BIOREACTION ENGINEERING

Characteristic Features of Bioreactors

VOLUME 2

KARL SCHÜGERL

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Volume 2

Characteristic Features of Bioreactors

Karl Schügerl

Institut für Technische Chemie
Universität Hannover

Translated from the German by
Valerie Cottrell

Edited by
D. A. John Wase

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Characteristic features of bioreactors

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Foreword to German Edition

Scarcely any other discipline has become so involved with other scientific fields to such great effect as chemical engineering has over the last few decades. The vast oil and gas deposits discovered during the post-war period started off the process and more recently, the concern over natural resources, energy supplies and environmental issues has helped to keep it going. Biologists, geologists and medical experts are all aware of the theoretical and practical importance of process engineering and chemical engineers incorporate the latest developments from the fields of mathematics, information technology, physics and electrotechnology amongst others into their work.

Although this mutual involvement is to be welcomed, it does make literature reviews rather difficult and this is where the 'Principles of Chemical Technology' series comes in. As stated in the foreword to the first series, it covers the principles of physics, chemistry, measurement and control technology, materials and process technology as used in basic physical processes and chemical reaction technology.

The publishers are aware that it is impossible to complete the overall concept by extending the series into the field of systems technology. All that can be done is to fit various pieces of the puzzle together depending on how topical a subject is and the level of expert knowledge available. Most specialists in a position to make a positive contribution are too heavily involved in their research and teaching, but there are always some who are prepared to find the time to give an overall summary and review of this enormously large field and even to write a book on the subject. Therefore, the publishers are confident that this series will produce work of benefit to a wide range of engineers, chemists and physicists working in the fields of process and machine technology both during their time as students and afterwards throughout their industrial career. At the same time, it is intended to provide a basis for new developments and openings into areas as yet unknown. The publishers welcome any support or constructive comments which could further the above objectives.

The series has also sparked off interest in other countries, several volumes being already translated into Spanish, French, English and Polish.

Preface

Volume 2 describes the actual submerged and surface reactors, compares them with each other and discusses selection and construction aspects. Furthermore, a review on measuring techniques for reactor characterization is given.

Introduction

Volume 1 describes the principles of bioreactor engineering, with special emphasis on the methods of operation of reactors, idealized types of reactors and classical kinetics of cell growth and product formation under ideal conditions.

Volume 2 describes actual submerged and surface reactors, compares them with each other and discusses the selection and construction aspects, together with a review of measuring techniques for reactor characterization.

Volume 3 will present the complex interaction between cell regulation, cell morphology, cell environment, reactor properties and closed-loop reactor control.

Simple cell and reactor models will be presented to aid the better understanding of the interaction processes. The dynamic behaviour of linked systems will also be featured. On-line methods will be presented for determining cell and reactor states and the information is then processed by means of models to provide an appraisal of bioreactor state and control.

Equations, figures and tables are numbered separately, Roman numerals being used for references to other volumes, e.g. Fig. I.50 (Fig. 50 in Volume 1), Table II.10 (Table 10 in Volume 2) or equation III.25 (equation 25 in Volume 3).

List of Symbols

L = length, M = mass, T = time, Θ = temperature, 1 = dimensionless

A	reactor/column cross-section	L^2
A_h	heat exchange surface	L^2
a	constant	
a	thermal diffusivity coefficient	L^2T^{-1}
$a = a'/V_L$	specific gas/liquid interfacial area	L^{-1}
$a^* = a'/V$	specific gas/liquid interfacial area	L^{-1}
a'	gas/liquid interfacial area	L^2
$Bd = \Delta\rho g\ \mathrm{d}/\sigma$	Bond number	1
$Bo_L = w_L H_s / D_{ax,L}$	Bodenstein number in liquid	1
B_R	stirrer blade width	L
C	concentration	ML^{-3}
COD	chemical oxygen demand	ML^{-3}
c, c_L	specific heat of liquid	$L^2T^{-2}\Theta^{-1}$
c_v, c_p	specific heat at constant volume and pressure conditions	$L^2T^{-2}\Theta^{-1}$
D	dilution rate	
D, D_m	molecular diffusion coefficient	L^2T^{-1}
D_{ax}	axial dispersion coefficient	L^2T^{-1}
De	Deborah number [equation (1.80)]	1
D_L	diameter of draft tube	L
D_0	diameter of holes in perforated plate	L
D_R, D_S	vessel and column diameter	L
d_B	bubble diameter	L
d_D	diameter of nozzle holes	L
d_d	orifice of reciprocating jet reactor	L
d_j	jet diameter	L
d_L	hole diameter	L
d_N	diameter of driving jet	L
d_P	particle diameter	L
d_R	impeller diameter	L
d_S	Sauter bubble diameter	L
E	energy dissipated per unit mass and time	L^2T^{-3}

E_G	relative gas hold-up	1
E_L	relative liquid hold-up	1
E_{O_2}	oxygen transfer efficiency with respect to power input	T^2L^{-2}
e	local energy dissipation rate	ML^2T^{-3}
Fr	Froude number	1
$Fr_R = N_R^2\ d_R/g$	agitator Froude number	1
f	stroke frequency	T^{-1}
$Ga = d_R^3 g/\nu^2$	Galileo number	
g	acceleration due to gravity	LT^{-2}
H	level of aerated liquid	L
Ha	Hatta number [equations (6.13) and (6.14)]	1
H_0	liquid level	L
He	Henry's constant	L^2T^{-2}
H_L	height of draft tube	L
H_S	height of column	L
ΔH_S	substrate heat of combustion	L^2T^{-2}
ΔH_x	cell mass heat of combustion	L^2T^{-2}
h	axial coordinate in the column	L
Δh	distance between agitator blades	L
h_L	liquid level above gas distributor	L
h_R	height of agitator blades	L
I	ionic strength	ML^{-3}
K_G	overall mass transfer coefficient through the gas film at gas/liquid interface	LT^{-1}
K_L	overall mass transfer coefficient through the liquid film at gas/liquid interface	LT^{-1}
K_La	overall volumetric mass transfer coefficient	T^{-1}
$(K_La)^*$	$= K_La(\nu/g^2)^{0.33}$	
K_O	Monod's constant for oxygen absorption	ML^{-3}
K_S	Monod's constant for substrate consumption	ML^{-3}
k	consistency factor	$ML^{-1}T^{-m}$
k_G	gas-side mass transfer coefficient	LT^{-1}
k_L	liquid-side mass transfer coefficient	LT^{-1}
k_R	impeller pumping capacity	1
k^*	empirical constant [equation (1.20)]	1
L	length	L

L_s	length of free jet	L
l	length	L
M_G	molar mass of gas	1
$\dot{M}_G$	oxygen mass flow through the interface	MT^{-1}
M_R	torque	ML^2T^{-2}
m	flow behaviour index	1
m_L	liquid mass	M
m_O	cell maintenance coefficient with respect to oxygen consumption	T^{-1}
m_S	cell maintenance coefficient with respect to substrate consumption	T^{-1}
N_G, N_L	cascade model parameter in gas and liquid phases	1
N_R	impeller speed	T^{-1}
N_{sh}	specific impeller speed [equation (1.117)]	1
Ne_G	Newton number (with aeration)	1
Ne_R	Newton number (without aeration)	1
$Nu = \alpha d/\lambda$	Nusselt number	1
O_F	dissolved oxygen concentration	ML^{-3}
$O_F{}^*$	O_F at the interface	ML^{-3}
ΔO_F	$O_F{}^* - O_F$	ML^{-3}
P	power input	ML^2T^{-3}
P_B	power input through gas expansion	ML^2T^{-3}
P_G	power input through agitator (with aeration)	ML^2T^{-3}
P_N	power input through liquid jet	ML^2T^{-3}
P_R	power input through agitator (without aeration)	ML^2T^{-3}
P_S	power input through liquid plunging jet	ML^2T^{-3}
$Pr = \nu/a$	Prandtl number	1
P_x	productivity of cell mass	$ML^{-3}T^{-1}$
P/V_L	specific power input	$ML^{-1}T^{-3}$
$(P_G/V_L)^*$	$= (P_G/V_L)[\rho_L(g\nu^4)^{0.33}]^{-1}$	1
$(P_G/q_G)^*$	$= (P_G/q_G)[\rho_L(g\nu)^{2/3}]^{-1}$	1
Q	substrate throughput	MT^{-1}
$Q_G = q_G/N_R d_R{}^3$	aeration group	1
Q_W	heat production rate	ML^2T^{-3}
Q_{O_2}	oxygen transfer rate	$ML^{-3}T^{-1}$
q_G	gas throughput	T^{-1}
$q_G^* = q_G/V_L$	specific aeration rate	T^{-1}

$(q_G/V_L)^*$	$=(q_G/V_L)[\rho_L(g\nu)^{0.67}]^{-1}$	1
q_L	liquid throughput	L^3T^{-1}
q_O	specific oxygen consumption rate	T^{-1}
$q_R = k_R N_R d_R{}^3$	pumping speed of agitator	L^3T^{-1}
q_S	specific substrate consumption rate	T^{-1}
q_W	specific heat production rate	L^2T^{-3}
R	radius of column	L
R	general gas constant	$ML^2T^{-2}\Theta^{-1}$
R_O	rate of oxygen consumption	$ML^{-3}T^{-1}$
R_P	rate of product formation	$ML^{-3}T^{-1}$
R_S	rate of substrate consumption	$ML^{-3}T^{-1}$
R_x	growth rate	$ML^{-3}T^{-1}$
Re	Reynolds number	1
$Re_D = w_{Ld}d_N/\nu_L$	Reynolds number for nozzle system	1
$Re_R = d_R N_R/\nu_L$	Reynolds number for a mechanically agitated system	1
Re_r	representative Reynolds number [equation (1.17)]	1
$Re_S = W_S L_S/\nu_G$	Reynolds number for a free jet system	1
r	radial coordinate	L
r_R	impeller radius	L
rpm	revolutions per minute	T^{-1}
S	substrate concentration	ML^{-3}
$Sc = \nu/D_m$	Schmidt number	1
$Sc = \nu_r/D_m$	modified Schmidt number	1
SCP	single-cell protein	
Sh	Sherwood number	1
$Sh_R = K_L a d_R{}^2/D_m$	modified Sherwood number	1
s	mean residence time of liquid elements at the interface	T
T	temperature	Θ
t	time	T
$U = S_0 - S_e/S_0$	substrate conversion	1
u	shear rate	LT^{-1}
V	volume of aerated two-phase system	L^3
V_G	gas volume	L^3
V_G^*	$= q_G/V_L$	T^{-1}
V_L	liquid volume	L^3
$\dot{V}_L$	liquid volume throughput	L^3T^{-1}
v	velocity	LT^{-1}
$We = W_S{}^2 d_D\rho/\sigma$	Weber number	1

w	velocity	LT^{-1}
w_D	liquid velocity in jet	LT^{-1}
$w_G = w_{SG}/E_G$	gas velocity	LT^{-3}
w_j	jet velocity	LT^{-1}
$w_L = w_{SL}/(1 - E_G)$	liquid velocity	LT^{-1}
w_{Ld}	liquid speed in hydrodynamic driving jet	LT^{-1}
w_R	relative bubble speed	LT^{-1}
w_S	free jet speed	
w_{SG}	superficial gas velocity	LT^{-1}
w_{SL}	superficial liquid velocity	LT^{-1}
w_T	single bubble rise velocity	LT^{-1}
X	cell concentration	ML^{-3}
x	local coordinate	L
$X = (P_G/q_G)[\rho(g\nu)^{2/3}]^{-1}$	gas dispersion factor [equation (1.128)]	1
Y	$= K_L a/w_{SG})(\nu^2/g)^{1/3}$ sorption factor [equation (1.127)]	1
$Y_{P/X}$	product yield coefficient based on cell mass formed	1
$Y_{P/S}$	product yield coefficient based on substrate consumed	1
$Y_{X/O}$	cell yield coefficient based on oxygen consumed	1
$Y_{X/S}$	cell yield coefficient based on substrate consumed	1
$Y_{X/W}$	cell yield coefficient based on heat generated	L^2T^{-3}
α, β	constants	
α	heat transfer coefficient	$MT^{-3}\Theta^{-1}$
α	blade angle	1
α	gas circulation ratio	1
β_k	coefficient of cubic expansion	Θ^{-1}
δ	thickness of diffusion layer	L
η	dynamic viscosity	$ML^{-1}T^{-1}$
η_r	representative viscosity	$ML^{-1}T^{-1}$
η	pump efficiency	1
θ	mixing time without aeration	T
θ_G	mixing time with aeration	T
θ_P	particle residence time at interface	T
λ	coefficient of thermal conductivity	$MLT^{-3}\Theta^{-1}$
λ^*	characteristic time [equation (1.80)]	T

μ	specific growth rate	T^{-1}
ν	kinematic viscosity	L^2T^{-1}
π	specific product production rate	T^{-1}
ρ_L, ρ_G	density of liquid, of gas	ML^{-3}
$\Delta\rho = \rho_L - \rho_G$	density difference	ML^{-3}
σ	surface tension	MT^{-2}
τ	shear stress	$ML^{-1}T^{-2}$
τ	dynamic turbulence pressure	$ML^{-1}T^{-2}$
Φ	Thiele modulus [equation (2.5a)]	1

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