Predictive Model on the Characteristics of Substrate Uptake by Microbial Film in a Non Gel-Like Medium

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Abstract

Predictive model was developed to monitor and simulate the characteristics of substrate uptake by microbial film in a non-gel-like medium. Mathematical model was developed to predict the rate of N/N_{max} upon the influence of the kinetics of K_3 C* at various incremental steps of K_2L which is dependent of Damkohler method. The results obtained from the investigation revealed increase in N/N_{max} rate with increase in K_3C^* as well as decrease in K_2L data. The variation in the predictive mode can be attributed to the variation on the functional parameters and the coefficients of the system. The diffusion rate of the microorganism was depended of the biochemical reaction in a non-gel-like media and the microbial rate equations defines the velocity rate of substrate and oxygen uptake in bioreactor of the system, in which the three coefficients of K_1, K_2, K_3 also is the functional parameters that inhibits characteristics size and the rate limiting substance that influence the enzymes-substrate complex concentration.

Keywords: Functional parameters, predictive model, non-gel-like, bioreactor, substrate uptake, microbial film

Introduction

Investigation conducted by various research groups revealed that when the solution in a bioreactor is favorable the addition of nutrient into the system will enhance rapid growth of living cell mass as well the addition of essential nutrients to the bioreactor mixture at a suitable condition of the physicochemical parameters will enhance the cell growth [1-15]. The rate in which the cell grows depends on the following factors such as the rate of uptake of substrate by the cell mass as well as the rate of release of metabolic end products into the environment [7-13]. The microorganism uses the substrate as food to gain the required energy to enable them biodegradation the contaminants in a bioreactor [12]. In most cases, a batch or continuous stirred tank bioreactors are used in growing cell mass, increase in cell mass will be observed once the system is stable for microbial activity [10]. In many biochemical processes involving batch growth of micro-organisms cell growth commences after seeding a liquid medium of appropriate composition with an inoculums of living cells [4-7]. The cell reproduces, the composition of the substrate changes and the product, which can be toxic to the cells forms. Number of living cells in the culture varies with time as shown [1-2]

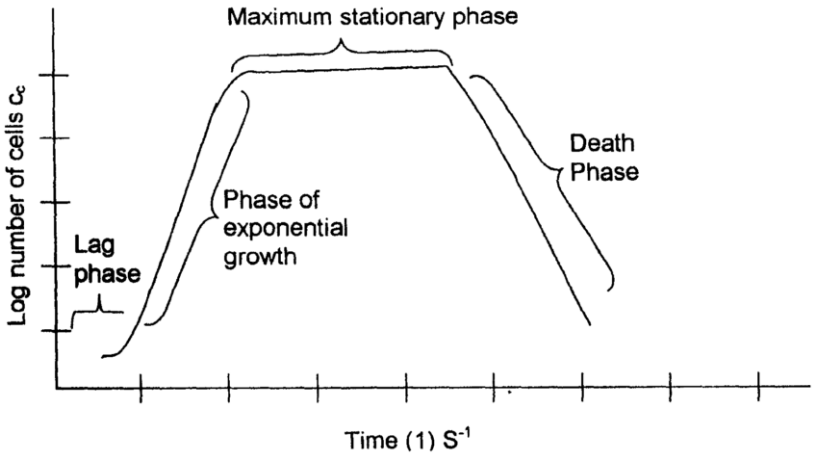

Figure 1: batch growth curve of a microbial culture.

Figure 1 illustrates the batch growth graph of a microbe, in which the lag phase (time lag), the progressive or exponential phase, stationary phase and the decline or death phase was experience by cell. Decrease in cell mass is always observed when the source of energy decreases for their optimum growth is lacking such as food as well as available nutrients. If high energy is stored in the ATP this means that the cell mass in the bioreactor will increase as they make use up the food supply optimum growth, once this is experience increase in enzymetic activity will lead to decrease in low molecular weight chemicals diffuse out, and the cells age. In most cases, a change in environment influence in the adaption period of cell introduced into the batch reactor, as environment favors the cells they adjust to meet up with the new environment [5-8]. The progressive phase indicate the region of progress in the cell mass in the batch bioreactor after the cell has experience a lag phase which yield a decrease in cell mass as well as progressive phase which now yielded a rapid growth increase in cell mass, that is, the cell mass increases progressively with time. This stage of batch culture is called progressive or exponential phase or logarithmic phase.

Naturally in a closed vessel the cells cannot multiply indefinitely and a stationary phase follows the period of exponential growth. At this point the population achieves its maximum size and an exponential decline in cell numbers occurs during the death phase. The eventual drop in cell growth is governed either by depletion of food or nutrient as well as accumulation of toxic materials. The above define function influence all phases of the cell growth in a batch reactor and each phase are of potential importance in microbiological processes. For example, the general objective of a good process design is to minimize the length of the lag phase and to maximize the rate and length of the exponential phase, the last objective being achieved by slowing the onset of the transition to stationary growth. To achieve such goals, we should understand the variables, which influence the phases of batch growth.

The aim and objective of the research is to develop mathematic equations that will monitor and predict the physical and chemical processes occurring in batch reactor for cell grow upon the influence of the uptake of substrate and oxygen in a non-gel-like media. In this case, the Monod model for the rate of substrate uptake did not influence the contribution of the diffusional parameter of the substrate transport from the outer region of the micro-organism. The equations developed will useful to monitor and predict the influence of both the substrate concentration and the film thickness upon influence of substrate uptake in a microbial medium. Far research has been conducted in theses area of substrate uptake in a non-gel-like medium, yet non-gel-like medium is an important medium because most micro-organisms exists in a non- gel- like medium.

In most cases, the microbial activities are found useful in beer, wine and vinegar and other alcoholic beverage production. The research focus is based on the rate equations for the overall rate of substrate uptake in a non-gel-like media as well as oxygen uptake in a non-gel-like media.

2. Materials and Methods

Predictive Model for Substrate Uptake by Microbial Film in Non Gel-Like Medium

For a thin non-gel-like microbial film the reaction occurs at the interface between the microbial film and the substrates solution. In this case the limiting process for transporting substrate from bulk of the solution to the microbial film is assumed to be molecular or connective diffusion through the layer of solution immediate to the carrier.

Under steady state conditions, the rate of reaction at the active sites is equal to the rate at which substrate arrives at the site [3].

The material balance will be as follows:

(1)

h_D= the mass transfer coefficient

C= the bulk substrate concentration

C* = the substrate concentration at the surface

R^1 = the rate of reaction per unit surface area of microbial film.

Assuming that the microbial film follows Monod Kinetics regardless of mobilization then equation (1) will give

$$h_D (C - C^*) = \frac{\mu_{\max} C^*}{K_S + C^*} \qquad (2)$$

Where

μ_m =Maximum rate of reaction per unit surface are

And K_S = Michealis or the Monod constant

Expressing equation (2) in dimensionless form will give:

$$\beta - \beta^* = \frac{\beta^*}{1+\beta^*} \frac{\mu_m}{h_D K_S} \qquad (3)$$

The subscript $\beta \text{ and } \beta^*$ refers to bulk and surface dimensionless concentration parameters.

$\frac{\mu^1 m}{h_D K_S}$ is a dimensionless group called Damkohler number

Thus we have a mathematical expression of

$$\beta - \beta^* = \frac{\beta^*}{1+\beta^*} Da \qquad (4)$$

In equation (4) the Damkohler number represents the ratio of the maximum rate of reaction to the maximum transport rate of substrate to the surface.

$$\text{Da} = \frac{\max imum\, reaction\, rate}{\max imum\, transport\, rate}$$

When Da is high the overall substrate utilization is transport limiting and the observed rate of reaction decreases, a small value of Da shows that the overall substrate utilization is reaction limiting. Where there is no diffusional resistance Da = 0. Let the reaction rate when there is no diffusion restrictions be $\mu^1 k$ then an effectiveness factor may be defined as

$$\eta e = \frac{\eta^1}{\eta_K^1} \qquad (5)$$

$$= \frac{flux\ with\ diffusion}{flux\ without\ diffusion}$$

A plot of η_e versus Da shows that η_e is dependent on β and Da, and shows three identifiable regions.

(1) kinetic control (2) intermediate domain (3) diffusion control.

At low values of Da, kinetic control of the reaction is observed while at high values of Da, diffusion control of the reaction is observed. At low values of Da, η_e approaches unity for most substrate concentration the effectiveness factors η_e still approaches unity even for Da of hundred.

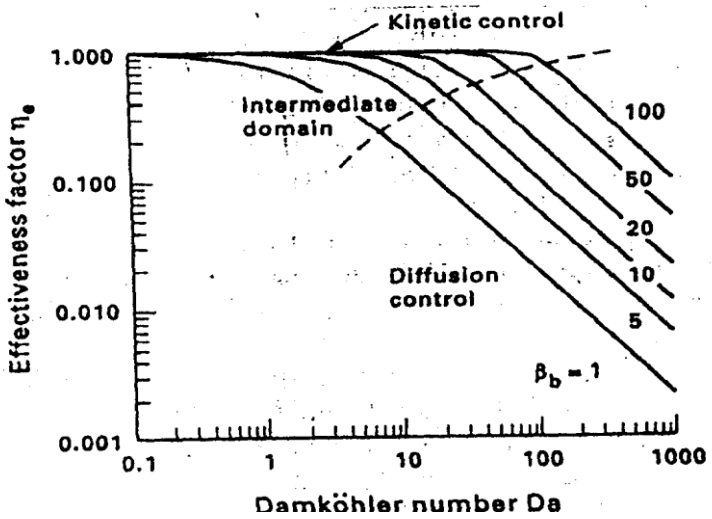

Figure 2: Variation of effectiveness factor for a surface immobilized enzyme with Damkohler number

The figure 2 illustrates the variation of effectiveness factor for a surface immobilized enzyme with Damkohler number graph characteristics.

From above the predictive model for substrate uptake by microbial film in a non-gel-like medium will be:

$$\beta - \beta^* = \frac{\beta^*}{1+\beta^*} Da$$

Where

$$\beta = \frac{C}{K_S}$$

$$\beta^* = \frac{C^*}{K_S} = K_3 C^*$$

$$\beta - \beta^* = \frac{K_3 C^*}{1+K_3 C^*} Da \qquad (6)$$

Where Damkohler * (Da),

$$\frac{\mu_m}{h_D\, k_S} \qquad (7)$$

$$= \frac{\max imum\, rate\, of\ reaction\ per\ unit\ surface\, area}{\max imum\, rate\, of\ transport\, to\, the\, surface}$$

Predictive Model for Oxygen Uptake by Microbial Film in a Non - Gel-Like Medium

The rate of oxygen absorption $= k_1\, a(C^* - C).$

The maximum oxygen utilization rate is given as:

$$\frac{x\mu_{max}}{Y_{02}} \qquad (8)$$

Equation (7) is the total microbial oxygen demand

Where x = population of cell

Y_{02} = ratio of moles of cell carbon formed per mole of oxygen consumed.

At steady state the rate of oxygen consumption

$$h_{D02}\ a(C-C^*)=\frac{x\mu_{max}}{Y_{02}} \qquad (9)$$

If the oxygen dependence of the specific growth rate follows the Monod Kinectics

$$Y_{02}\ h_{D02}\ a\ (C-C^*)=x\ \frac{\mu_{max}\ C}{K_{02}+C} \qquad (10)$$

For a unit mole per unit time per unit area equation (10) will become:

$$h_{D02}\ (C-C^*)=\frac{\mu_{max}\ C^*}{K_{02}+C^*} \qquad (11)$$

Expressing equation in dimensionless form will give:

$$H_{D02}\ (\beta^*-\beta)=\frac{\mu max\ \beta}{1+\beta}$$

Where $\beta=\frac{C^*}{k_{02}}$

$$\beta^*-\beta=\frac{\mu_{max}}{h_{DO2}K_{O2}}\ \frac{\beta}{1+\beta} \qquad (12)$$

$$\beta^*-\beta=D_{a02}\ \frac{\beta}{1+\beta}$$

Where $D_{a02}=\frac{\mu_{max}}{h_{Do2}\ K_{o2}}$

Assumptions

The following assumptions were made in the model development

1. Steady state i.e. constant composition, concentration, temperature; constant liquid hold up and wetted area; no net accumulation of microbial mass constant net metabolic rate.
2. No chemical reaction or biological oxidation by microorganisms in suspension in the liquid phase.
3. Thickness of the non-gel-like region is uniform.

4. Diffusion through the membrane is uniform everywhere. There is no longitudinal mixing.
5. There is only soluble substrate removal. Contribution of suspended solids to slime thickness as a result of filtration and subsequent bio-oxidation is ignored.
6. BOD taken as single substrate i.e. oxidation rates of all chemical species is identical.
7. Excess oxygen available i.e. gas/liquid interface area and liquid phase mass transfer coefficients are sufficiently large so that the dissolved oxygen concentrations at the liquid/gelly interface result in bio-oxidation reactions which are zero order with respect to oxygen.
8. There is uniform temperature distribution. The temperature is independent of position in the microbial membrane i.e. local equilibrium between heat generation by oxidation reactions and heat loss to the atmosphere.

3. Results and Discussion

As a means of predicting the characteristics behavior of bioreactors and also understanding the effect of change on any of the variables on the overall substrate uptake or degradation, a simulation package has been developed to test the correlation of the experimental data with the model equations are presented in Table 1 and Figures as shown below.

Table 1: Simulation Results from the Developed Model

K3C*	N/N_{max}						
	K_2L=0.5	K_2L=1	K_2L=3	K_2L=5	K_2L=10	K_2L=20	K_2L=30
0.1	0.08	0.07	0.03	0.02	0.01	0	0
0.2	0.16	0.14	0.06	0.04	0.02	0.01	0.01
0.4	0.27	0.24	0.12	0.07	0.04	0.02	0.01
0.6	0.36	0.33	0.17	0.1	0.05	0.03	0.02
0.8	0.43	0.39	0.21	0.13	0.07	0.03	0.02
1	0.48	0.45	0.25	0.16	0.08	0.04	0.03
2	0.65	0.63	0.42	0.27	0.13	0.07	0.04
4	0.79	0.77	0.66	0.43	0.22	0.11	0.07
6	0.85	0.84	0.78	0.55	0.28	0.14	0.09
8	0.88	0.87	0.83	0.65	0.34	0.17	0.11
10	0.91	0.9	0.86	0.74	0.39	0.19	0.13
20	0.95	0.95	0.93	0.91	0.57	0.29	0.19
40	0.97	0.97	0.96	0.95	0.83	0.42	0.28
60	0.98	0.98	0.98	0.97	0.96	0.53	0.35
80	0.99	0.99	0.99	0.98	0.97	0.61	0.41
100	0.99	0.99	0.99	0.99	0.97	0.97	0.46
200	0.99	0.99	0.99	0.99	0.99	0.99	0.65
400	1	1	1	1	0.99	0.99	0.93
600	1	1	1	1	1	0.99	0.99
800	1	1	1	1	1	0.99	0.99

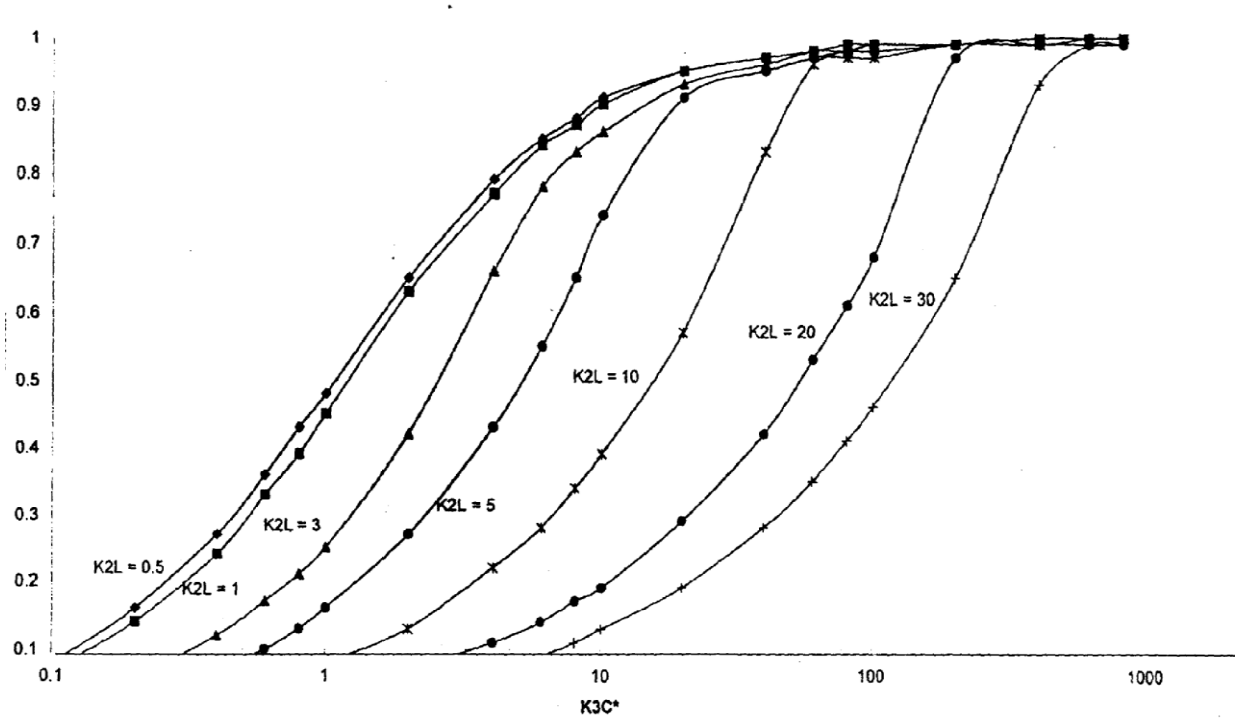

Figure 3: Graph of N/Nmax against K_3C^* at K_2L = 0.5, 1, 3, 5, 10, 20, 30

The result presented in Figure 3 illustrates the relationship between the ratio of N/N_{max} and K_3C^* concentration for various range of K_2L values. Increase in K3C* was observed with increase in N/N_{max} for various value K_2L considered during the investigation. The variation in the ratio concentration of N/N_{max} can be attributed to the variation in the K_3C^* as well as the variation on the K_2L and other contributing factors.

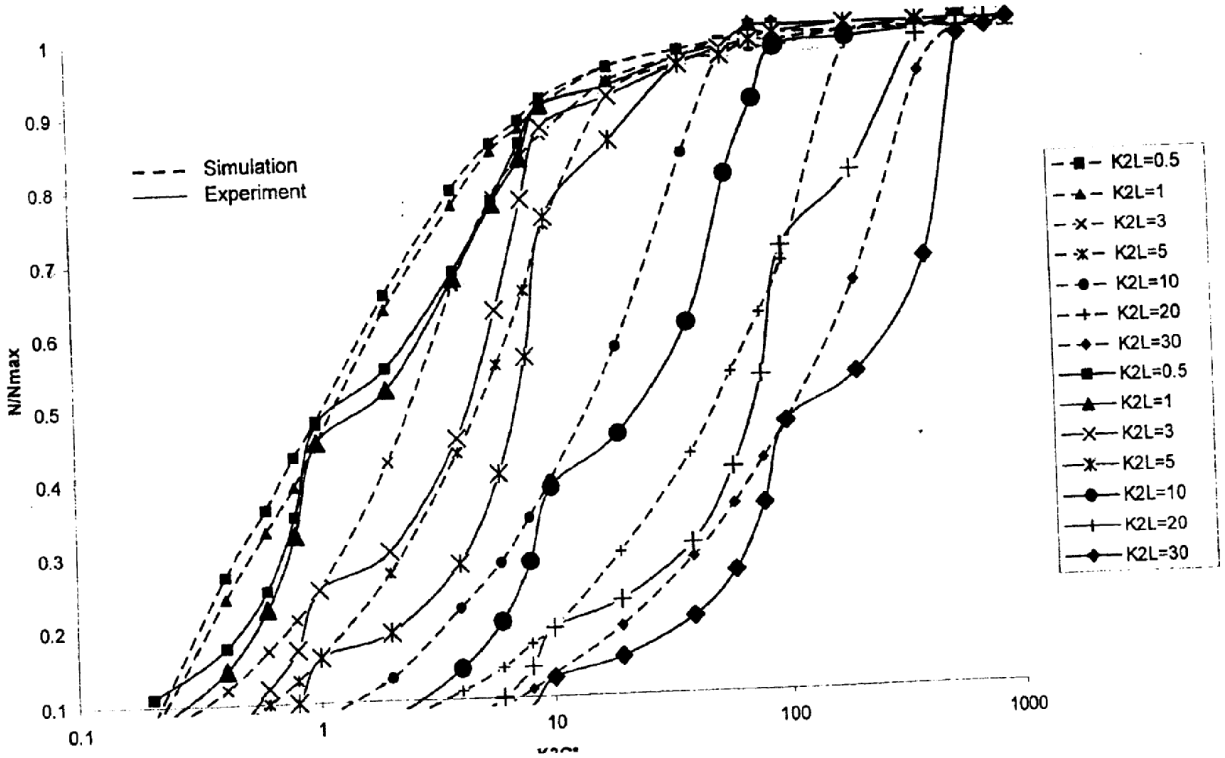

Figure 4: Graph of N/N_{max} against K_3C^* at k_2L= 0.5,1,3,5,10,20,30

The result illustrated in Figure 4 shows the relationship between experimental and simulated data for various value range of K_2L (0.5 to 30) with the incremental step in the K_3C^* concentration which yielded increase in N/N_{max}. The comparison of the result shows a good match, indicating the reliability of the developed mathematical model. Although, the ratio of N/N_{max} is influence by the nature of the nutrient and other functional parameters in the bioreactor. The variation in concentration of K_3C^* can be attributed to the variation in the value of K_2L as well as the concentration of the nutrient, functional parameters, nature of cell, the toxic nature of the substrate.

4. Conclusion

The following conclusion was drawn from the investigation as stated below: 1.The substrate diffusion a coefficient in non-gel-like medium is depended of the characteristics of microbial medium interaction with the oxygen concentration in the batch reactor as well the concentration of the nutrient added in the system. 2. The functional coefficient of K_1 and K_3 act as inhibiting factor in the system.

3. The property of the medium influence the cells growth rate in the bioreactor

4. The rate of oxygen utilization by the cell mass determines how fast the reaction process will be

5. The cell external surface area as well as the external area of a wet microbial floe region in the batch reactor will be influence by the characteristics of the mixture.

6. Concentration of the nutrient help to improve the cell mass growth as well as increases the rate of substrate consumption

Nomenclature

a = External surface area of viable micro-organisms per unit

volume of microbial mass (m)

B_n = Biomass concentration define by controls in equation (kg/m^3)

C = Substrate concentration (mass/volume) (kg/m^3)

C* = Substrate concentration at the interface between the micro-organism and the aqueous solution (kg/m^3)

D = Rate of biomass decay (kg/s), (m^3/s)

Da = Damkohler number

Dc = Effective diffusion coefficient within microbial mass (m^2/s)

hD = Mass transfer coefficient (m/s)

Ks = System coefficient (kg/m^3)

K_1 = Biological rate equation coefficient (s1)

K_2 = Biological rate equation coefficient (m^3/kg)

K_3 = Biological rate equation coefficient

L = "Wet" biological film thickness (m)

N = Rate of substrate consumption per unit interfacial area

N_{max} = Maximum rate of substrate uptake (m^3/cm^2s)

N = Rate of substrate uptake (m^3/cms)

R = Rate of reaction per unit surface area of microbial film (mol/cm^2s)

Vmax = Maximum rate of degradation (mol/cm^{2}s)

V = Cell volume (cm^3)

X = Dimensionless space

x = Space co-ordinate (m)

Yo = Yield of microbial mass per unit mass of substrate consumed

β = Bulk dimensionless coefficient

β^* = Surface dimensionless concentration

ηe = Effectiveness factor

λ = Effectiveness factor

μ = Specific microbial growth rate (s^{-1})

$\mu^1{}_k$ = Rate of reaction without diffusional restriction (mol/cm^2.s

μ_{max} = Maximum specific microbial growth rate (S)

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