

# ***BIOREACTION ENGINEERING***

Characteristic Features  
of Bioreactors

**VOLUME 2**

**KARL SCHÜGERL**



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# **Bioreaction engineering Volume 2**

## **Characteristic Features of Bioreactors**

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# **Bioreaction engineering**

## **Volume 2**

**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,  $\Theta$  = temperature, 1 = dimensionless

$A$	reactor/column cross-section	$L^2$
$A_h$	heat exchange surface	$L^2$
$a$	constant	
$a$	thermal diffusivity coefficient	$L^2 T^{-1}$
$a = a' / V_L$	specific gas/liquid interfacial area	$L^{-1}$
$a^* = a' / V$	specific gas/liquid interfacial area	$L^{-1}$
$a'$	gas/liquid interfacial area	$L^2$
$Bd = \Delta \rho g d / \sigma$	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	$L^2 T^{-2} \Theta^{-1}$
$c_v, c_p$	specific heat at constant volume and pressure conditions	$L^2 T^{-2} \Theta^{-1}$
$D$	dilution rate	
$D, D_m$	molecular diffusion coefficient	$L^2 T^{-1}$
$D_{ax}$	axial dispersion coefficient	$L^2 T^{-1}$
$De$	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	$L^2 T^{-3}$



$E_G$	relative gas hold-up	1
$E_L$	relative liquid hold-up	1
$E_{O_2}$	oxygen transfer efficiency with respect to power input	$T^2 L^{-2}$
$e$	local energy dissipation rate	$ML^2 T^{-3}$
$Fr$	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	$L^2 T^{-2}$
$H_L$	height of draft tube	$L$
$H_S$	height of column	$L$
$\Delta H_S$	substrate heat of combustion	$L^2 T^{-2}$
$\Delta H_x$	cell mass heat of combustion	$L^2 T^{-2}$
$h$	axial coordinate in the column	$L$
$\Delta h$	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	$LT^{-1}$
$K_L a$	overall volumetric mass transfer coefficient	$T^{-1}$
$(K_L a)^* = K_L a(\nu/g^2)^{0.33}$		
$K_O$	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	$ML^{-3}$
$\Delta O_F$	$O_F^* - O_F$	$ML^{-3}$
$P$	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
$Re_t$	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
$Sc = \nu_t/D_m$	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	$\Theta$
$t$	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	$L^2T^{-3}$
	$\alpha, \beta$	constants	
	$\alpha$	heat transfer coefficient	$MT^{-3}\Theta^{-1}$
	$\alpha$	blade angle	1
	$\alpha$	gas circulation ratio	1
	$\beta_k$	coefficient of cubic expansion	$\Theta^{-1}$
	$\delta$	thickness of diffusion layer	$L$
	$\eta$	dynamic viscosity	$ML^{-1}T^{-1}$
	$\eta_r$	representative viscosity	$ML^{-1}T^{-1}$
	$\eta$	pump efficiency	1
	$\theta$	mixing time without aeration	$T$
	$\theta_G$	mixing time with aeration	$T$
	$\theta_P$	particle residence time at interface	$T$
	$\lambda$	coefficient of thermal conductivity	$MLT^{-3}\Theta^{-1}$
	$\lambda^*$	characteristic time [equation (1.80)]	$T$



$\mu$	specific growth rate	$T^{-1}$
$\nu$	kinematic viscosity	$L^2 T^{-1}$
$\pi$	specific product production rate	$T^{-1}$
$\rho_L, \rho_G$	density of liquid, of gas	$ML^{-3}$
$\Delta\rho = \rho_L - \rho_G$	density difference	$ML^{-3}$
$\sigma$	surface tension	$MT^{-2}$
$\tau$	shear stress	$ML^{-1} T^{-2}$
$\tau$	dynamic turbulence pressure	$ML^{-1} T^{-2}$
$\Phi$	Thiele modulus [equation (2.5a)]	1



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