_n - U_{n-1}) - \frac{(L_R)^2 Q_{O_2}}{D_S Y}\left(\frac{X}{\tau} + K_d X\right) \quad (23)$$

Equations (22) and (23) are the model equations for predicting substrate biodegradation and oxygen utilization in a Rotating Biological Contactor.

For Stage 1, n = 1

$$\frac{dS_1}{dZ} = \frac{\omega r L_R}{D_S}(S_1 - S_0) - \frac{(L_R)^2}{D_S Y}\left(\frac{X}{\tau} + K_d X\right) \quad (24)$$

$$\frac{dU_1}{dZ} = \frac{\omega r L_R}{D_S}(U_1 - U_0) - \frac{(L_R)^2 Q_{O_2}}{D_S Y}\left(\frac{X}{\tau} + K_d X\right) \quad (25)$$

For Stage 2, n = 2

$$\frac{dS_2}{dZ} = \frac{\omega r L_R}{D_S}(S_2 - S_1) - \frac{(L_R)^2}{D_S Y}\left(\frac{X}{\tau} + K_d X\right) \quad (26)$$

$$\frac{dU_2}{dZ} = \frac{\omega r L_R}{D_S}(U_2 - U_1) - \frac{(L_R)^2 Q_{O_2}}{D_S Y}\left(\frac{X}{\tau} + K_d X\right) \quad (27)$$

For Stage 3, n = 3

$$\frac{dS_3}{dZ} = \frac{\omega r L_R}{D_S}(S_3 - S_2) - \frac{(L_R)^2}{D_S Y}\left(\frac{X}{\tau} + K_d X\right) \quad (28)$$

$$\frac{dU_3}{dZ} = \frac{\omega r L_R}{D_S}(U_3 - U_2) - \frac{(L_R)^2 Q_{O_2}}{D_S Y}\left(\frac{X}{\tau} + K_d X\right) \quad (29)$$

For Stage 4, n = 4

$$\frac{dS_4}{dZ} = \frac{\omega r L_R}{D_S}(S_4 - S_3) - \frac{(L_R)^2}{D_S Y}\left(\frac{X}{\tau} + K_d X\right) \quad (30)$$

$$\frac{dU_4}{dZ} = \frac{\omega r L_R}{D_S}(U_4 - U_3) - \frac{(L_R)^2 Q_{O_2}}{D_S Y}\left(\frac{X}{\tau} + K_d X\right) \quad (31)$$

Equations (24) to (31) are the final model equations that will be solved for the four-stage RBC. These systems of differential equations will be solved simultaneously using the following conditions initial and boundary conditions:

Initial Condition:

$S_b = 0$ (except at boundary condition), $S_b = S_o$

Boundary Conditions:

$$\left.\frac{dS}{dZ}\right]_{Z=L} = 0, \left.\frac{dU}{dZ}\right]_{Z=L} = 0, \begin{matrix} S = S_b \\ U = U_b \end{matrix} \} \text{ in bulk liquid}$$

Where, L = biofilm thickness, S_o =concentration of substrate in influent, S_b = concentration of substrate in bulk liquid, U_b = concentration of oxygen in bulk liquid.

2.3. Materials and Method

2.3.1. Materials

Data for the validation of model was obtained from the Port Harcourt Refining Company of Nigeria (PHRC). Others were obtained from literatures and journals.

The data obtained from PHRC is as tabulated below:

Table-1. Substrate and Oxygen concentration from PHRC Waste Water Treatment Plant [13]

Substrate	Concentration (mg/L)	
	Initial	Final
Phenol	250	0.050
Oxygen (Dissolved oxygen)	1st Stage: 0.5 - 1 Last Stage: 2 – 4	
Biomass	3000	3000

Table-2. Process Parameters for the Industrial Rotating Biological Contactor [13]

Parameters	Values
Reactor Length	5.5 m
Bio – Reactor Radius	0.5 m
Rotational Speed	1.6 rpm
Hydraulic Retention Time	4.8 hrs

Table-3. kinetic Parameters for phenol Biodegradation and Oxygen Utilization [14]

Parameters	Values
Yield coefficient	2.0 – 5.0
Endogenous Death rate	0.1 hr^{-1}
Diffusivity Coefficient for oxygen	5.0 * 10^{-5} cm^3/sec
Diffusivity Coefficient for Phenol	0.64*10^{-5} cm^3/sec

2.3.2. Solution Technique

The set of parabolic Ordinary Differential Equation (ODE) obtained from the model is not amenable to analytical solution technique. The equations can be solved numerically if all the parameters are known. There are two methods of solving Ordinary Differential Equations with

boundary conditions. The system of differential equations will be solved using the fourth order Runge Kutta method. Visual Basic 6.0 program was used to simulate the model.

3. RESULTS AND DISCUSSION

Table 4 summarizes the model results obtained from equations (24) to (31) for substrate degradation and oxygen concentration in the 4-staged RBC bio- reactor. A biodegradation of approximately 70mg/l with oxygen concentration utilization of approximately 0.087mg/l at residence time of 10hours, 56mg/l with oxygen concentration utilization of 0.087mg/l at residence time of approximately 8.5hours,, 57mg/l with oxygen concentration utilization of 0.087mg/l at residence time of approximately 7.5hours, and 68mg/l with oxygen concentration utilization of 0.087mg/l at residence time of approximately 6.0hours for the first, second, third and fourth-stage respectively, were obtained.

Table-4. Model Result Showing Substrate and Oxygen Concentration in the 4-Stage RBC Reactor

Length	Phenol Concentration				Oxygen Concentration			
	Stage 1	Stage 2	Stage 3	Stage 4	Stage 1	Stage 2	Stage 3	Stage 4
0.0000	250.00	181.82	125.03	68.2322	0.5000	0.3758	0.2515	0.1273
0.1000	243.20	176.15	119.36	61.4310	0.4876	0.3633	0.2391	0.1148
0.2000	236.39	170.48	113.69	54.6261	0.4752	0.3509	0.2267	0.1024
0.3000	229.59	164.81	108.02	47.8174	0.4627	0.3385	0.2142	0.0900
0.4000	222.77	159.13	102.34	41.0050	0.4503	0.3261	0.2018	0.0776
0.5000	215.96	153.45	96.66	34.1887	0.4379	0.3136	0.1894	0.0651
0.6000	209.14	147.77	90.98	27.3686	0.4255	0.3012	0.1770	0.0527
0.7000	202.31	142.09	85.30	20.5448	0.4130	0.2888	0.1645	0.0403
0.8000	195.49	136.40	79.61	13.717	0.4006	0.2764	0.1521	0.0279
0.9000	188.65	130.72	73.92	6.8857	0.3882	0.2639	0.1397	0.0154
1.0000	181.82	125.03	68.23	0.0505	0.3758	0.2515	0.1273	0.0030

3.1. Validation of Developed Model

The result obtained was validated by comparing it with industrial plant data from the New Port Harcourt Refinery. The result obtained agrees well with the plant data with a deviation of 0.12% as shown in Table 5. Hence the model can be used to optimize the operation of the bio-reactor.

Table-5. Validation Table Comparing Model Results with Plant Data

Parameter	Model Prediction	Plant Data	% Deviation
Effluent Concentration (Mg/l)	0.0505	0.0500	1.0

3.1.1. Model Discussion

In attached growth systems or fixed films bio-reactors for industrial wastewater treatment, a microbial layer is allowed to grow on the surface of a media. The media is exposed to the atmosphere, thus enabling the microorganisms to take in oxygen. Wastewater is brought into

intimate-contact with the media containing the immobilized microorganisms in a reacting vessel. The microorganisms feed on the substrate in the wastewater, thus reducing the concentration of the substrate in the wastewater. Oxygen is very important in the operations of the bio-reactor since it is an aerobic system. Oxygen is generated in the system through the surface renewal of the exposed area of the bio-disc as it rotates in and out of the wastewater. This surface renewal due to exposure to the atmosphere ensures that oxygen is continuously supplied to the microorganisms.

Figure 2 shows the profile of oxygen and phenol concentration at each stage of the four-staged RBC bioreactor. The phenol in the wastewater is degraded from a concentration of 250mg/l to 0.0505 mg/l. At this concentration the wastewater can be discharged to the environment after final testing in the observation pond. Also the concentration decreases in each stage of the reactor, as biodegradation progresses. This is because the microorganism uses the oxygen for biodegradation and cell maintenance. These cellular activities increase the oxygen utilization of the system, thus reducing the oxygen concentration in the reactor.

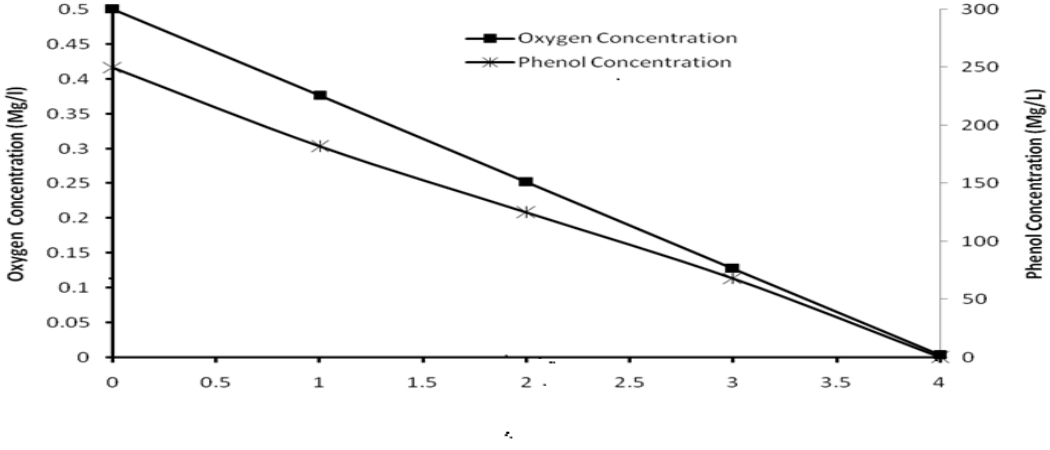

Figure-2 Profile of Oxygen and Phenol Concentration at each Bioreactor Stage

The relationship between phenol concentration and oxygen concentration at each stage of the RBC reactor is shown in Figure 3.

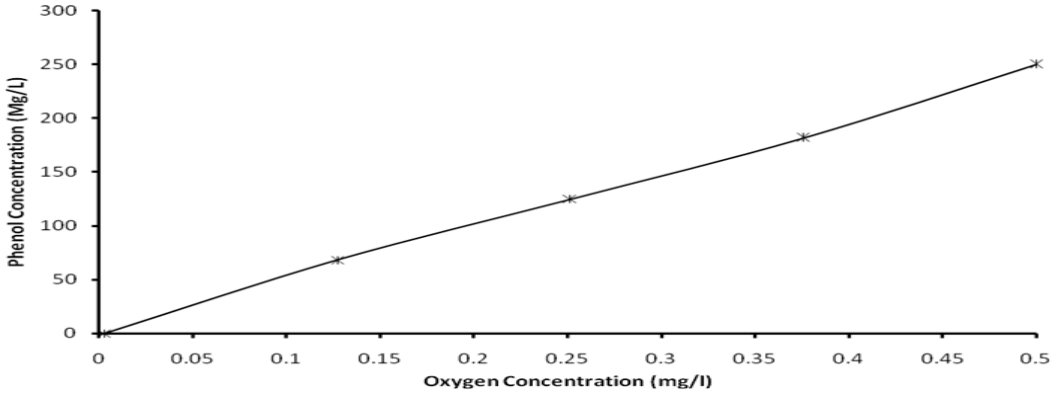

Figure-3. Relationship between Phenol Concentration and Oxygen Concentration at each stage of the RBC Reactor.

As shown in Figure 3, at the initial phenol concentration of 250 mg/L the oxygen concentration is 0.5 mg/L. As biodegradation increases, cellular activity of the microorganism also increases. This leads to increase in oxygen utilization and a reduction in the concentration of oxygen to 0.003 mg/L as the phenol degrades to 0.0506 mg/L. The surface renewal of the bio-disc as it rotates in and out of the reactor ensures that the microorganisms are not starved of oxygen.

3.2. Model Simulation

A simulation study or sensitivity analysis was carried out on the retention time, rotational speed (angular velocity), biomass concentration, cell yield, and respiratory coefficient to optimize the RBC reactor.

3.2.1. Variation of Retention Time

Retention time of substrate and microorganisms in the system is very important for effective biodegradation. The retention time should be sufficient enough for substrates to be absorbed by the microorganisms through diffusion. As the retention time increases, biodegradation also increases. This is because the microorganism has sufficient time to feed on the substrate. The system requires balance between degradation and oxygen transfer. In limited oxygen supply, biodegradation is inhibited [15]. Long residence time of biomass in the waste water will lead to limitation of the process by phenol as reported by Sokol [16].

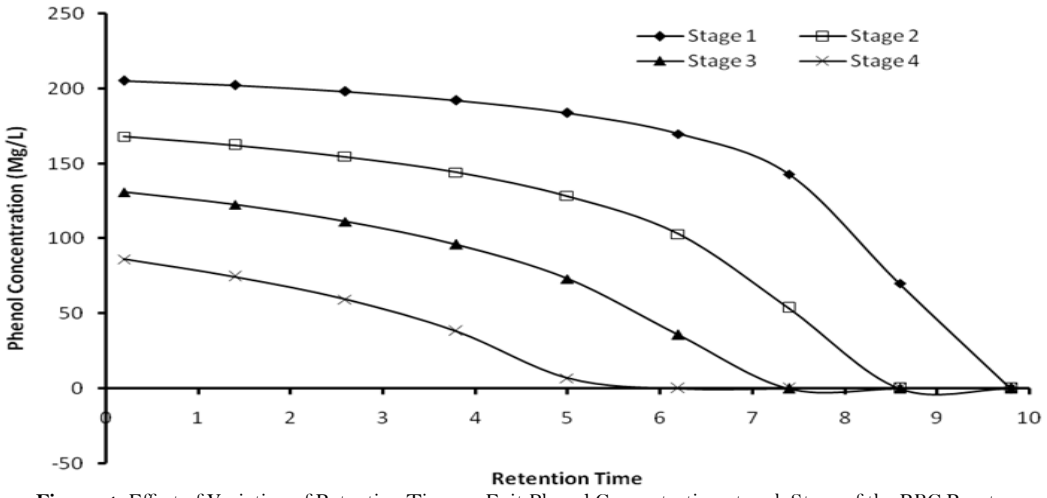

Figure-4. Effect of Variation of Retention Time on Exit Phenol Concentration at each Stage of the RBC Reactor.

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Fig.4 and Fig. 5 shows the effect of the variation of retention time on the exit concentrations of phenol and oxygen concentrations respectively. The graph follows the trend discussed. The exit concentrations of phenol and oxygen reduce with increase in the retention time. At low retention time, biodegradation is ineffective; the concentration of phenol in the system is high, suggesting that the time is not enough for biodegradation to come to conclusion. The oxygen concentration profile in Fig. 5 also follows the same profile. Concentration of oxygen reduces with increase in retention time because as the rate of biodegradation increases, cellular activities of the microorganisms also increase. The net effect is that there is a reduction in the concentration of oxygen in the system.

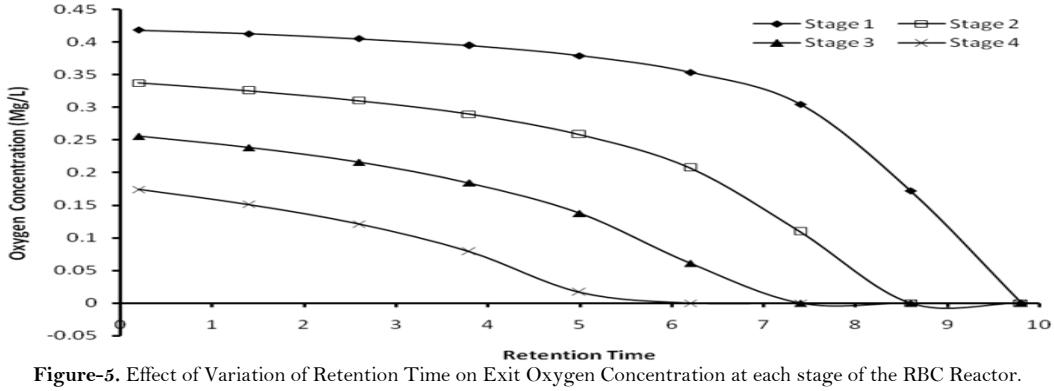

Figure-5. Effect of Variation of Retention Time on Exit Oxygen Concentration at each stage of the RBC Reactor.

3.2.2. Variation of Rotational Speed

Biodegradation and oxygen utilization in the system has a direct proportional relationship. That is, as biodegradation increases, oxygen utilization increases. The rotational speed of the reactor affects the generation of oxygen within the system thus affecting biodegradation. The disc should be rotated at a speed that is slow enough to allow for effective oxygen transfer and good

residence time for biodegradation. If the rotation is too high, the air exposure ratio of the disc will be small and oxygen will not be adequately transferred. Also if the rotation is too slow, the disc spends much time in the wastewater and the microorganisms are starved of oxygen.

Figure 6 shows the effect of the variation of rotational speed on the exit concentrations of phenol and oxygen of the final stage of the reactor. The graphs in Figure 6 support the above trend. At low rotational speed, the concentration of phenol in the system is high, since enough oxygen is not generated within the system. This means that biodegradation is inhibited by insufficient oxygen in the system. As rotation speed increases, oxygen generation increases sufficiently enough to complete the degradation of the substrate. Though sufficient oxygen is generated within the system at high rotational speed, the net oxygen concentration in the reactor continues to fall because it is been used up by the microorganisms for respiration and cell maintenance.

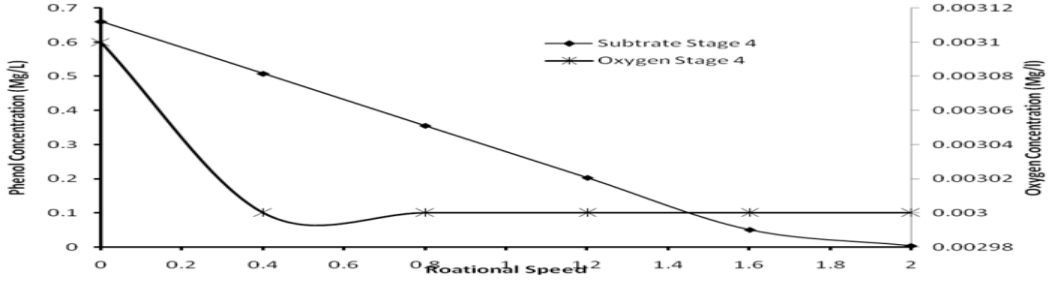

Figure-6. Effect of Variation of Rotational Speed on Exit Phenol Concentration and Oxygen Concentration at the Final Stage of the RBC Reactor.

3.2.3. Variation of Biomass Concentration

The biomass (microorganisms) is solely responsible for biodegradation. Higher biomass concentration results in higher degradation rate. Also, if the biomass concentration is large, oxygen utilization will also increase thus reducing the concentration of oxygen in the reactor. The above condition is true at specific loading condition.

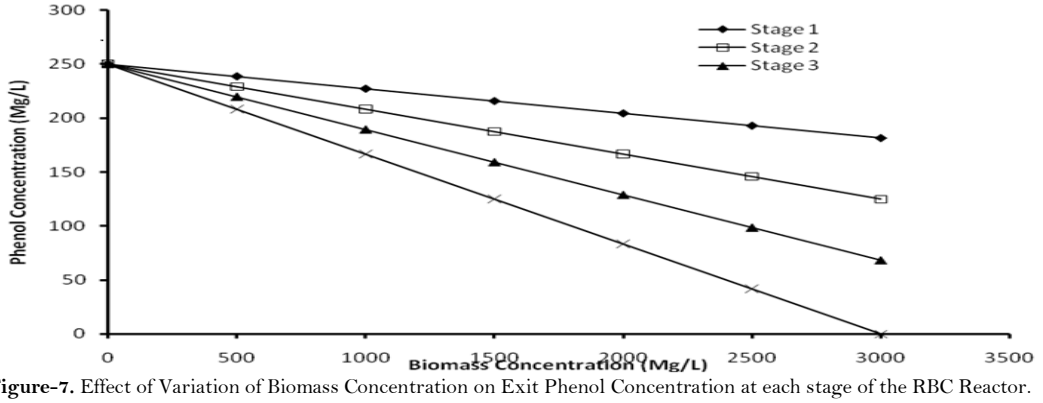

Figure-7. Effect of Variation of Biomass Concentration on Exit Phenol Concentration at each stage of the RBC Reactor.

Figure 7 and Figure 8 supports the above trend. The graphs show the effect of varying the biomass concentration on the exit concentrations of phenol and oxygen respectively. At low biomass concentration, biodegradation is low. This is seen in the high concentration of phenol at low biomass value. As biomass concentration increases, biodegradation increases, thus leading to a reduction in the concentration of phenol in the wastewater. Also oxygen utilization increases with increase biomass concentration with a resultant decrease in the dissolved oxygen concentration as shown in Figure 8. This is understandable because larger biomass population will use more oxygen than a lower population.

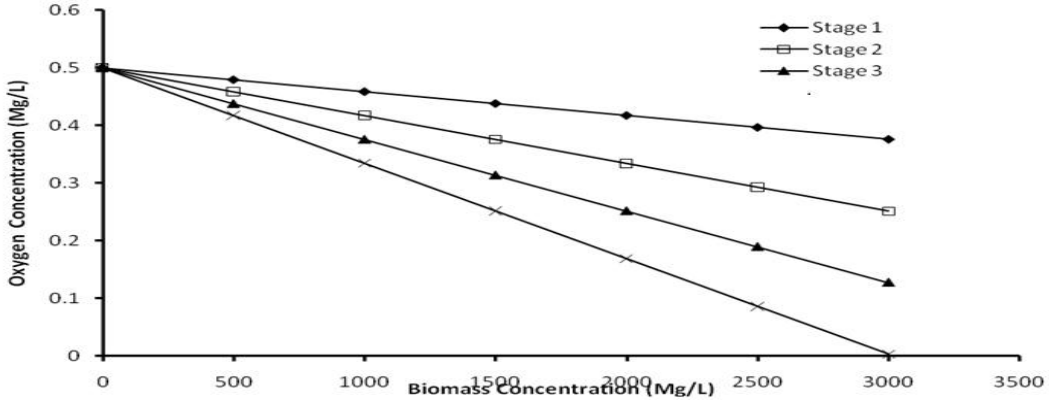

Figure-8. Effect of Variation of Biomass Concentration on Exit Oxygen Concentration at each stage of the RBC Reactor.

3.2.4. Variation of Yield Coefficient

The cell yield or yield coefficient is used to describe the fraction of the substrate converted to biomass. It is the ratio of the mass of new cells formed to the mass of substrate consumed. This is because during biodegradation some of the substrates are used for cell maintenance, while some are used for cell growth or are converted to biomass. A high yield coefficient means that more of the substrate is converted to biomass. Thus, increase in yield coefficient results in increase in biomass concentration and a reduction in the concentration of the substrate.

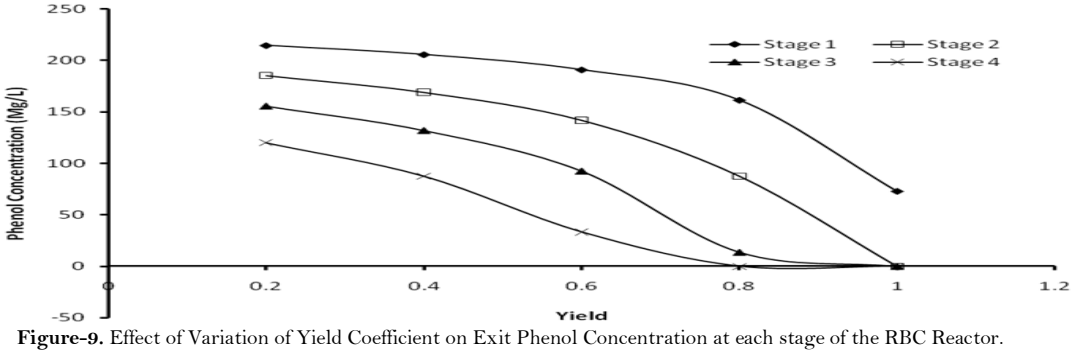

Figure-9. Effect of Variation of Yield Coefficient on Exit Phenol Concentration at each stage of the RBC Reactor.

Figure 9 shows the effect of the variation of yield coefficient on the exit concentrations of phenol for each stage of the reactor. The graph follows the discussed trend. The phenol concentration reduces with increase in the yield coefficient as more of the substrate is being converted to biomass.

3.2.5. Variation of Respiratory Coefficient

The respiratory coefficient is ratio of the mass of oxygen consumed to the mass of living microorganism. Respiration coefficient less than zero show that the mass of oxygen consumed is less than the mass of microorganism and vice versa.

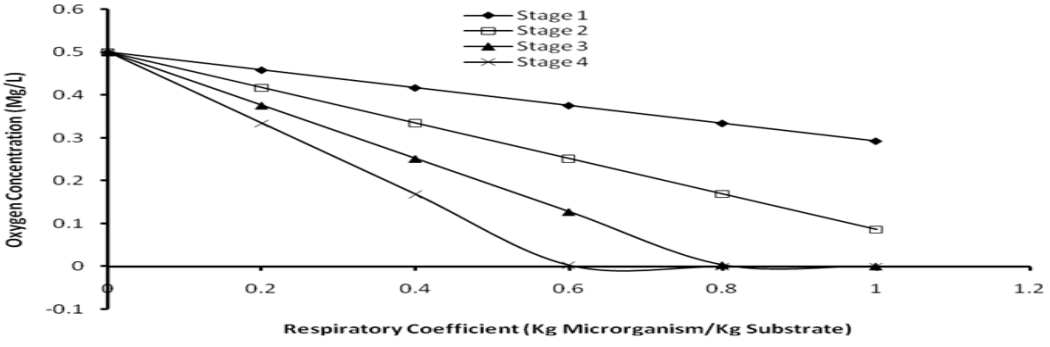

Figure-10. Effect of Variation of Respiratory Coefficient on Exit Oxygen Concentration at each stage of the RBC Reactor.

Figure 10, shows that an inverse proportional relationship exists between oxygen concentration and respiratory coefficient. This means that the higher the respiratory coefficient, the lower the concentration of oxygen in the system

4. CONCLUSION

A model to predict the degradation of phenol has been developed in this work for the RBC. The bio-reactor is modeled as systems of stirred tank reactors in series. The model also gives us an insight into how oxygen – which can be a limiting factor in biodegradation, is utilized in the system. The model was derived by applying mass conservation principle to the important parameters of the systems; substrate, oxygen and biomass. The famous Monod's kinetic was incorporates into the models to predict substrate degradation rate. The resulting parabolic Ordinary Differential Equations (ODE) were solved numerically using the fourth-order Runge Kuttta algorithm and adapted to a Visual Basic 6.0 Programming language compiler. The effluent discharge value of 0.0505 mg/L obtained from the model compares reasonably well with the plant data value of 0.05 mg/L with a deviation of 1%. This suggests that the model can be used to design, simulate and optimize the system. The simulated result predicts the system's behaviour at different operating condition. From the simulated result it is seen that the system functions optimally at specified loading conditions.

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