

Journal of Food Engineering 64 (2004) 277-283

JOURNAL OF FOOD ENGINEERING

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Bioreactor design via spreadsheet—a study on the monosodium glutamate (MSG) process

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Abstract

Preliminary design calculation of a unit operation is always necessary to determine an order of magnitude of the proposed chemical plant. This paper describes an application of a spreadsheet in preliminary design of a bioreactor. There are a few steps in bioreactor design which are mass/mole balances and energy balances calculations before carrying out the bioreactor sizing. A spreadsheet was used as a tool to make a quick and accurate calculation. Glutamic acid fermentation is used to describe the overall method in this bioreactor design via spreadsheet. The method presented here is easy to learn and easy for the designer to scale up and to simulate different operating conditions to meet an optimum design from time to time by changing only a few variable such as flow rate and substrate concentration of the feed in the previously constructed spreadsheet. © 2003 Elsevier Ltd. All rights reserved.

Keywords: Bioreactor; Spreadsheet; Glutamic acid; Fermentation; Monosodium glutamate

1. Introduction

It is often necessary to develop data for a range of operating conditions, so that the optimum configuration of a bioreactor can be found. There are two conventional methods to perform such a task, either by hand calculation (which is somewhat inaccurate and time consuming) or by any of a number of commercial simulations that are faster but costly to licence. A third alternative is presented here: Insert all the manual calculation equations into any spreadsheet program such as Microsoft Excel. This will eliminate the need for employing expensive simulation software and labouring over hand calculations. Further, the time involved from the programmer's point of view is no more (or considerably less) than that required to learn how to use a commercial simulation package.

Microsoft Excel is a commercial spreadsheet software developed by Microsoft[®] Corporation, which is widely used today. Microsoft Excel is part of the package Microsoft Office and it is fully developed with statistics, mathematical and engineering applications (Bloch, 2000; Liengme, 1997). One of the engineering applications that is available in Microsoft Excel is a root-finding function such as 'solver' and 'goal seek' which play an important role in process engineering to find a correspondence input with a fixed output. Normally in design, the target output is a fixed variable but the input variable is always very difficult to determine via hand calculation because it requires the designer to run a reversed calculation and work with more than one equation and unknown variable.

The method presented here is easy to learn, and offers a quick way to make preliminary estimates of the bioreactor diameter and height, cooling coil required, diameter of baffle, impeller, and sparger ring. Fig. 1 shows a basic configuration of a typical bioreactor.

2. Spreadsheet calculation procedure

Monosodium glutamate (MSG) is widely used not only by housewives to enhance the taste of dishes but also by professional chefs in restaurants all over the world including Malaysia. It is also added into a variety of processed foods, frozen foods, soups, snacks, instant noodles, etc. The process for producing MSG is a typical bioreaction by applying an enzyme. The first step in

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^{0260-8774/\$ -} see front matter @ 2003 Elsevier Ltd. All rights reserved. doi:10.1016/j.jfoodeng.2003.10.009

Nomeno	clature		
C_P	heat capacity, kJ/kg°C	$Q_{\rm B}$	power absorbed by broth, W
Ε	energy	Q_{q}	heat flow into system
'n	mass flow rate, kg/s	$Q_{\rm w}$	work done by system
P_{b}	bioreactor bottom pressure, atm	R	gas constant m ³ Pa/mole K
$P_{\rm atm}$	atmospheric pressure, atm	Т	temperature, °C
$P_{\rm air}$	power absorbed by air flow, W	T_1	inlet cooling water temperature, °C
PAmmonia	power absorbed by ammonia, W	T_2	outlet cooling water temperature, °C
P_{F}	net power generated in fermentation, W	$T_{\rm p}$	Broth temperature, °C
$P_{\rm e}$	energy produced within the system	$T_{\rm LMTD}$	log mean temperature difference
Q_{Gen}	total power generated in fermentation, W	U	overall heat transfer coefficient, W/m ² °C
$Q_{\rm A}$	power result by agitation heat, W	ρ	density, kg/m ³
$Q_{\rm F}$	power resultant by micro-organism activity,		
-	W		

bioreactor design calculation is a mass/mole and energy balance on the bioreactor. The calculation presented here is based on a glutamic acid fermentation process (Fig. 2). the yield of glutamic acid over glucose, $Y_{x/s}$ into the spreadsheet. Subsequently the reaction spreadsheet was developed based on the stoichiometry of glutamic acid fermentation. The full mole/mass balance spreadsheet is

2.1. Mass/mole balance

First of all, related information on the chemicals utilised (i.e. density, molarity and molecular weight) and



Fig. 1. Typical bioreactor configuration (James & David, 1986).



Fig. 2. Bioreactor design calculation procedure.



Fig. 3. Summary of mass and heat transfer from MS Excel spreadsheet.

constructed by linking each cell from the reaction spreadsheet to the equation and chemical or physical properties. From this mole/mass balance the amount of substrate (glucose), ammonia, and air (oxygen supply) required can be calculated. The ideal gas law is applied in the spreadsheet for the automatic calculation of air and ammonia flow rate. The ideal gas law is considered applicable since the air pressure is not more than 2 atm. The summary of the mass/mole balance calculated by the Excel spreadsheet is shown in Fig. 3.

The stoichiometric equation of L-glutamic acid fermentation is as follow (Murray, 1985):

$$\begin{split} & C_6 H_{12} O_6 + 2.21 O_2 + 0.84 N H_3 \\ & \rightarrow 0.84 C_5 H_9 O_4 N + 1.78 \, CO \ + 3.74 H_2 O_4 N \\ \end{split}$$

The mass balance for the component A in a bioreactor vessel as stated in Biotol (1992) is:

$$V\frac{\delta C_A}{\delta t} = \dot{v}_{\rm in}C_{A,\rm in} - \dot{v}_{\rm out}C_{A,\rm out} + r_A V \tag{1}$$

The mole balance of component A of a bioreactor from Biotol (1992) is written as:

$$V\frac{\delta \dot{h}_A}{\delta t} = \dot{v}_{\rm in}\dot{n}_{A,\rm in} - \dot{v}_{\rm out}\dot{n}_{A,\rm out} + r_A V \tag{2}$$

The ideal gas law applied to estimates the volume flow rate of gases given as:

$$PV = \dot{n}RT \tag{3}$$

Broth final volume, which is equal to the bioreactor working volume, is estimated as:

$$V = \frac{m}{\rho} \tag{4}$$

Table 1

Bioreactor design criteria (Hall, Stanbury, & Whitaker, 1999)

Dimension	Ratio
Working volume/bioreactor vessel volume	0.8
Height/vessel diameter (H/D)	2
Vessel diameter/impeller diameter (D/D_i)	3
Sparger ring diameter/impeller diameter (D_s/D_i)	1–1.2
Baffle/vessel diameter (D_b/D)	0.1
Foam breaker diameter/vessel diameter	0.6
$(D_{\rm FB}/D)$	
$L/D_{\rm i}$	0.25
E/W	1
$W/D_{ m i}$	0.2

Table 2 Bioreactor sizin

Bioreactor sizing spreadsheet	
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	A	В	С	D	Е	F	G	Н	Ι	J
1	Bioreac	tor sizin	g spre	adshe	et					
2										
3	Bioreactor	r	Di	Db	Ds	L	W	Е	D _{FB}	
4	d (m)	6.051	2.017	0.605	1.614	0.504	0.403	0.403	3.631	
5	h (m)	12.102								
6	v (m ³)	290.000								

2.2. Bioreactor sizing

After performing the mass/mole balance, the working volume of the bioreactor can be calculated. A typical working volume of a bioreactor is 80% of the total volume as shown in Table 1 (Hall et al., 1999). Based on

this information the total volume of a bioreactor can be calculated. A spreadsheet for the bioreactor sizing is constructed by linking the cells of working volume in the mass/mole balance spreadsheet to the bioreactor design criteria as shown in Table 1. Table 2 is an example of the constructed spreadsheet for bioreactor sizing (Fig. 4).

_	A .	р	C	l n		E E	G	ч	I T	T I	V	
1	Bioreactor oper	ation specific	ration			F	0	п		,	ĸ	
2	proreactor open	atton specific	CHION									
3	Sirrer tank reacto	г										
4	Stoichiometry		C6H12O6 + 2.2	2065O ₂ + 0.843N	H ₃ => 0.843C	5H9O4N + 1.	785CO ₂ + 3	.741H ₂ O				
5	Microorganism u	ised Coryneb	acterium glutar	nicium								
6	Ammount of anti	foam, vitam	ins and H ₃ PO ₄ i	is neglected								
7	Working Volume	e 231 m ³ , Tot	al volume 290	m ³								
8	Fermentation cyc	le 30 hr										
9	Overall fermenta	tion cycle 48	hr (including p	reparation and st	erilization)							
10	3 Fermenter requ	ired for prod	uction 1000 T/r	month (2 ferment	er operates and	i 1 standby)						
11	Glucose conversi	ion essentiall	y is 70%, 30% i	is used for microe	rganism grow	th						
12]											
13	-											
14												
15	Feed		1	-								
16	NH ₃	100.00%		4								
1/	Giucose	80	g/L	J								
10	n . 171		000 70	3	٦							
19	Fermenter Volun	ne	288.73	m								
20	Head space		57.75	n m -	-							
21	Working volume		231	. [m [°]	_							
22	Seed 3% ferment	er volume		-								
23	Volume	6	m ³]								
24	Broth			-								
25	[[GA]	0.131	kg/L	4								
26	рн	7.00	L	L								
27	4											
28	4											
29	4											
30	4											
22	Chamical &	hysical	onartics	Starting an-	dition of bi	presetor						
32	MW CA	JAYSICAL DI	opernes	Starting con		oreactor	NILI	но	CHNC		чо	1
24	MW Glucoso	180.00	1	Stoichiomate	1 00	2 2 21	0.84	n ₂ U	0.94	1 70	3 47	1
35	GA/Glucose	0.82	1	MW g	180.00	32.00	17.00	18.00	147.00	44.00	18 00	1
36	GA Yeild	68.85%	1	Conc g/L	100.00	22.00	1	1.00			10.00	1
37	GA prod	123.92	1	Vol L	200000			170149.3				
38	Mol GA	0.84]	Molarity	0.56							
39	MW NH3	17.00		Kmol y=68.85%	6 77.78	171.62	65,57		65,57	138,83	269.97	
40	H ₂ O kg/L	1.00		Mass bal kg	14000.0	5491.73	1114.63	170149.3	9638.30	6108.67	4859.40	
41	C ₆ H ₁₂ O ₆ kg/L	0.67		Balance	20606.37				20/0/ 27			
1									20000.37			1
42	ρ GA kg/L	1.538]	Mass out					14497.70	(Liquid pha	ses only)	1
42 43	ρ GA kg/L ρ broth kg/L	1.538 1.4		Mass out Volume L					20606.37 14497.70 6266.78	(Liquid pha	ses only)	
42 43 44	ρ GA kg/L ρ broth kg/L T in °C	1.538 1.4 30		Mass out Volume L Ov Mass					20606.37 14497.70 6266.78 184646.95	(Liquid pha (Liquid pha	ses only) ses only)	
42 43 44 45	ρ GA kg/L ρ broth kg/L T in °C C ₁₂ H ₂₂ O ₁₁	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentration	on				20606.37 14497.70 6266.78 184646.95 0.073	(Liquid pha (Liquid pha kg/L	ises only) ises only)	
42 43 44 45 46 47	$\begin{array}{l} \rho \text{ GA kg/L} \\ \rho \text{ broth kg/L} \\ T \text{ in }^{\circ}\text{C} \\ C_{12}\text{H}_{22}\text{O}_{11} \\ \end{array}$	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentration Liquid volume	on				20606.37 14497.70 6266.78 184646.95 0.073 131891	(Liquid pha (Liquid pha kg/L L	ses only) ses only)	
42 43 44 45 46 47	$\begin{array}{c} \rho \text{ GA kg/L} \\ \rho \text{ broth kg/L} \\ T \text{ in }^{\circ}C \\ C_{12}H_{22}O_{11} \end{array}$	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentration Liquid volume	m				20606.37 14497.70 6266.78 184646.95 0.073 131891	(Liquid pha (Liquid pha kg/L L	ses only) ses only)	
42 43 44 45 46 47 48	$\begin{array}{l} \rho \ GA \ kg/L \\ \rho \ broth \ kg/L \\ T \ in \ ^{\circ}C \\ C_{12}H_{22}O_{11} \end{array}$	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentration Liquid volume Bioreactor v	n rith fed-bat	ch (after 3	hours op	eration)	20006.37 14497.70 6266.78 184646.95 0.073 131891	(Liquid pha (Liquid pha kg/L L	ises only)	
42 43 44 45 46 47 48 49	$\begin{array}{l} \rho \; GA \; kg/L \\ \rho \; broth \; kg/L \\ T \; in \; {}^{\circ}C \\ C_{12}H_{22}O_{11} \end{array}$	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentration Liquid volume Bioreactor v	rith fed-bat	ch (after 3	hours op	eration) H ₂ O	20606.37 14497.70 6266.78 184646.95 0.073 131891 C ₅ H ₉ NO ₄	(Liquid pha (Liquid pha kg/L L	ses only) ses only) H ₂ O	
42 43 44 45 46 47 48 49 50 51	$ \begin{array}{c} \rho \ GA \ kg/L \\ \rho \ broth \ kg/L \\ T \ in \ ^{\circ}C \\ C_{12}H_{22}O_{11} \end{array} $	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentration Liquid volume Bioreactor v Stoichiometry	ith fed-bat C ₆ H ₁₂ O ₆ 1.00	ch (after 3 O ₂ 2.21	hours op NH ₃ 0.84	eration) H ₂ O	20606.37 14497.70 6266.78 184646.95 0.073 131891 C ₅ H ₉ NO ₄ 0.84 147.00	(Liquid pha (Liquid pha kg/L L CO ₂ 1.79	ses only) ses only) H ₂ O 3.47	
42 43 44 45 46 47 48 49 50 51 51 52	$\frac{\rho GA kg/L}{\rho broth kg/L}$ $\frac{T in ^{\circ}C}{C_{12}H_{22}O_{11}}$	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentratie Liquid volume Bioreactor v Stoichiometry MW g Conc g/f	vith fed-bat C ₆ H ₁₂ O ₆ 1.00 180.00 250.00	ch (after 3 O ₂ 2.21 32.00	hours op NH ₃ 0.84 17.00	eration) H ₂ O 18.00	20606.37 14497.70 6266.78 184646.95 0.073 131891 C ₃ H ₉ NO ₄ 0.84 147.00	(Liquid pha (Liquid pha kg/L L CO ₂ 1.79 44.00	ses only) ses only) H ₂ O 3.47 18.00	
42 43 44 45 46 47 48 49 50 51 52 53	$ \begin{array}{l} \rho \ GA \ kg/L \\ \rho \ broth \ kg/L \\ \hline T \ in \ ^C \\ C_{12}H_{22}O_{11} \end{array} $	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentration Liquid volume Bioreactor v Stoichiometry MW g Conc g/L Vol L	rith fed-bat C ₆ H ₁₂ O ₆ 1.00 180.00 250.00 171680	ch (after 3 O ₂ 2.21 32.00	hours op NH ₃ 0.84 17.00	eration) H ₂ O 18.00 1.00 107620 3	20606.37 14497.70 6266.78 184646.95 0.073 131891 C ₃ H ₉ NO ₄ 0.84 147.00	(Liquid pha (Liquid pha kg/L L CO ₂ 1.79 44.00	ses only) ses only) H ₂ O 3.47 18.00	
42 43 44 45 46 47 48 49 50 51 52 53 54	$ \begin{array}{l} \rho \ GA \ kg/L \\ \rho \ broth \ kg/L \\ T \ in \ ^{C}C \\ \hline C_{12}H_{22}O_{11} \end{array} $	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentratie Liquid volume Bioreactor v Stoichiometry MW g Conc g/L Vol L Molarity	vith fed-bat C ₆ H ₁₂ O ₆ 1.00 180.00 250.00 171680 1.39	ch (after 3 O ₂ 2.21 32.00	hours op NH ₃ 0.84 17.00	eration) H ₂ O 18.00 1.00 107620.3	20606.37 14497.70 6266.78 184646.95 0.073 131891 C ₃ H ₉ NO ₄ 0.84 147.00	(Liquid pha (Liquid pha kg/L L CO ₂ 1.79 44.00	ses only) ses only) H ₂ O 3.47 18.00	
42 43 44 45 46 47 48 49 50 51 52 53 54 55	$\begin{array}{l} \rho \; GA \; kg/L \\ \rho \; broth \; kg/L \\ T \; in \; {}^{\circ}C \\ C_{12}H_{22}O_{11} \end{array}$	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentratic Liquid volume Bioreactor v Stoichiometry MW g Conc g/L Vol L Molarity Kmol y= 68.85°	rith fed-bat C ₆ H ₁₂ O ₆ 1.00 180,00 250,00 171680 1.39 6 166,91	ch (after 3 O ₂ 2.21 32.00 368.29	hours op NH ₃ 0.84 17.00	eration) H ₂ O 18.00 1.00 107620.3	20606.37 14497.70 6266.78 184646.95 0.073 131891 C ₃ H ₉ NO ₄ 0.84 147.00	(Liquid pha (Liquid pha kg/L L CO ₂ 1.79 44.00 297.94	ses only) ses only) H ₂ O 3.47 18.00 579.35	
42 43 44 45 46 47 48 49 50 51 52 53 54 55 56	ρ GA kg/L \overline{D} broth kg/L \overline{T} in °C $\overline{C}_{12}H_{22}O_{11}$	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentrati Liquid volume Stoichiometry MW g Conc g/L Vol L Molarity Kmol y=68.85 [°] Mass bal kg	rith fed-bat C ₆ H ₁₂ O ₆ 1.00 180.00 250.00 171680 1.39 6 166.91 30044.0	ch (after 3 O ₂ 2.21 32.00 368.29 11785.26	hours op NH ₃ 0.84 17.00 140.71 2392,00	eration) H ₂ O 18.00 1.00 107520.3 107620.3	20606.37 14497.70 6266.78 184646.95 0.073 131891 C ₃ H ₉ NO ₄ 0.84 147.00 140.71 20683.79	(Liquid pha (Liquid pha kg/L L CO ₂ 1.79 44.00 297.94 13109.20	ses only) ses only) H ₂ O 3.47 18.00 579.35 10428.27	
42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 57	$ \begin{array}{l} \rho \; GA \; kg/L \\ \rho \; broth \; kg/L \\ T \; in \; ^CC \\ \hline C_{12}H_{22}O_{11} \end{array} $	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentratie Liquid volume Bioreactor v Stoichiometry MW g Conc g/L Vol L Molarity Kmol y=68.85 ^o Mass bal kg Balance	rith fed-bat C ₆ H ₁₂ O ₆ 1.00 180.00 250.00 171680 1.39 6 166.91 30044.0 44221.26	ch (after 3 O ₂ 2.21 32.00 368.29 11785.26	hours op NH ₃ 0.84 17.00 140.71 2392.00	eration) H ₂ O 18.00 107620.3 107620.3	20606.37 14497.70 6266.78 184646.95 0.073 131891 C ₃ H ₉ NO ₄ 0.84 147.00 140.71 20683.79 44221.26	(Liquid pha (Liquid pha kg/L L CO ₂ 1.79 44.00 297.94 13109.20	ses only) ses only) H ₂ O 3.47 18.00 579.35 10428.27	
42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59	p GA kg/L p broth kg/L T in °C C ₁₂ H ₂₂ O ₁₁	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentrati Liquid volume Bioreactor v Stoichiometry MW g Conc g/L Vol L Molarity Kmol y=68.85% Mass bal kg Balance Mass out Volume !	rith fed-bat C ₆ H ₁₂ O ₆ 1.00 180.00 250.00 171680 1.39 6 166.91 30044.0 44221.26	ch (after 3 O ₂ 2.21 32.00 368.29 11785.26	hours op NH ₃ 0.84 17.00 140.71 2392.00	eration) H ₂ O 18.00 1.07620.3 107620.3	20606.37 14497.70 6266.78 184646.95 0.073 131891 C_3H ₉ NO ₄ 0.84 147.00 140.71 140.71 140.71 140.71 140.71 140.71 140.71 140.71	(Liquid pha (Liquid pha kg/L L CO ₂ 1.79 44.00 297,94 13109.20 (Liquid pha	ses only) ses only) H ₂ O 3.47 18.00 579.35 10428.27 ses only)	
42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60	ρ GA kg/L Τ in °C C ₁₂ H ₂₂ O ₁₁	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentratie Liquid volume Bioreactor v Stoichiometry MW g Conc g/L Vol L Molarity Kmol y~68.85° Mass bal kg Balance Mass out Volume L Ov Mase	ith fed-batt C ₆ H ₂ O ₆ 1.00 180.00 250.00 171680 171680 16.91 30044.0 44221.26	ch (after 3 O ₂ 2.21 32.00 368.29 11785.26	hours op NH ₃ 0.84 17.00 140.71 2392.00	eration) H ₂ O 18.00 1.00 107620.3 107620.3	20605.37 14497,70 6266.78 184646.95 0.073 131891 20,84 147,00 140,71 20683,79 44221,26 31112,06 13448,50 134733,36	(Liquid pha (Liquid pha kg/L L CO ₂ 1.79 44.00 44.00 44.00 43109.20 (Liquid pha (Liquid pha	ses only) ses only) H ₂ O 3.47 18.00 579.35 10428.27 ses only) ses only)	
42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61	p GA kg/L p broth kg/L T in °C C ₁₂ H ₂₂ O ₁₁	1.538 1.4 30 0.8		Mass out Volume L. Ov Mass GA concentratie Liquid volume Stoichiometry MW g Conc g/L. Vol L. Molarity Kinol y=68.859 Mass bal kg Balance Mass out Volume L. Ov Mass	rith fed-bat C ₆ H ₁₂ O ₆ 1.00 180.00 1.39 6 166.91 3004.4 44221.26	ch (after 3 O ₂ 2.21 32.00 368.29 11785.26	hours op NH ₃ 0.84 17.00 140.71 2392.00	eration) H ₂ O 18.00 1.00 107620.3 107620.3	2060.37 14497,70 6266.78 184646.95 0.073 131891 C_5H ₉ NO ₄ 0.84 147.00 140.71 20683.79 44221.26 31112.06 13484.50 138732.36	(Liquid pha (Liquid pha kg/L L CO ₂ 1.79 44.00 297.94 13109.20 (Liquid pha (Liquid pha	ses only) ses only) H ₂ O 3.47 18.00 579.35 10428.27 ses only) ses only)	
42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62	p GA kg/L p broth kg/L T in °C C ₁₂ H ₂₂ O ₁₁	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentrati Liquid volume Bioreactor v Stoichiometry MW g Conc g/L Vol L Molarity Kmol y=68.85° Mass bal kg Balance Mass out Volume L Ov Mass	m ith fed-batt C _g H ₁ O ₆ 1.00 180.00 259.00 171680 1.39 6 166.91 3004.0 44221.26	ch (after 3 O ₂ 2.21 32.00 368.29 11785.26	hours op NH ₃ 0.84 17.00 140.71 2392.00	eration) H ₂ O 18.00 1.07620.3 107620.3	20606.37 14497,70 6266.78 184646.95 0.073 131891 C.H.NO. 0.84 147.00 140.71 20683.79 4422126 31112.06 13448.50 138732.36	(Liquid pha kg/L L CO ₂ 1.79 44.00 297.94 13109.20 (Liquid pha (Liquid pha	ses only) ses only) H ₂ O 3.47 18.00 579.35 10428.27 ses only) ses only)	
42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63	ρ GA kg/L ¬ broth kg/L T in °C C ₁₂ H ₂₂ O ₁₁	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentratie Liquid volume Bioreactor v Stoichiometry MW g Conc g/L Vol L Molarity Kmol y=68.85° Mass bal kg Balance Mass bal kg Balance Volume L Ov Mass Overall Bior	m ith fed-bat CeH₂Q₀ 1.00 180.00 2.50.00 1.39 4.166.91 3004.0 4.4221.26 ■ ■	ch (after 3 O ₂ 2.21 32.00 368.29 11785.26	hours op NH ₃ 0.84 17.00 140.71 2392.00	eration) H ₂ O 18.00 1.00 107620.3 107620.3	2060.57 14497,70 6266.78 184646.95 0.073 131891 C ₂ H ₈ NO ₄ 0.84 147.00 147.00 147.00 147.00 147.00 147.00 13112.06 13448.50 138732.36	(Liquid pha (Liquid pha kg/L L CO ₂ 1.79 44.00 297.94 13109.20 (Liquid pha (Liquid pha	ses only) ses only) H ₂ O 3.47 18.00 579.35 10428.27 ses only) ses only)	
42 43 44 45 46 47 48 49 50 51 52 53 54 55 55 56 57 58 59 60 61 62 63 64	p GA kg/L p broth kg/L T in °C C ₁₂ H ₂₂ O ₁₁	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentratic Liquid volume Bioreactor v Stoichiometry MW g Cone g/L Vol L Molarity Kmol y=68.85° Mass bal kg Balance Mass out Volume L Ov Mass	rith fed-bat C ₆ H ₁ O ₆ 1.00 1.80.00 1.39 6 166.91 3.004.4 4.4221.26 eactor calc C ₆ H ₁ O ₈	ch (after 3 O ₂ 2.21 32.00 368.29 11785.26	hours op NH ₃ 0.84 17.00 140.71 2392.00	eration) H ₂ O 18.00 107620.3 107620.3	2060.37 14497,70 6266.78 184646.95 0.073 131891 C ₂ H ₆ NO ₄ 0.84 147.00 140.71 20683.79 44221.26 31112.06 31112.06 31112.06 31112.05 3112.23 6 3112.23 6 3112.23 6 3112.23 6 3112.23 6 3112.23 7 3448.50 138732.36	(Liquid pha (Liquid pha kg/L L CO ₂ 1.79 44.00 44.00 497.94 13109.20 (Liquid pha (Liquid pha (Liquid pha	ses only) ses only) H ₂ O 3.47 1800 579.35 10428.27 ses only) ses only) H ₂ O	
42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65	p GA kg/L _ broth kg/L T in °C C ₁₂ H ₂₂ O ₁₁	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentrati Liquid volume Bioreactor v Stoichiometry MW g Conc g/L Vol L Molarity Kmol y=68.85% Mass bal kg Balance Balance Mass out Vol Mass Ov Mass Coverall Bior Kmol y=68.85%	m ith fed-batt C _q H ₁ O ₆ , 1.00 1.00 1.00 1.39 4.4221.26 4.4221.26 ↓ 4.4221.26 ↓ C _q H ₁ O ₆ , ↓ O ₄ ↓ 0 0 0 0 0 0 0 0 0 0 0 0 0	ch (after 3 O ₂ 2.21 32.00 368.29 11785.26 Ulation O ₂ 539.91	hours op NH ₃ 0.84 17.00 140.71 2392.00 NH ₃ 206.27	eration) H ₂ O 18.00 1.07620.3 107620.3 107620.3 H ₂ O	20606.37 14497,70 6266.78 184646.95 0.073 131891 C,H ₉ NO, 0.84 147.00 140.71 20683.79 4422126 31112.06 13448.50 138732.36	(Liquid pha (Liquid pha kg/L L CO ₂ 1.79 44.00 297.94 13109.20 (Liquid pha (Liquid pha (Liquid pha	ses only) H ₂ O 3.47 18.00 579.35 10428.27 ses only) ses only) H ₂ O 849.32	
42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66	ρ GA kg/L ¬ broth kg/L T in ^e C C ₁₂ H ₂₂ O ₁₁	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentratie Liquid volume Bioreactor v Stoichiometry MW g Conc g/L Vol L Molarity Kmol y=68.85° Mass bal kg Overall Bior Kmol y=68.85% Mass bal kg	ith fed-bat ccH₁20₀ 1.00 180.00 250.00 1.39 6 1.39 6 1.39 4 164.01 240.00 1.39 4 1.39 4 1.30 4 1.00	ch (after 3 O ₂ 2.21 32.00 368.29 11785.26 Ulation O ₂ 539.91 17277.0	hours op NH ₃ 0.84 17.00 140.71 2392.00 NH ₃ 206.27 3506.6	eration) H ₂ O 18.00 1.00 107620.3 107620.3 H ₂ O H ₂ O	20606.37 14497,70 6266.78 184646.95 0.073 131891 C ₂ H ₈ NO, 0.84 147.00 147.00 140.71 20683.79 44221.26 31112.06 13448.50 138732.36 C ₃ H ₈ NO, 206.27 206.27 206.22 206.	(Liquid pha kg/L L CO ₂ 1.79 44.00 297.94 13109.20 (Liquid pha (Liquid pha CO ₂ 436.77 19217.9	ses only) ses only) H ₂ O 3.47 18.00 579.35 10428.27 ses only) ses only) H ₂ O 849.32 15287.7	238.4
42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 57 58 8 59 60 61 62 63 64 65 66 66 67 7 7	p GA kg/L p broth kg/L T in °C C ₁₂ H ₂₂ O ₁₁	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentratic Liquid volume Bioreactor v Stoichiometry MW g Cone g/L Vol L Molarity Kmol y=68.85° Mass bal kg Overall Bior Coverall Bior Kmol y=68.85° Mass bal kg Total mass in	minimize ith fed-bat CeH₁Qe 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.01 1.02 250.00 1.139 6 166.91 30044.0 44221.26 244.69 44044.0 64827.63	ch (after 3 O ₁ 2.21 368.29 11785.26 11785.26 02 539.91 17277.0	hours op NH ₃ 0.84 17.00 140.71 2392.00 NH ₃ 206.27 3506.6	eration) H ₂ O 18.00 1.00 107620.3 107620.3 107620.3 H ₂ O 277769.6 Total mass out	20000.37 14497,70 6266.78 184646.95 0.073 131891 20,45 131891 149,70 149,70 140,71 20683,79 44221.26 31112.06 13448.50 138732.36 206.27 30322.1 64827.63	(Liquid pha kg/L L CO ₂ 1.79 44.00 44.00 (Liquid pha (Liquid pha (Liquid pha CO ₂ 436.77 19217.9	ses only) H ₂ O 3.47 18.00 19.55 10428.27 19.55 19.	238.4
42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 57 57 58 8 59 60 61 62 63 64 65 66 66 67 68	p GA kg/L T in °C C ₁₂ H ₂₂ O ₁₁	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentrati Liquid volume Bioreactor v Stoichiometry MW g Conc g/L Vol L Molarity Kmol y=68.85% Mass bal kg Ov Mass Ov Mass Overall Bior Kmol y=68.85% Mass bal kg Total mass in	m ith fed-bat C ₆ H ₁₂ O ₆ 1.00 180.00 250.00 171680 171680 44221.26 44221.26 C ₆ H ₁₂ O ₆ 244.04 44044.0 64827.63	ch (after 3 O ₂ 2.21 32.00 368.29 11785.26 Ulation O ₂ 539.91 17277.0	hours op NH ₃ 0.84 17,00 140.71 2392.00 NH ₃ 206.27 3596.6	eration) H ₂ O 18.00 107620.3 107620.3 107620.3 H ₂ O 277769.6 Total mass out	20000.37 14497,70 6266.78 184646.95 0.073 131891 C,H ₉ NO, 0.84 147.00 140.71 20683.79 4422126 31112.06 13448.50 138732.36 C,H ₉ NO, 206.27 30322.1 3032.1 3032.	(Liquid pha kg/L L CO ₂ 1.79 44.00 297.94 13109.20 (Liquid pha (Liquid pha (Liquid pha (Liquid pha	ses only) ses only) H ₂ O 3.47 18.00 579.35 10428.27 ses only) ses only) H ₂ O 849.32 15287.7	238.4
42 43 44 45 46 47 48 49 50 51 52 53 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 970	p GA kg/L T in ^e C C ₁₂ H ₂₂ O ₁₁	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentratie Liquid volume Bioreactor v Stoichiometry MW g Conc g/L Vol L Molarity Kmol y=68.85° Mass bal kg Dalance Mass out Volume L Ov Mass Overall Bion Kmol y=68.85° Mass bal kg Total mass in	ith fed-bat ccH3206 1.00 180.00 250.00 1.39 6 1.39 4 1.39 4 1.22 244.69 44044.0 64827.63	ch (after 3 O ₂ 2.21 32.00 368.29 11785.26 Ulation O ₂ 539.91 17277.0	hours op NH ₃ 17.00 140.71 2392.00 NH ₃ 206.27 3506.6	eration) H ₂ O 18.00 1.00 107620.3 107620.3 H ₂ O 277769.6 Total mass out Broth mass GA cone	20606.37 14497,70 6266.78 184646.95 0.073 131891 C,H ₈ NO, 0.84 147.00 147.00 147.00 147.00 147.00 147.00 147.00 131891 C,H ₈ NO, 0.84 147.00 147.00 1317226 30322.1 64827.63 33337.32	(Liquid pha kg/L L CO ₂ 1.79 44.00 297.94 13109.20 (Liquid pha (Liquid pha CO ₂ 436.77 19217.9	ses only) ses only) H ₂ O 3.47 18.00 579.35 10428.27 ses only) ses only) H ₂ O 849.32 15287.7	238.4
42 43 44 45 46 47 48 49 50 51 52 53 53 54 55 56 57 58 59 60 61 62 63 64 65 66 66 67 68 69 70 70	p GA kg/L p broth kg/L T in °C C ₁₂ H ₂₂ O ₁₁	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentrati Liquid volume Bioreactor v Stoichiometry MW g Cone g/L Vol L Molarity Kmol y=68.85° Mass bal kg Balance Overall Bion Overall Bion Kmol y=68.85° Mass bal kg Total mass in	ith fed-batt C ₆ H ₁₂ O ₆ 1.00 180.00 250.00 171680 1.39 4 166.91 30044.0 44221.26 2 2 2 2 2 2 44044.0 64827.63	ch (after 3 O ₁ 2.21 368.29 11785.26 02 539.91 17277.0	hours op NH ₃ 0.84 17.00 140.71 2392.00 NH ₃ 206.27 3596.6	eration) H ₂ O 18.00 1.00 107620.3 107620.3 107620.3 107620.3 Total mass out Broth mass GA conc. Broth mass GA conc.	20000.37 14497,70 6266.78 184646.95 0.073 131891 20,073 131891 20,073 131891 149,70 149,70 140,71 20683,79 44221,26 31112,06 13448,50 138732,36 13	(Liquid pha kg/L L CO ₂ 1.79 44.00 297.94 13109.20 (Liquid pha (Liquid pha CO ₂ 436.77 19217.9	ses only) H ₂ O 3.47 18.00 579.35 10428.27 ses only) ses only) H ₂ O 849.32 15287.7	238.4
42 43 44 45 46 47 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 869 70 71 72	p GA kg/L T in °C C ₁₂ H ₂₂ O ₁₁	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentrati Liquid volume Bioreactor v Stoichiometry MW g Conce g/L Vol L Molarity Kmol y=68.85% Mass bal kg Ov Mass Overall Bior Kmol y=68.85% Mass bal kg Total mass in	m ith fed-bat C ₆ H ₁₂ O ₆ 1.00 180.00 250.00 171680 171680 44221.26 44221.26 C ₆ H ₁₂ O ₆ 244.69 44044.0 64827.63	ch (after 3 O ₂ 2.21 32.00 368.29 11785.26	hours op NH ₃ 0.84 17,00 140.71 2392.00 NH ₃ 206.27 3596.6	eration) H ₂ O 18.00 107620.3 107769.6 107620.3 107769.6 107620.3 107769.6 10	20000.37 14497,70 6266.78 184646.95 0.073 131891 C,H ₉ NO, 0.84 147.00 140.71 20683.79 44221.26 31112.06 13448.50 138732.36 C,H ₉ NO, 206.27 33373.23 (13127286 230985.226	(Liquid pha (Liquid pha kg/L L CO ₂ 1.79 44.00 297.94 13109.20 (Liquid pha (Liquid pha (Liquid pha (Liquid pha	ses only) ses only) H ₂ O 3.47 18.00 579.35 10428.27 10428.27 ses only) ses only) H ₂ O 849.32 15287.7	238.4
42 43 44 45 46 47 47 48 49 50 51 52 53 54 55 55 60 61 62 63 64 65 66 67 68 69 0 70 71 72 73	p GA kg/L T in ^e C C ₁₂ H ₂₂ O ₁₁	1.538 1.4 30 0.8		Mass out Volume L Ov Mass GA concentratie Liquid volume Bioreactor v Stoichiometry MW g Conc g/L Vol L Molarity Kmol y=68.85? Mass bal kg Balance Ov Mass Overall Bior Kmol y=68.85? Mass bal kg Total mass in	ith fed-bat ith fed-bat C ₆ H ₃ Q ₆ 1.00 180.00 250.00 1.71680 1.39 6 16.91 30044.0 44221.26 244.05 244.05 244.04 64827.63	ch (after 3 O ₂ 2.21 32.00 11785.26 02 539.91 17277.0	hours op NH ₃ 17.00 140.71 2392.00 NH ₃ 206.27 3506.6	eration) H ₂ O 18.00 1.00 107620.3 107620.3 107620.3 107620.3 107620.3 Total mass out Broth mass GA conc. Broth volume	20606.37 14497,70 6266.78 184646.95 0.073 131891 C,H ₈ NO, 0.84 147,00 140.71 20683.79 44221.26 31112.06 13448.50 138732.36 C,H ₈ NO, 206.27 30322.1 64827.63 323379.32 0.13127286 230985.226	(Liquid pha kg/L L CO ₂ 1.79 44.00 297.94 13109.20 (Liquid pha (Liquid pha CO ₂ 436.77 19217.9	ses only) ses only) H ₂ O 3.47 18.00 579.35 10428.27 1858 only) ses only) H ₂ O 849.32 15287.7	238.4
42 43 44 45 50 51 52 53 54 55 56 57 58 56 60 61 62 63 64 65 66 67 70 71 72 73 74	p GA kg/L p broth kg/L T in °C C ₁₂ H ₂₂ O ₁₁	1.538 1.4 30 0.8	uired calcul	Mass out Volume L Ov Mass GA concentratic Liquid volume Bioreactor v Stoichiometry MW g Conc g/L Vol L Molarity Kmol y=68.85° Mass bal kg Balance Overall Bion Cov Mass Overall Bion Kmol y=68.85° Mass bal kg Total mass in	ith fed-batt C ₆ H ₁₂ O ₆ 1.00 180.00 250.00 171680 1.39 6 166.91 30044.0 44221.26 244.69 244.69 44044.0 64827.63	ch (after 3 O ₂ 2.21 368.29 11785.26 0 3368.29 11785.26 0 339.91 17277.0	hours op NH ₃ 0.84 140.71 2392.00 NH ₃ 206.27 3596.6	eration) H ₂ O 18.00 1.00 107620.3 107620.3 107620.3 107620.3 Total mass out Broth mass GA conc. Broth volume	2000.57 14497, 70 6266.78 184646.95 0.073 131891 20,073 131891 149,70 0.84 147,00 147,00 147,00 147,00 147,00 147,00 147,00 147,00 13112,06 13448,50 138732,36 138732,36 138732,36 20,06.27 303221, 64827,63 303279,32 0.13127286 230985,226	(Liquid pha kg/L L CO ₂ 1.79 44.00 297.94 13109.20 (Liquid pha (Liquid pha CO ₂ 436.77 19217.9	ses only) ses only) H ₂ O 3.47 18.00 579.35 10428.27 ses only) ses only) H ₂ O 849.32 15287.7	238.4
42 43 44 45 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 70 71 72 73 74 75	p GA kg/L T in °C C ₁₂ H ₂₂ O ₁₁ NH ₁ & air flot [NH ₁]	1.538 1.4 30 0.8	<u>wired calcu</u>	Mass out Volume L Ov Mass GA concentratic Liquid volume Bioreactor v Stoichiometry MW g Conc g/L Vol L Molarity Kenol y=68.859 Mass bal kg Balance Ov Mass Overall Bior Kenol y=68.859 Mass bal kg Total mass in	m ith fed-bat C _q H ₁₂ O ₆ 1.00 180.00 250.00 171680 171680 44221.26 44221.26 C _q H ₁₂ O ₆ 244.04 44221.26 4404.0 64827.63	ch (after 3 O ₂ 2.21 32.00 368.29 11785.26 0 2 539.91 17277.0 uired calco	hours op NH ₃ 0.84 17.00 140.71 2392.00 	eration) H ₂ O 18.00 107620.3 107620.3 107620.3 107620.3 107620.3 107620.3 107769.6 Total mass out Broth mass out Broth volume	20000.37 14497, 70 6266, 78 184646, 95 0.073 131891 С.,H ₉ NO, 0.84 147.00 140.71 20683.79 44221 26 31112.06 13448.50 138732.36 45827.63 323379.32 0.13127286 230985.226	(Liquid pha kg/L L CO ₂ 1.79 44.00 297.94 13109.20 (Liquid pha (Liquid p	ses only) ses only) H ₂ O 3.47 18.00 579.35 10428.27 ses only) ses only) H ₂ O 849.32 15287.7	238.4
42 43 44 45 46 47 48 49 50 51 52 53 54 55 55 56 57 58 59 60 61 62 63 63 64 65 66 66 67 70 71 72 73 74 75 75 75	p GA kg/L p broth kg/L T in °C C ₁₂ H ₂₂ O ₁₁ NH, & air flo [NH ₃] [NH ₃]	1.538 1.4 30 0.8 w rate reg	nired calcul mol/min	Mass out Volume L Ov Mass GA concentratie Liquid volume Bioreactor v Stoichiometry MW g Conc g/L Vol L Molarity Kmol y=68.85? Mass bal kg Balance Overall Bior Kmol y=68.85? Mass bal kg Total mass in	ith fed-bat ith fed-bat CcR _{H2} O ₆ 1.00 180.00 250.00 1.39 6 166.91 30044.0 44221.26 244.694 244.694 44044.0 64827.63	ch (after 3 O ₂ 2.21 32.00 11785.26 02 539.91 17277.0 17277.0	hours op NH ₃ 0.84 17.00 140.71 2392.00 	eration) H ₂ O 18.00 1.00 107620.3 107600.3 107620.3 1076	20000.37 14497,70 6266.78 184646.95 0.073 131891 20,40 0.84 147,00 140,71 20683,79 44221,26 31112,06 13448.50 138732.36 C,3H ₂ NO, 206.27 30322,1 64827,63 23379,32 0.13127286 230985,226	(Liquid pha kg/L L CO ₂ 1.79 44.00 297.94 13109.20 (Liquid pha (Liquid pha (Liquid pha (Liquid pha (Uiquid pha) (Liquid p	ses only) ses only) H ₂ O 3.47 18.00 579.35 10428.27 1858 only) ses only) H ₂ O 849.32 15287.7	238.4
42 43 44 45 46 47 48 49 50 51 52 53 54 47 48 49 50 51 52 53 54 55 66 61 62 63 64 65 66 66 67 68 869 70 71 72 73 74 57 77 77	p GA kg/L p broth kg/L T in °C C ₁₂ H ₂₂ O ₁₁ NH ₁ & air flo [NH ₃] Flow rate NH ₃	1.538 1.4 30 0.8 w rate reco 229.19 100.00%	uired calcul	Mass out Volume L Ov Mass GA concentratic Liquid volume Bioreactor v Stoichiometry MW g Cone g/L Vol L Molarity Kmol y-68.85° Mass bal kg Overall Bior Kmol y=68.85° Mass bal kg Total mass in	ith fed-batt C ₆ H ₁₂ O ₆ 1.00 180.00 250.00 171680 171680 171680 166.91 30044.0 44221.26 244.69 244.69 44044.0 64827.63 NH ₄ , Reg NH ₄ , pH C	ch (after 3 O ₂ 2.21 32.00 368.29 11785.26 0 539.91 17277.0 uired calc: [NH3] kg/L	hours op NH ₃ 0.84 17.00 140.71 2392.00 140.71 2392.00 140.71 2392.00 140.71 2392.00	eration) H ₂ O 18.00 1.00 107620.3 107620	20000.37 14497, 70 6266.78 184646.95 0.073 131891 20,073 131891 20,073 131891 14497, 70 0.84 147,00 147,00 147,00 146,71 20683,79 44221,26 31112,06 13448,50 138732,36 138732,36 230985,226 230985,226 Mass kg 3506.64	(Liquid pha (Liquid pha kg/L L CO ₂ 1.79 44.00 297.94 13109.20 (Liquid pha (Liquid pha (Li	ses only) ses only) H ₂ O 3.47 18.00 579.35 10428.27 10428.27 ses only) ses only) H ₂ O 849.32 15287.7	238.4
422 43 44 45 46 47 48 49 50 51 52 53 54 47 48 49 50 51 52 53 54 55 65 65 67 61 62 63 64 65 66 66 67 67 77 77 77 77 77 77 77 77 77	p GA kg/L T in °C C ₁₂ H ₂₂ O ₁₁ NH ₃ & air flot [NH ₃] Flow rate NH ₃ Pressure	1.538 1.4 30 0.8 229.19 100.00%	uired calcul mol/min aum	Mass out Volume L Ov Mass GA concentrati Liquid volume Bioreactor v Stoichiometry MW g Conc g/L Vol L Molarity Kmol y=68.859 Mass bal kg Balance Mass out Volume L Ov Mass Overall Bior Kmol y=68.859 Mass bal kg Total mass in	m ith fed-batt C _q H ₁ O ₆ 1.00 180.00 250.00 171680 1.39 44021.26 44221.26 C _q H ₁ O ₆ 244.06 44221.26 MH ₃ pH C NH ₃ pH C NH ₃ Ren	ch (after 3 O ₂ 2.21 32.00 368.29 11785.26 0 539.91 17277.0 uired calco [NH3] kg/L	hours op NH ₃ 0.84 17.00 140.71 2392.00 140.71 2392.00 140.71 2392.00 140.71 2392.00 140.71 2392.00	eration) H ₂ O 18.00 107620.3 107769.6 10	20000.37 14497, 70 6266,78 184646,95 0.073 131891 2003 131891 2003 131891 2003 131891 2003 131891 2003 131891 2003 2003 2003 2003 2003 2003 2003 200	(Liquid pha kg/L L CO ₂ 1.79 44.00 297.94 13109.20 (Liquid pha (Liquid pha (Liquid pha (Liquid pha (Liquid pha (Liquid pha (Liquid pha (Liquid pha)) (Liquid pha) (Liquid pha	ses only) ses only) H ₂ O 3.47 18.00 579.35 10428.27 ses only) ses only) H ₂ O 849.32 15287.7	238.4
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Fig. 4. Bioreactor mass/mole balance spreadsheet.

The general energy balance equation around the tank is given by Biotol (1992) as:

$$\frac{\delta E}{\delta t} = \dot{m}_{\rm in} E_{\rm in} - \dot{m}_{\rm out} E_{\rm out} + Q_{\rm q} + Q_{\rm w} + P_{\rm e} \tag{5}$$

For both hemispherical end and H = 2D shape factor, bioreactor volume is defined as:

 $V = \frac{\pi D^3}{6} + \frac{\pi D^3}{4}$ (6)

2.3. Energy balance and cooling coil design

Since the heat generated by microorganism activity is very hard to predict, we estimate it based on the typical



281

Table 3 Data for typical glutamic acid fermentation from Atkinson and Mavituna (1992)

Agitator power required	15 hp (1000 gal) ⁻¹
Heat of fermentation	100 Btu (h)(gal) ⁻¹
Agitation heat	38 Btu (h)(gal) ⁻¹
Broth temperature	37–38 °C
Inlet cooling water	10 °C

operation data for fermentation as shown in Table 3 (Atkinson & Mavituna, 1992). The energy balance spreadsheet constructed by linking this design data to the cells of the bioreactor working volume, air and ammonia flow rate and the substrate flow rate. This spreadsheet will calculate the net fermentation heat generated per unit time (power), which is equal to the cooling coil duty that is yet, to be designed. Water is chosen as the coolant

Table 4

Energy balance and cooling coil design spreadsheet

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Table 5Summary of calculated results

Parameter	Value
Total volume	290 m ³
Liquid volume (working volume)	231 m ³
Tank OD	6 m
Total height/diameter	2
Percentage fill	80
Pressure (liquid surface)	1 atm
Pressure (bottom)	1.64 atm
Air flow rate	36.1 m ³ /min
Oxygen flow rate	7.6 m ³ /min
Ammonia flow rate	5.8 m ³ /min
Sparger diameter	2.22 m
Sparger hole diameter	6 mm
Sparger pipe diameter	0.1 m
Off segmented baffle (total) d_b	0.6 m
Baffle ratio $d_{\rm b}/d_{\rm t}$	1/10
Baffle plate $d'_{\rm b}$	0.5 m
No. of turbine	3
Impeller diameter	2.12 m
Impeller d_i/d_t ratio	0.3
Motor power required	9.8 MW
Heat load	1.7 MW
U	550 W/m ² °C
Coolant inlet temperature (water)	10 °C
Coolant flow	3.2 m ³ /min
Coil side velocity	1.62 m/s
Coil area required	206.1 m ²
Coil pipe diameter OD	73 mm
Coil pipe diameter ID	63 mm
Coil diameter	4.53 m
Coil spacing	0.06 m
No. of coil	64
Area provided	209.4 m ²

because it is cheap and available. A spreadsheet to calculate heat transfer area required is then constructed by linking Eqs. (7)-(10). The design parameter such as cooling pipe diameter and size of coolant inlet are fixed by the designer. The heat transfer area, pipe diameter and size of inlet value are used to determine the coolant side velocity. The purpose of coolant side velocity or coil inner velocity calculation is to check whether the design is applicable or not. If the coolant side velocity is larger than 2 m/s mean then the designed cooling coil is not applicable because of lack in heat transfer. The way to overcome such a problem is to design a larger coolant. A larger coolant inlet will reduce the flow rate of coolant without reducing the total heat transfer area so that the tendency will be to reduce the coolant side velocity into the correct operating range. Table 4 shows an example of the constructed spreadsheet for the energy balance and design of the cooling coil.

The energy contained in the liquid is given by Kern (1965) as:

$$P = \dot{m}C_P \Delta T \tag{7}$$

By substituting $m = i\rho$ the energy contained in the gasses phase is written as:

$$P = \dot{v}\rho C_P \Delta T \tag{8}$$

the log mean temperature difference, T_{LMTD} is defined as:

$$T_{\rm LMTD} = \frac{(T_1 - T_1)}{\ln[(T_P - T_2)/(T_P - T_1)]}$$
(9)

Duty of a cooling coil with heat transfer coefficient U is given by Sinnott (1996) as:

$$P = UAT_{\rm LMTD} \tag{10}$$

Table 5 shows the summary results of the bioreactor design, carried out MS Excel.

3. Conclusions

A bioreactor design spreadsheet is easy to learn, and offers a quicker way for preliminary calculation of the bioreactor design. A spreadsheet also eliminates human error in doing the iteration calculation, which is commonly used in design calculation. This method also offers an easy way for the designer to scale up and optimise the process. By using this method the designer also escapes the costly simulation software license. The spreadsheet method also provides a cheaper alternative to the designer compared to costly commercial software.

Acknowledgements

The authors would like to thank very much to Dr. Tey Beng Ti and Ajinomoto (Malaysia) Berhad for their guidance and support.

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