QUIZ CE204

Bioprocess Engineering – Part 1

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PROBLEMS

▶ Problem 1

A bacteria/cell culture is in the exponential growth phase, and the evolution of the cell mass concentrations are described by the following table. Calculate the specific growth rate and, with reference to the following data, answer: what type of bacteria/cell is most likely being cultivated in this case?

Time (h)	0	5	10	15	20	25	30
Cell concentration (kg dry cell/m³ medium)	1	2.86	8.17	23.3	66.7	191	545

Bacteria or cell	**Specific growth rate (h^{-1})**
Escherichia coli at 40°C	2.0
Aspergillus niger at 30°C	0.35
Saccharomyces cerevisiae at 30°C	0.17 – 0.35
HeLa cell at 37°C	0.015 – 0.023

A) *Escherichia coli*

B) *Aspergillus niger*

C) *Saccharomyces cerevisiae*

D) HeLa cell

▶ Problem 2 (Modified from Lee, 1992)

For a series of batch runs with a constant enzyme concentration, the following initial rate data were obtained as a function of initial substrate concentration.

Substrate concentration (mmol/L)	**Initial reaction rate (mmol/L·min)**
1	0.20
2	0.22
3	0.30
5	0.45
7	0.41
10	0.50

Fit the data to a Langmuir model, a Lineweaver-Burk model, and an Eadie-Hofstee model in order to determine the maximal rate $r_{\max}$ and the Michaelis constant K_M. List your results in the table below.

	r_{max}	K_M
Langmuir		
Lineweaver-Burk		
Eadie-Hofstee		

▶ Problem 3 (Modified from Katoh et al., 2015, w/ permission)

A substrate L-benzoyl arginine p-nitroanilide hydrochloride was hydrolyzed by trypsin with inhibitor concentrations of 0, 0.25, and 0.5 mmol/L. The hydrolysis rates, given in μmol L^{-1} s^{-1}, are listed in the following table. Determine the inhibition mechanism and the kinetic parameters (K_M, $r_{\max}$, and K_I) of this enzyme reaction. True or false?

Substrate concentration (mmol/L)	Inhibitor concentration (mmol/L)		
	0	**0.25**	**0.50**
0.1	0.79	0.57	0.45
0.15	1.11	0.84	0.66
0.2	1.45	1.06	0.86
0.3	2.00	1.52	1.22

1.( ) The inhibition mechanism is competitive inhibition..
2.( ) The maximal rate $r_{\max}$ is greater than 10 mmol/(m^3·s).
3.( ) The Michaelis constant K_M is greater than 0.75 g·mol/m^3.
4.( ) The inhibition constant K_I is greater than 0.85 g·mol/m^3.

➜ Problem 4.1 (Modified from Dutta, 2008, w/ permission)

A chemostat study was performed with yeast. The medium flow rate was varied and the steady-state concentration of cells and glucose in the fermenter were measured and recorded. The volume of the fermenter contents was 500 mL. The inlet stream was sterile.

Flow rate, F (mL/hr)	Cell conc. (g/L)	Substrate conc. (g/L)
31	5.97	0.5
50	5.94	1.0
71	5.88	2.0
91	5.76	4.0
200	0	100

Assuming that Monod kinetics are valid, find the maximum growth rate $\mu_{\max}$ and the saturation constant K_S for this situation.

A) $\mu_{\max}$ = 0.251 h^{-1} and K_S = 1.52 g/L
B) $\mu_{\max}$ = 0.251 h^{-1} and K_S = 3.04 g/L
C) $\mu_{\max}$ = 0.502 h^{-1} and K_S = 1.52 g/L
D) $\mu_{\max}$ = 0.502 h^{-1} and K_S = 3.04 g/L

➜ Problem 4.2

Reconsider the system introduced in the previous problem. What should be the minimum flow rate to prevent washout of the cells?

A) F = 0.0814 L/hr
B) F = 0.161 L/hr
C) F = 0.312 L/hr
D) F = 0.505 L/hr

▶ Problem 5 (Modified from Dutta, 2008, w/ permission)

Suppose you have a microorganism that obeys the Monod equation

$$\frac{dC_X}{dt} = \frac{\mu_{\max} C_S C_X}{K_S + C_S}$$

where $\mu_{\max}$ = 0.6 hr^{-1} and K_S = 4.0 g/L. The cell yield ($Y_{X/S}$) is 0.58. You want to cultivate this microorganism in either one fermenter or two in series. The flow rate and the substrate concentration of the inlet stream should be 650 L/hr and 90 g/L, respectively. The substrate concentration of the outlet stream must be 6 g/L. True or false?

1.( ) If we use a single CSTF, the size of the fermenter should be greater than 2000 L.
2.( ) In operation of a single CSTF, the cell concentration of the outlet stream is greater than 42 g/L.
3.( ) If the operation is carried out by two CSTFs in series, the substrate concentration in the outlet stream of the first fermenter will be greater than 12 g/L.
4.( ) If the operation is carried out by two CSTFs in series, the sum of the two reactor volumes will be greater than 1800 L.

5.( ) The best combination is a CSTF operated at the maximum rate followed by a PFF. The combined volume of the two reactors, in this case, is greater than 1650 L.

▶ Problem 6 (Modified from Ravi et al., 2017, w/ permission)

When a continuous culture is fed with substrate of concentration 1.00 g/L, the critical dilution rate for washout is 0.31 h^{-1}. This changes to 0.095 h^{-1} if the same organism is used but the feed concentration is 2.5 g/L. Which of the following is true?

A) The substrate concentration for the increased flow rate is 53% greater than the substrate concentration at the lower feed.

B) The substrate concentration for the increased flow rate is 105% greater than the substrate concentration at the lower feed.

C) The substrate concentration for the increased flow rate is 181% greater than the substrate concentration at the lower feed.

D) The substrate concentration for the increased flow rate is 244% greater than the substrate concentration at the lower feed.

▶ Problem 7 (Modified from Ravi et al., 2017, w/ permission)

Two continuous stirred-tank fermenters are arranged in series such that the effluent of one forms the feed stream of the other. The first fermenter has a working volume of 100 L and the other has a working volume of 50 L. The volumetric flow rate through the fermenters is 24 L/h and the substrate concentration in the fresh feed is 4.6 g/L. The microbial growth follows Monod kinetics with μ_{max} = 0.29 h^{-1}, K_S = 0.14 g/L, and the yield coefficient is 0.47. True or false?

1.( ) The biomass concentration in the first fermenter is greater than 2 g/L.

2.( ) The substrate concentration in the effluent from the second fermenter is greater than 0.008 g/L.

3.( ) The biomass concentration in the effluent from the second fermenter is greater than 2.4 g/L.

▶ Problem 8 (Modified from Katoh et al., 2015, w/ permission)

Immobilized enzyme beads of 0.5 cm diameter contain an enzyme that converts a substrate S to a product P in an irreversible unimolecular enzyme reaction with K_S = 0.05 kmol/m³ and maximum rate $\mu_{\max}$ = 4.8×10^{-7} kmol/(kg bead·s). The density of the beads and the effective diffusion coefficient for the substrate in the catalyst beads are 1080 kg/m³ and 7.8×10^{-7} cm²/s, respectively. Determine the effectiveness factor and the initial reaction rate when the substrate concentration is 0.5 kmol/m³.

A) E_f = 0.25 and r_p = 1.02×10^{-4} kmol/(m³·s)

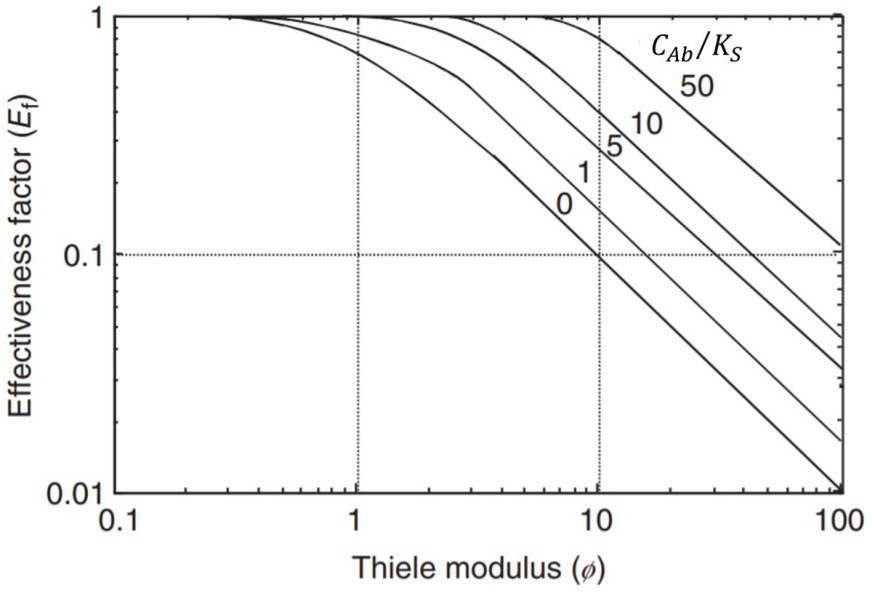
B) E_f = 0.25 and r_p = 2.04×10^{-4} kmol/(m³·s)

C) E_f = 0.40 and r_p = 1.02×10^{-4} kmol/(m³·s)

D) E_f = 0.40 and r_p = 2.04×10^{-4} kmol/(m³·s)

ADDITIONAL INFORMATION

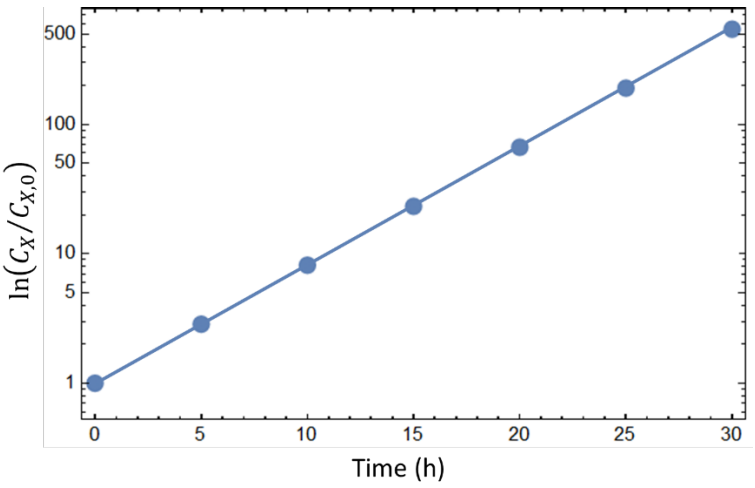
Figure 1 Effectiveness factor (E_f) for various values of C_{Ab}/K_S (Michaelis-Menten-type reaction, catalyst particles are spheres)



SOLUTIONS

P.1 ➡ *Solution*

The data are plotted on a semilog plane, as shown.



The specific growth rate is given by the slope of the line, which is seen to be 0.21. Comparing this with the values in the table, we surmise that the cells being cultivated are *Saccharomyces* cells.

♦ The correct answer is **C.**

P.2 ➡ *Solution*

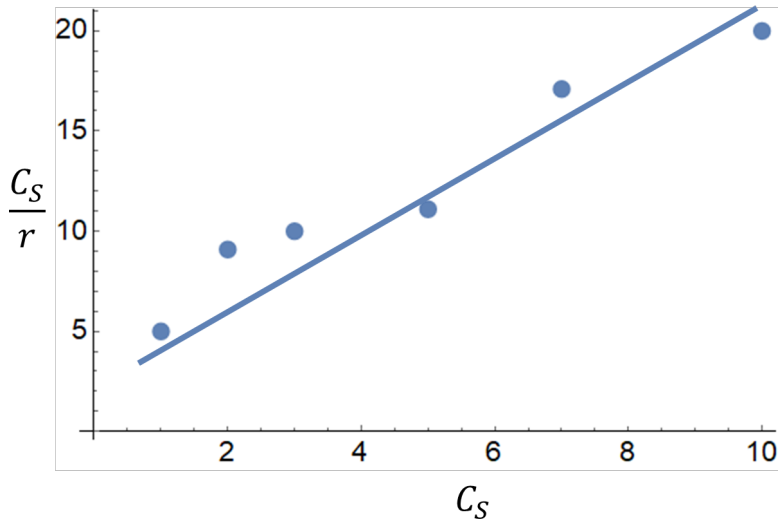
To begin, consider the Langmuir plot. In this case, the pertaining equation is

$$\frac{C_S}{r} = \frac{K_M}{r_{\max}} + \frac{C_S}{r_{\max}}$$

The data are processed below.

C_S (mmol/L)	C_S/r
1	1/0.20 = 5
2	2/0.22 = 9.09
3	10
5	11.1
7	17.1
10	20

The data are plotted below.



The line that fits the data has the form $y = 1.59x + 4.64$. Comparing this with the Langmuir equation, we see that

$$\frac{1}{r_{\max}} = 1.59 \rightarrow \boxed{r_{\max} = 0.629 \text{ mmol/L} \cdot \text{min}}$$

Further,

$$\frac{K_M}{r_{\max}} = 4.64 \rightarrow K_M = 4.64 \times 0.629 = \boxed{2.92 \text{ g} \cdot \text{mmol/L}}$$

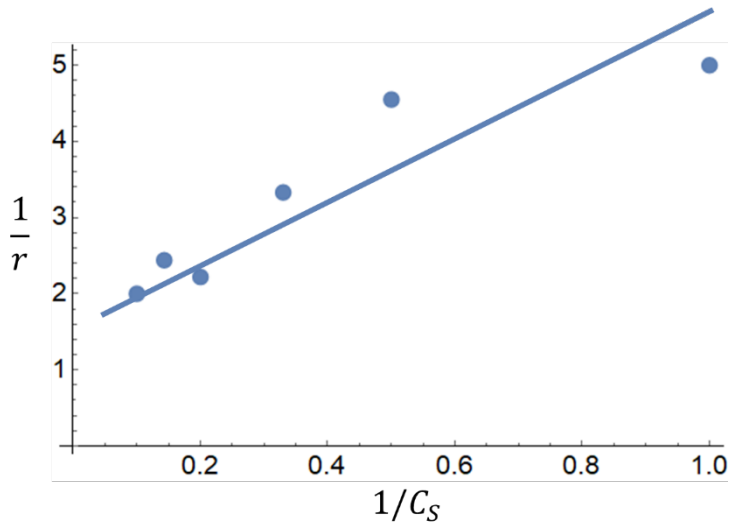
Consider now the Lineweaver-Burk plot, which is represented by the equation

$$\frac{1}{r}=\frac{1}{r_{\max}}+\frac{K_M}{r_{\max}}\frac{1}{C_S}$$

The data are processed below.

$1/C_S$	$1/r$
1/1 = 1.0	1/0.2 = 5.0
1/2 = 0.5	1/0.22 = 4.55
1/3 = 0.33	1/0.30 = 3.33
0.2	2.22
0.143	2.44
0.1	2.0

The data are plotted below.



The line that fits the data is of the form $y = 3.46x + 1.95$. Comparing this with the Lineweaver-Burk equation, we verify that

$$\frac{1}{r_{\max}}=1.95\rightarrow \boxed{r_{\max}=0.513\ \text{mmol/L}\cdot\text{min}}$$

and

$$\frac{K_m}{r_{\max}}=3.46\rightarrow K_m=3.46\times 0.513=\boxed{1.77\ \text{g}\cdot\text{mmol/L}}$$

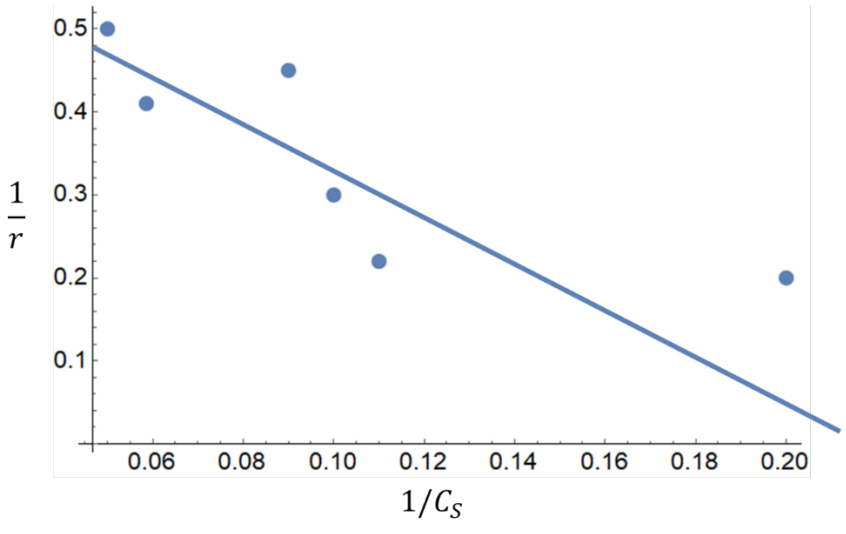
The third model we must consider is the Eadie-Hofstee equation, namely

$$r=r_{\max}-\frac{K_M r}{C_S}$$

The data are processed below.

r/C_S	r
0.20/1.0 = 0.2	0.2
0.22/2 = 0.11	0.22
0.30/3 = 0.10	0.30
0.09	0.45
0.0586	0.41
0.05	0.50

The data are plotted below.



The line that models the data is $y = -1.89x + 0.539$. Thus, it is easily seen that

$$\boxed{r_{\max} = 0.539 \text{ mmol/L} \cdot \text{min}}$$

and

$$-K_M = -1.89 \rightarrow \boxed{K_M = 1.89 \text{ g} \cdot \text{mmol/L}}$$

The constants obtained with the three models are summarized below.

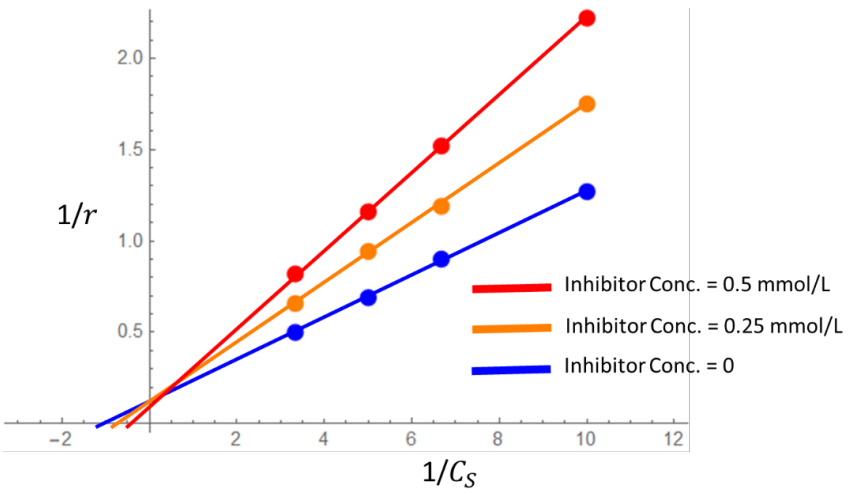
	r_{max} (mmol/L·min)	K_M (g·mmol/L)
Langmuir	0.629	2.92
Lineweaver-Burk	0.513	1.77
Eadie-Hofstee	0.539	1.89

P.3 ➡ *Solution*

The data required to outline the Lineweaver-Burk plots are processed below.

$1/C_S$	$1/r$ for inhibitor concentration = 0	$1/r$ for inhibitor concentration = 0.25	$1/r$ for inhibitor concentration = 0.50
1/0.1 = 10	1/0.79 = 1.27	1.75	2.22
1/0.15 = 6.67	1/1.11 = 0.901	1.19	1.52
1/0.2 = 5.0	1/1.45 = 0.690	0.943	1.16
1/0.3 = 3.33	1/2.00 = 0.5	0.658	0.820

The data are plotted below.



From the positioning of the Lineweaver-Burk lines, it is clear that the inhibition mechanism is competitive inhibition. The line for the data without the inhibitor has the form $y = 0.116x + 0.116$, which, comparing with the general L-B equation, implies that

$$\frac{1}{r_{\max}} = 0.116 \rightarrow \boxed{r_{\max} = 8.62 \text{ mmol}/\left(\text{m}^3 \cdot \text{s}\right)}$$

and

$$\frac{K_M}{r_{\max}} = 0.116 \rightarrow K_M = 0.116 \times 8.62 = \boxed{1.0 \text{ g} \cdot \text{mol/m}^3}$$

For competitive inhibition, the Lineweaver-Burk plot is given by

$$\frac{1}{r} = \frac{1}{r_{\max}} + \frac{K_M}{r_{\max}}\left(1 + \frac{C_I}{K_I}\right)\frac{1}{C_S}$$

where C_I is the inhibitor concentration. The L-B plot for an inhibitor concentration of 0.25 mmol/L is represented by $y = 0.163x + 0.116$. Comparing this with the general form above, we see that

$$\frac{K_M}{r_{\max}}\left(1 + \frac{C_I}{K_I}\right) = 0.163 \rightarrow \frac{1.0}{8.62} \times \left(1 + \frac{0.25}{K_I}\right) = 0.163$$

$$\therefore \boxed{K_I = 0.617 \text{ g} \cdot \text{mol/m}^3}$$

- Statements **1** and **3** are true, whereas statements **2** and **4** are false.

P.4 ➡ *Solution*

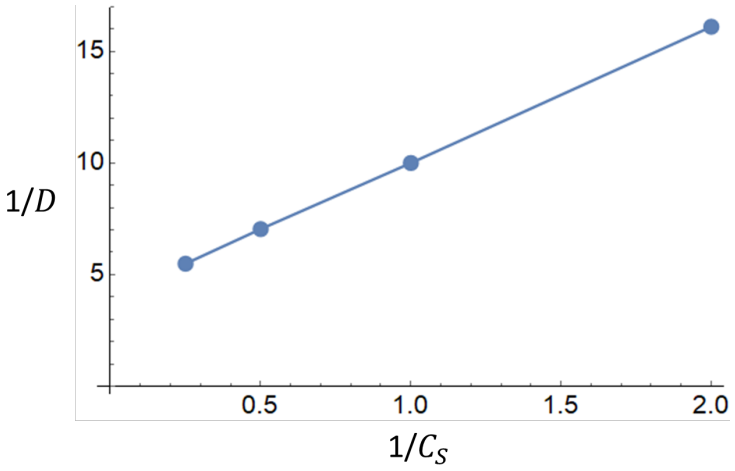
Part 1: Let us assume that the growth rate can be represented by Monod kinetics. If this assumption is reasonable, a plot of $1/\mu$ versus $1/C_S$ should yield a straight line, in accordance with the equation

$$\frac{1}{\mu} = \frac{K_S}{\mu_{\max}} \frac{1}{C_S} + \frac{1}{\mu_{\max}}$$

If a certain microorganism follows Monod kinetics, the plot of $1/\mu$ versus $1/C_S$ should yield the values of $\mu_{\max}$ and K_S by reading the intercept and the slope of the straight line. This plot is equivalent to the Lineweaver-Burk plot for Michaelis-Menten kinetics. For steady-state conditions, the reaction rate equals the dilution rate, D. The dilution rate for the chemostat is $D = F/V$, where V = 500 mL is the volume of the fermenter. The data are processed in the following table.

$1/C_S$	$1/D = V/F$
1/0.5 = 2.0	500/31 = 16.1
1/1.0 = 1.0	500/50 = 10
0.5	7.04
0.25	5.49

The data are plotted below.



The graph above shows a straight line with intercept $1/\mu_{\max}$ = 3.98, so that

$$\frac{1}{\mu_{\max}} = 3.98 \rightarrow \boxed{\mu_{\max} = 0.251 \text{ hr}^{-1}}$$

Further, the line has slope $K_S/\mu_{\max}$ = 6.05, so that

$$\frac{K_S}{\mu_{\max}} = 6.05 \rightarrow K_S = 6.05 \times 0.251 = \boxed{1.52 \text{ g/L}}$$

The rate equation for cell growth is determined to be

$$r_X = \frac{0.251 C_S C_X}{1.52 + C_S}$$

♦ The correct answer is **A.**

Part 2: To prevent washout of the cells, the cell concentration should be maintained such that it will be greater than zero. In mathematical terms,

$$C_X = Y_{X/S}\left(C_{S,0} - \frac{K_S}{\tau_m \mu_{\max} - 1}\right) > 0$$

Solving the equation for τ_m gives

$$\tau_m = \frac{K_S + C_{S,0}}{C_{S,0}\mu_{\max}}$$

We know that $\tau_m = V/F$. Thus, the minimum feed is determined to be

$$F = \frac{V C_{S,0} \mu_{\max}}{K_S + C_{S,0}} = \frac{0.65 \times 100 \times 0.251}{1.52 + 100} = \boxed{0.161 \text{ L/hr}}$$

♦ The correct answer is **B.**

P.5 ➡ *Solution*

1. False. For a single steady-state CSTF with a sterile feed, the dilution rate is equal to the specific growth rate; that is,

$$D = \frac{F}{V} = \frac{\mu_{\max} C_S}{K_S + C_S} = \frac{0.6 \times 6.0}{4.0 + 6.0} = 0.36 \text{ hr}^{-1}$$

so that

$$D = \frac{F}{V} \rightarrow V = \frac{F}{D}$$

$$\therefore V = \frac{650}{0.36} = \boxed{1810 \text{ L}}$$

2. True. The cell concentration of the outlet stream is

$$C_X = Y_{X/S}\left(C_{S,0} - C_S\right) = 0.58 \times (90 - 6) = \boxed{48.7 \text{ g/L}}$$

3. True. For two CSTFs in series, the first fermenter must be operated at maximum productivity conditions; we first require parameter α, namely

$$\alpha = \sqrt{\frac{K_S + C_{S,0}}{K_S}} = \sqrt{\frac{4.0 + 90}{4.0}} = 4.85$$

The cell concentration in the first fermenter is the optimum concentration $C_{X,opt}$, which in turn is given by

$$C_{X,1} = C_{X,\text{opt}} = Y_{X/S} C_{S,0} \frac{\alpha}{\alpha + 1} = 0.58 \times 90 \times \frac{4.85}{4.85 + 1} = 43.3 \text{ g/L}$$

The outlet substrate concentration, also assuming optimal conditions, is

$$C_{S,1} = C_{S,\text{opt}} = \frac{C_{S,0}}{\alpha + 1} = \frac{90}{4.85 + 1} = \boxed{15.4 \text{ g/L}}$$

4. False. The residence time, again assuming optimal conditions, follows as

$$\tau_{m,1} = \tau_{m,\text{opt}} = \frac{\alpha}{\mu_{\max}(\alpha - 1)} = \frac{4.85}{0.6 \times (4.85 - 1)} = 2.10 \text{ hr}$$

It remains to compute the volume of the first reactor,

$$V_1 = \tau_{m,1} F = 2.10 \times 650 = 1370 \text{ L}$$

For the second fermenter, the following relation holds,

$$F\left(C_{X,1} - C_{X,2}\right) + \frac{V_2 \mu_{\max} C_{S,2} C_{X,2}}{K_S + C_{S,2}} = 0$$

Solving for V_2 and substituting our data, we obtain

$$V_2 = \frac{F\left(C_{X,2} - C_{X,1}\right)}{\mu_{\max} C_{S,2} C_{X,2} / \left(K_S + C_{S,2}\right)} = \frac{650 \times (48.7 - 43.3)}{0.6 \times 6 \times 48.7 / (4 + 6)} = 200 \text{ L}$$

The total volume of the two CSTFs is then

$$V' = V_1 + V_2 = 1370 + 200 = \boxed{1570 \text{ L}}$$

This is about 13.3% lower than the volume calculated for operation of a single CSTF.

5. False. The volume of the CSTR has been determined as 1370 L in the analysis of the previous statement. It remains to compute the volume of the PFF. The mean residence time is

$$\tau_{m,2} = \frac{1}{\mu_{\max}}\left[\left(\frac{K_S Y_{X/S}}{C_{X,1} + C_{S,1} Y_{X/S}} + 1\right)\ln\left(\frac{C_{X,2}}{C_{X,1}}\right) + \frac{K_S Y_{X/S}}{C_{X,1} + C_{S,1} Y_{X/S}} \ln\left(\frac{C_{S,1}}{C_{S,2}}\right)\right]$$

$$\therefore \tau_{m,2} = \frac{1}{0.6} \times \left[\left(\frac{4.0 \times 0.58}{43.3 + 15.4 \times 0.58} + 1 \right) \ln\left(\frac{48.7}{43.3} \right) + \frac{4.0 \times 0.58}{43.3 + 15.4 \times 0.58} \ln\left(\frac{15.4}{6} \right) \right] = 0.274 \text{ h}$$

Accordingly,

$$V_2 = \tau_{m,2} F = 0.274 \times 650 = 178 \text{ L}$$

The sum of the reactor volumes is then

$$V'' = V_1 + V_2 = 1370 + 178 = \boxed{1550 \text{ L}}$$

This is about 14.4% lower than the volume calculated for operation of a single CSTF.

P.6 ➡ *Solution*

At incipient washout, the critical dilution rate, D_{crit}, is related to the Monod constants by an equation of the form

$$D_{\text{crit}} = \frac{\mu_m C_S}{K_S + C_S}$$

where S_0 is the concentration of substrate in the feed. Rearranging, we write

$$\mu_m = \frac{D_{\text{crit}} \left(K_S + C_S \right)}{C_S}$$

For initial conditions, we have

$$\mu_m = \frac{0.31\left(K_S + 1.0 \right)}{1.0} \rightarrow \mu_m = 0.31 K_S + 0.31 \text{ (I)}$$

For the increased feed rate, we have D_{crit} = 0.095 h^{-1} and S_0 = 2.5 g/L, with the result that

$$\mu_m = \frac{0.095\left(K_S + 2.5 \right)}{2.5} = 0.038 K_S + 0.095 \text{ (II)}$$

Equations (I) and (II) constitute a system of linear equations with two unknowns. Solving it gives K_S = 0.790 g/L and μ_m = 0.065 h^{-1}. Now, the maximum cell productivity occurs at an optimum dilution rate, D_{opt}, given by

$$D_{\text{opt}} = \mu_m \left(1 - \sqrt{\frac{K_S}{K_S + C_S}} \right)$$

and the substrate concentration for any dilution rate below the critical value is given by

$$C_S = \frac{D K_S}{\mu_m - D}$$

Thus, for the initial conditions,

$$D_{\text{opt}} = 0.065 \times \left(1 - \sqrt{\frac{0.79}{0.79 + 1.0}} \right) = 0.0218 \text{ h}^{-1}$$

and

$$C_S = \frac{0.0218 \times 0.79}{0.065 - 0.0218} = 0.40 \text{ g/L}$$

For the increased flow rate, in turn,

$$D_{\text{opt}} = 0.065 \times \left(1 - \sqrt{\frac{0.79}{0.79 + 2.5}} \right) = 0.0331 \text{ h}^{-1}$$

and

$$C'_S = \frac{0.0331 \times 0.79}{0.065 - 0.0331} = 0.82 \text{ g/L}$$

Thus, the effluent substrate concentration for the increased flow rate is 105% greater than the initial substrate concentration.

♦ The correct answer is **B.**

P.7 ➡ *Solution*

1.False. Assuming Monod kinetics do apply, we have, for the first fermenter,

$$D_1 = \frac{\mu_{\max} C_{S,1}}{K_S + C_{S,1}}$$

This relation can be solved for $C_{S,1}$ to give

$$C_{S,1} = \frac{D_1 K_S}{\mu_{\max} - D_1}$$

The dilution rate in the first fermenter is $D_1 = F/V_1 = 24/100 = 0.24\ \text{h}^{-1}$. Thus,

$$C_{S,1} = \frac{0.24 \times 0.14}{0.29 - 0.24} = 0.672\ \text{g/L}$$

Since the feed to the first fermenter is sterile, $C_{S,0} = 0$. Given the yield coefficient $Y = 0.47$, the steady-state concentration of biomass in the first vessel is determined as

$$C_{X,1} = Y\left(C_{S,0} - C_{S,1}\right) = 0.47 \times \left(4.6 - 0.672\right) = \boxed{1.85\ \text{g/L}}$$

2.True. In a similar way, a mass balance over the second fermenter gives

$$D_2 = \frac{\mu_2 C_{X,2}}{C_{X,2} - C_{X,1}}$$

where D_2 is the dilution rate in the second fermenter, μ_2 is the specific growth rate in the second fermenter, and $C_{X,2}$ is the steady-state concentration of biomass. At this point, we appeal to the general equation

$$\left(\mu_{\max} - D_2\right) C_{S,2}^2 + \left(\frac{D_1 D_2 K_S}{\mu_{\max} - D_1} - D_2 K_S - \mu_{\max} C_{S,0}\right) C_{S,2} + \frac{D_1 D_2 K_S^2}{\mu_{\max} - D_1} = 0$$

The dilution rate in the second fermenter is $D_2 = 18/50 = 0.36\ \text{h}^{-1}$. Substituting this and other data brings to

$$\left(0.25 - 0.36\right) C_{S,2}^2 + \left(\frac{0.18 \times 0.36 \times 0.14}{0.29 - 0.18} - 0.36 \times 0.14 - 0.29 \times 4.6\right) C_{S,2} + \frac{0.18 \times 0.36 \times 0.14^2}{0.29 - 0.18} = 0$$

$$\therefore -0.11 C_{S,2}^2 - 1.30 C_{S,2} + 0.0115 = 0$$

$$\therefore 0.11 C_{S,2}^2 + 1.30 C_{S,2} - 0.0115 = 0$$

Solving the quadratic equation above yields $C_{S,2} = 0.00884$ g/L. This is the substrate concentration in the effluent from the second fermenter.

3.False. It remains to determine the biomass concentration in the effluent from the second fermenter. To do so, we adjust the expression for the yield coefficient as applied to the second vessel, giving

$$Y = \frac{C_{X,2} - C_{X,1}}{C_{S,1} - C_{S,2}} \rightarrow C_{X,2} = C_{X,1} + Y\left(C_{S,1} - C_{S,2}\right)$$

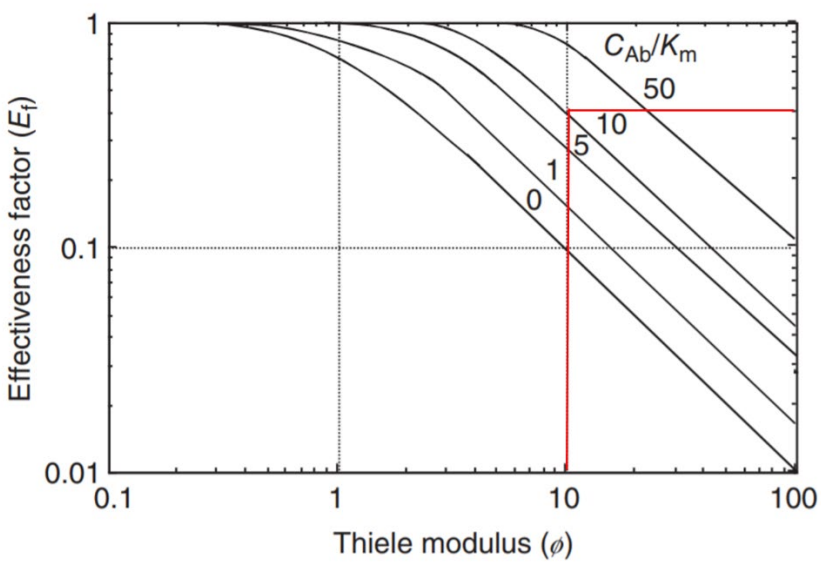
$$\therefore C_{X,2} = 1.85 + 0.47 \times \left(0.672 - 0.00884\right) = \boxed{2.16\ \text{g/L}}$$

P.8 ➡ *Solution*

Given the particle radius $R_p = 0.5/2$ cm, the maximum rate $\mu_{\max} = 4.8 \times 10^{-7}$ kmol/(kg bead·s), the diffusion coefficient $D_{\text{eff}} = 7.8 \times 10^{-7}$ cm²/s, the saturation constant $K_S = 0.05$ kmol/m³, and the bead density = 1170 km/m³, the Thiele modulus is calculated as

$$\phi = \frac{R_p}{3}\sqrt{\frac{\mu_{\max}}{D_{\text{eff}}K_S}} = \frac{(0.5/2)}{3}\sqrt{\frac{\left(4.8\times10^{-7}\right)\times1170}{\left(7.8\times10^{-7}\right)\times0.05}} = 10$$

We also require ratio C_{Ab}/K_S = 0.5/0.05 = 10, where C_{Ab} = 0.5 kmol/m³ is the substrate concentration at the catalyst particle surface. Entering the pertinent quantities into Figure 1, we read an effectiveness factor E_f = 0.4, as highlighted below.



The initial reaction rate follows as

$$r_p = E_f\frac{\mu_{\max}C_S}{K_S + C_S} = 0.40\times\frac{\left(4.8\times10^{-7}\times1170\right)\times0.5}{0.05+0.5} = \boxed{2.04\times10^{-4}\ \text{kmol/(m}^3\cdot\text{s)}}$$

♦ The correct answer is **D**.

ANSWER SUMMARY

Problem 1		C
Problem 2		Open-ended pb.
Problem 3		T/F
Problem 4	**4.1**	A
	4.2	B
Problem 5		T/F
Problem 6		B
Problem 7		T/F
Problem 8		D

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