Solid-State Fermentation Bioreactors

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Solid-State Fermentation Bioreactors

Fundamentals of Design and Operation

With 194 Figures and 32 Tables

Springer

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Preface

Although solid-state fermentation (SSF) has been practiced for many centuries in the preparation of traditional fermented foods, its application to newer products within the framework of modern biotechnology is relatively restricted. It was considered for the production of enzymes in the early 1900s and for the production of penicillin in the 1940s, but interest in SSF waned with the advances in submerged liquid fermentation (SLF) technology. The current dominance of SLF is not surprising: For the majority of fermentation products, it gives better yields and is easier to apply. It is notoriously difficult to control the fermentation conditions in SSF; these difficulties are already apparent at small scale in the laboratory and are exacerbated with increase in scale. However, there are particular circumstances and products for which SSF technology is appropriate. For example, a desire to reuse solid organic wastes from agriculture and food processing rather than simply discarding them leads naturally to the use of SSF. Further, some microbial products, such as fungal enzymes and spores, amongst others, are produced in higher yields or with better properties in the environment provided by SSF systems.

With recognition of this potential of SSF, a revival of interest began in the mid-1970s. However, the theoretical base for SSF bioreactor technology only began to be established around 1990. Before this, there were many examples of SSF bioreactors, especially those used in the *koji* industry, but there was little or no information about the efficiency of heat and mass transfer processes within them. The work that has been carried out over the last 15 years is sufficient to establish a general basis of engineering principles of SSF bioreactors. This book brings together this work in order to provide this basis. It makes the key point that, given the complexity of SSF systems, efficient performance of SSF bioreactors will only be achieved through: (1) the use of mathematical models in making design and operating decisions for bioreactors and (2) The application of control theory.

Before proceeding, we must point out that we are quite aware of the potential problems that might be used by our use of the word “fermentation”. In this book we use it not in its metabolic sense but rather in its more general sense of “controlled cultivation of microorganisms”. Although several terms are used to denote this fermentation technique, the most common by far is “solid-state fermentation”.

This book focuses on SSF bioreactors. It does not aim to introduce SSF itself. We assume that readers interested in learning about SSF bioreactors are familiar with SSF processes themselves. Even if not, a reader who understands the basic principles of SLF processes and SLF bioreactor design will be able to understand this book. In any case, readers requiring a general background regarding SSF can consult books or review articles (e.g., see the Further Reading section of Chap. 1).

Even with this focus on SSF bioreactors, the book deliberately addresses general issues and concepts. Specific examples are given to illustrate concepts, but the book neither considers all types of bioreactors that have been used nor presents all mathematical models that have been developed. We do not attempt to present all the engineering know-how so far generated for SSF bioreactors. Rather, we aim to introduce the fundamental concepts and ideas.

The main audience intended for this book is the researcher/worker in SSF who is currently developing an SSF process with the intention of eventually commercializing it. Our aim is to give this reader a broad overview of what is involved in designing a bioreactor and optimizing its performance.

We recognize that many readers may not have the necessary background to set up and solve mathematical models of bioreactor performance. This book does not attempt to teach the necessary modeling skills. Such a task would require a lengthy treatise on various mathematical and engineering fundamentals. A basic understanding of differential and integral calculus will help readers to understand various of the chapters, although it is by no means necessary to be an expert.

After reading this book, the "non-engineering reader" should:

- understand qualitatively the importance of the various mass transfer, heat transfer and biological phenomena that are important in SSF systems, and the interactions amongst these various phenomena;
- understand what mathematical models of bioreactors can do. If you understand what models can and cannot do, then even if you do not have the skills to develop a model yourself, you will know when it is appropriate to seek the help of someone with such modeling skills (a "modeler");
- be able to "talk the same language" as the "modeler". In other words, you should be able to define clearly for the modeler what you wish to do, and you should be able to understand the questions that the modeler poses. In this way you can interact with modelers, even if they have no experience with SSF.

This book should also be useful for readers with modeling skills but who are working in SSF for the first time. In a succinct way, it outlines the important phenomena and the basic principles of SSF bioreactor design and operation.

We welcome comments, suggestions and criticisms about this book. Our aim is to help you to understand SSF bioreactors better. We would appreciate knowing just how well we have achieved this aim. The addresses of the editors and authors are given after the Table of Contents.

November 2005

DMitchell

David Mitchell Nadia Krieger Marin Berovič

Acknowledgements

As leader of the editorial team and the main contributing author of the book, I would first like to thank my PhD supervisors, Paul Greenfield and Horst Doelle. You set me on a path that I have found both challenging and interesting over the last twenty years or so. In fact, I still remember the moment, in mid-1984, when I decided to do my PhD in the area of solid-state fermentation. Paul Greenfield said to me "I have heard of this area called solid-state fermentation, I think that you can make some contributions in the area". Well Paul, you were right, I have managed something. Thanks! Of course, there is still much to do.

I must also thank my co-editors and co-authors. This book would never have been written without your input. From each of you I have learnt something about solid-state fermentation. Further, I recognize that I am indebted to many colleagues who, while not being co-authors, have helped me to understand solid-state fermentation better. I will not cite names because the list is enormous. It includes not only colleagues with whom I have interacted personally, but also colleagues who have published papers in the area of solid-state fermentation that have helped me to develop my understanding of this area.

This book, in part, represents a synthesis of work undertaken by my research group and supported by various funding agencies. I am indebted to these agencies for funding my research over the last 15 years or so. I received two grants to work on solid-state fermentation bioreactors from the "Australian Research Council Small Grants Scheme". Since my move to Brazil, I have received funding from several state and federal granting bodies. These include (1) the "Araucaria Foundation" (Fundação Araucária), a research agency of the state of Paraná; (2) the Brazilian National Council for Scientific and Technological Development (CNPq, Conselho Nacional de Desenvolvimento Científico e Tecnológico) and (3) the Brazilian-Argentinean Biotechnology Committee (CBAB, Comitê Brasileiro-Argentino de Biotechnologia), for which the funds originated from the Brazilian Ministry of Science and Technology (MCT, Ministério de Ciência e Tecnologia) and were administered by CNPq. CNPq has also been kind enough to award me a research scholarship.

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Contents

Abbreviations

A/D	analog-digital
ASFB	air-solid fluidized bed
a_w	water activity
CER	CO_2 evolution rate
COU	cumulative O_2 uptake
CRDB	continuous rotating drum bioreactor
CSSFB	continuous-flow solid-state fermentation bioreactor
CSTB	continuous stirred-tank bioreactor
CTFB	continuous tubular flow bioreactor
DM	dry matter
D/A	digital-analog
DMC	dynamic matrix control
FCV	flow control valve
GA_3	gibberellic acid
GC	gas chromatography
GC/MS	gas chromatography coupled with mass spectrometry
GPM	gallons per minute
HEPA	high efficiency particulate air
HPLC	high-performance liquid chromatography
IBM	International Business Machines
IDS	initial dry solids
IDM	initial dry matter
INRA	*Institut National de la Recherche Agronomique* (National Agronomic Research Institute)
ISFET	ion sensitive field effect transistor
IR	infrared
IWC	initial water content
$k_F a$	biofilm conductance (used to characterize the efficiency of O_2 transfer between the gas and biofilm phases in SSF)
$k_L a$	overall mass transfer coefficient (used to characterize the efficiency of O_2 transfer between the gas and liquid phases in SLF)
L/D	length to diameter ratio

MPC	model predictive control
NLMPC	nonlinear model predictive control
ODE	ordinary differential equation
OUR	O_2 uptake rate
PDE	partial differential equation
PI	proportional/integral
PID	proportional/integral/derivative (as defined in Chap. 27.2.2)
PLC	Programmable Logic Controller
PUC	Pontificia Universidad Católica
RTD	resistance temperature detector
RQ	respiratory quotient
SI	*Système International* (international metric system)
SLF	submerged liquid fermentation
SSF	solid state fermentation (as defined in Chap. 1)
t_{90}	time for the biomass to reach 90% of its maximum value
TC	thermocouple
TDR	time domain reflectometry
T_{opt}	optimum temperature
$T_{subscript}$	temperature, with the meaning as indicated by the subscript
UV	ultraviolet
vvm	volume per volume per minute
WC	water content
wt	weight
X	dry biomass
Z-N	Ziegler and Nichols (in relation to controller tuning rules)

Notation

Please note that, due to the fact that different models use different nomenclature and units, the nomenclature is covered chapter-by-chapter. In most cases the symbols are also explained where they first appear in the text.

Chapter 3

Pr	productivity (kg h^{-1} m^{-3})
$t_{process}$	time between successive harvests (h)
$V_{bioreactor}$	bioreactor volume (m^3)
$X_{harvest}$	amount of biomass (or product) at the time of harvesting (kg)
$X_{initial}$	amount of biomass (or product) at zero time (kg)

Chapter 4

$T_{subscript}$	temperature of phase or subsystem indicated by subscript (°C)

Chapter 5

H	superficial velocity of the air (m s^{-1})
$T_{subscript}$	temperature of phase or subsystem indicated by subscript (°C)
V_Z	bed height (m)

Chapter 6

C	O_2 concentration in the surrounding atmosphere (g cm^{-3})
D	effective diffusivity of O_2 in the bed (cm^2 h^{-1})
D_c	critical tray depth (cm)
k	thermal conductivity of the bed (W m^{-1} $°C^{-1}$)
N_{Bi}	Biot number
R_Q	volumetric heat production rate (W m^{-3})
R_X	overall growth rate (kg-dry-biomass m^{-3} h^{-1})
R_{XM}	maximum growth rate (g-dry-biomass cm^{-3}-bed h^{-1})
T_a	surrounding air temperature (°C)
T_s	bed surface temperature (°C)
X	biomass density (kg-dry-biomass m^{-3})
X_{max}	maximum possible biomass density (kg-dry-biomass m^{-3})
Y_{XO}	yield coefficient of biomass from O_2 (g-dry-biomass g-O_2^{-1})
z	spatial coordinate as a dimensionless fraction of the total bed height
Z	total bed height (m)
α	coefficient for bed-to-air heat transfer at the bed top (W m^{-2} $°C^{-1}$)
α_b	coefficient for bed-to-air heat transfer at the bed bottom (W m^{-2} $°C^{-1}$)

μ	specific growth rate parameter (h^{-1})
Θ	temperature difference between the bottom of bed and the tray surface when no heat transfer through the bottom of the tray (°C)
μ_{FO}	fractional specific growth rate based on O_2 (dimensionless)
μ_{FT}	fractional specific growth rate based on temperature (dimensionless)
μ_{max}	maximum value that the specific growth rate parameter can have (h^{-1})

Chapter 8

$A_{subscript}$	area, with meaning indicated by subscript (m^2)
D	drum diameter (m)
F_{mix}	volumetric exchange rate between the dead and plug-flow regions relative to the drum volume and mean residence time (dimensionless)
h	coefficient for bed-to-headspace heat transfer (W m^{-2} °C^{-1})
N_C	critical rotational speed (rpm)
R_B	ratio of exposed surface area of the bed to the bed volume (m^{-1})
R_{conv}	rate of convective heat removal to the headspace gases (W)
$T_{subscript}$	temperature of phase or subsystem indicated by subscript (°C)
$V_{subscript}$	volume, with meaning indicated by subscript (m^3)
θ_{ω}	angle subtended at the center of the drum by the bed surface for fractional filling ω (radians)
ω	fractional filling of the drum (m^3-bed m^{-3}-total-bioreactor-volume)

Chapter 11

F	mass flow of fresh solids (kg h^{-1})
f_m	solids flow through well-mixed region (kg h^{-1})
f_p	solids flow through plug-flow region (kg h^{-1})
f_R	recycled solid-flow (kg h^{-1})
M	overall mass of solids in the bioreactor (kg)
M_m	mass of solids in the well-mixed region (kg)
M_p	mass of solids in the plug-flow region (kg)
X	biomass content in product and recycle streams (g kg-dry-matter^{-1})
X_{max}	maximum possible biomass content (g kg-dry-matter^{-1})
X_o	initial biomass content in the fresh feed stream (g kg-dry-matter^{-1})
X_o'	biomass content after mixing the fresh feed and recycle streams (g kg-dry-matter^{-1})
α	fraction of the flow that passes through the plug-flow region (f_p/f_m)
β	fraction of the "in-bioreactor" mass in the plug-flow region (M_p/M_m)
γ	recycle ratio (dimensionless)
μ	specific growth rate parameter (h^{-1})

Chapter 12

a	constant in the double-Arrhenius equation (h^{-1})
A	area across which heat transfer takes place (m^2)
b	constant in the double-Arrhenius equation (dimensionless)
C_{Pair}	heat capacity of dry air (J kg-dry-air^{-1} °C^{-1})

C_{PB}	overall bed heat capacity (J kg^{-1} °C^{-1})
C_{Pvapor}	heat capacity of water vapor (J kg-vapor^{-1} °C^{-1})
$Ea1$, $Ea2$	constants in the double-Arrhenius equation (J mol^{-1})
F	air flow rate on a dry basis (kg-dry-air h^{-1})
h	heat transfer coefficient (J m^{-2} s^{-1} °C^{-1})
H	outlet air humidity (kg-vapor kg-dry-air^{-1})
H_{in}	inlet air humidity (kg-vapor kg-dry-air^{-1})
M	total bed mass (kg)
R	universal gas constant (J mol^{-1} K^{-1})
S	dry substrate concentration (kg-dry-substrate m^{-3}).
t	time (h)
T	temperature of the substrate bed and the outlet air (°C)
T_{in}	inlet air temperature (°C)
T_{surr}	temperature of the surroundings (°C)
W	water content on a dry basis (kg-H_2O kg-dry-substrate^{-1})
X	amount of biomass in the bioreactor (kg)
X_{max}	maximum possible amount of biomass in the bioreactor (kg)
Y_Q	yield of metabolic heat from growth (J kg-biomass^{-1})
μ	specific growth rate parameter (h^{-1})
ΔH_{vap}	enthalpy of vaporization of water (J kg-H_2O^{-1})

Chapter 13

A	area for heat transfer as indicated by subscript (m^2)
a_w	water activity as indicated by subscript
D_S	diffusivity of the substrate (m^2 h^{-1})
h	heat transfer coefficient as indicated by subscript (J h^{-1} m^{-2} °C^{-1})
H	humidity of phase indicated by subscript (kg-vapor kg-dry-air^{-1})
k	mass transfer coefficient (kg m^{-2} h^{-1})
K_S	saturation constant of the Monod equation (g L^{-1})
r	radial position (m)
S	substrate concentration (g L^{-1})
$S\vert_r$	substrate concentration at radial position r (g L^{-1})
t	time (h)
T	temperature as indicated by subscript (°C)
X	biomass concentration (g L^{-1})
$X\vert_r$	biomass concentration at radial position r (g L^{-1})
Y_{XS}	yield of biomass from substrate (g-dry-biomass g-substrate^{-1})
μ_{max}	specific growth rate parameter (h^{-1})

Chapter 14

A	constant of the deceleration growth equation (dimensionless)
C	biomass content (basis not specified)
C_m	maximum biomass content (basis not specified)
C_o	initial biomass content (basis not specified)
C_{XA}	biomass content related to dry matter at zero time (g-dry-biomass g-initial-dry-solids^{-1})

C_{XM}	biomass content related to fresh matter at time of sampling (g-dry-biomass g-moist-solids^{-1})
C_{XR}	biomass content related to dry matter at time of sampling (g-dry-biomass g-dry-solids^{-1})
C_{XW}	biomass content related to fresh matter at zero time (g-dry-biomass g-initial-moist-solids $^{-1}$)
D	mass of dry solids (g)
D_o	initial mass of dry solids (g)
k	growth equation parameter (g-dry-biomass h^{-1} for the linear equation, h^{-1} for the deceleration equation)
M	mass of moist solids (g)
M_o	initial mass of moist solids (g)
S	mass of dry residual substrate (g)
S_o	initial mass of dry residual substrate (g)
t	time
W	mass of water (g)
W_o	initial mass of water (g)
X	mass of dry biomass (g)
μ	specific growth rate parameter (h^{-1})

Chapter 15

C_{XR}	biomass content, relative basis (g-dry-biomass g-dry-solids^{-1})
C_{XA}	biomass content, absolute basis (g-dry-biomass g-initial-dry-solids^{-1})
C_{CA}	concentration of a biomass component (mg-component g-initial-dry-solids^{1})
C_F	content of biomass component within the biomass (mg-component g-biomass^{-1})
d_i	dry mass of sample removed from the “ith” flask for determination of the moisture content (g)
D_i	dry mass of solids in the sample removed for biomass determination (g-dry-solids)
d_o	dry mass of sample removed at zero time (g)
G_x	biomass glucosamine content (mg-glucosamine mg-dry-biomass^{-1})
IDS_i	dry substrate initially added to the “ith” flask (g)
IWC	initial water content, wet basis (% by mass)
m_i	wet mass of sample removed from the “ith” flash for determination of the moisture content (g)
m_o	wet mass of sample removed at zero time (g)
M_i	fresh mass of the sample removed for biomass determination (g-moist-solids)
M_{oi}	mass of substrate initially added to the “ith” flask (g)
WC_i	moisture content of the “ith” flask at the time of sampling, wet basis (% by mass)
X	mass of biomass or a component (g)
λ	lag time (h)

Chapter 16

a_o to a_4	fitting parameters for Eq. (16.14)
a_{ws}	water activity of the solid substrate phase
A	parameter of the deceleration equation (dimensionless)
A	fitting parameter of the double-Arrhenius equation (h^{-1})
A_d	frequency factor for the death reaction (h^{-1})
A_g	frequency factor for the growth reaction (h^{-1})
A_D	frequency factor for denaturation reaction (dimensionless)
A_S	frequency factor for synthesis reaction (dimensionless)
b	fitting parameter of Eq. (16.16)
B	fitting parameter of the double-Arrhenius equation (dimensionless)
C_m	maximum biomass content (g-biomass 100-g-dry-matter^{-1})
C_{XA}	biomass content, absolute basis (g-dry-biomass g-initial-dry solids^{-1})
C_{XAM}	maximum biomass content, absolute basis (g-dry-biomass g-initial-dry-solids^{-1})
C_{XAO}	initial biomass content, absolute basis (g-dry-biomass g-initial-dry-solids^{-1})
C_{XAD}	absolute concentration of dead biomass (g-dry-biomass g-initial-dry solids^{-1})
C_{XAT}	absolute concentration of total biomass, i.e., both viable and dead (g-dry-biomass g-initial-dry solids^{-1})
C_{XAV}	absolute concentration of viable biomass (g-dry-biomass g-initial-dry solids^{-1})
C_{XR}	biomass content, relative basis (g-dry-biomass g-dry-solids^{-1})
D_1 to D_4	fitting parameters of Eq. (16.17)
D	total dry mass of solids in the bioreactor (kg)
D_o	initial total dry mass of solids in the bioreactor (kg)
E_{a1}, E_{a2}	fitting parameters of the double-Arrhenius equation (J mol^{-1})
E_{ad}	activation energy for the death reaction (J mol^{-1})
E_{ag}	activation energy for the growth reaction (J mol^{-1})
E_{aS}	activation energy for synthesis reaction (J mol^{-1})
E_{aD}	activation energy for denaturation reaction (J mol^{-1})
f	specific growth rate as a fraction of the specific growth rate under optimum conditions (dimensionless)
f_T	specific growth rate as a fraction of the specific growth rate under optimum conditions, based on temperature (dimensionless)
f_T	specific growth rate as a fraction of the specific growth rate under optimum conditions based on water activity (dimensionless)
F	state of the intracellular "essential enzyme pool" (dimensionless)
F_1 to F_3	fitting constants of Eq. (16.15)
k	growth equation parameter (g-dry-biomass g-initial-dry solids^{-1} h^{-1} in the linear equation, h^{-1} in the deceleration equation)
k_d	specific death rate coefficient (h^{-1})
k_D	coefficient of the denaturation reaction (h^{-1})
k_S	coefficient of the autocatalytic synthesis reaction (h^{-1})
m_S	maintenance coefficient (kg-dry-substrate kg-dry-biomass $^{-1}$ h^{-1})

r_d	death rate (g-dry-biomass g-initial-dry solids^{-1} h^{-1})
R	universal gas constant (J mol^{-1} °C^{-1})
S	total dry mass of residual substrate (kg)
t	time (h)
T	temperature (°C).
T_{max}	maximum temperature for growth (°C)
T_{min}	minimum temperature for growth (°C)
T_{opt}	optimum temperature for growth (°C)
X	total dry mass of biomass (kg)
X_{max}	maximum total dry mass of biomass (kg)
Y_{XS}	true growth yield (kg-dry-biomass kg-dry-substrate^{-1})
μ	specific growth rate parameter (h^{-1})
$\mu_{measured}$	measured value of the specific growth rate (h^{-1})
μ_{opt}	specific growth rate parameter under optimal growth conditions (h^{-1})
μ_T	specific growth rate parameter as a function of temperature (h^{-1})
μ_W	specific growth rate parameter as a function of water activity (h^{-1})

Chapter 17

$a_{w(subscript)}$	water activity of phase or subsystem indicated by subscript
CER	carbon dioxide evolution rate (mol-CO_2 h^{-1})
COU	cumulative O_2 uptake (mol-O_2)
C_{in}	inlet O_2 concentration (typically %volume)
C_{out}	outlet O_2 concentration (typically %volume)
C_{XA}	absolute biomass concentration (kg-dry-biomass kg-dry-solids^{-1})
D	inactivation parameter used in Eqs. (17.8) and (17.9)
D_o	initial mass of dry solids within the bioreactor (kg)
F	dry air flow rate (L h^{-1})
L	initial particle length (m)
l_c	residual particle length at time *t* (m)
m_A	maintenance coefficient for production or consumption of the species indicated by subscript (kg-A kg-dry-biomass^{-1} h^{-1})
m_c	maintenance coefficient for CO_2 (mol-CO_2 kg-dry-biomass^{-1} h^{-1})
m_d	fitting constant in Eq. (17.9)
m_o	maintenance coefficient for O_2 (mol-O_2 kg-dry-biomass^{-1} h^{-1})
m_N	maintenance coefficient for nutrient (kg-nutrient kg-dry-biomass^{-1} h^{-1})
m_P	coefficient for product formation related to maintenance metabolism (kg-product kg-dry-biomass^{-1} h^{-1})
m_Q	maintenance coefficient for heat production (J kg-dry-biomass^{-1} h^{-1})
m_S	maintenance coefficient for residual dry substrate (kg-dry-substrate kg-dry-biomass^{-1} h^{-1})
m_W	maintenance coefficient for water production (kg-H_2O kg-dry-biomass^{-1} h^{-1}).
OUR	oxygen uptake rate (mol-O_2 h^{-1})
P	mass of product (kg)
P_o	mass of product present at time zero (kg)

$r_{subscript}$	overall rate of change in a species, with the particular species being indicated by the subscript (kg h^{-1} or mol h^{-1})
r_C	overall rate of CO_2 production (mol-CO_2 h^{-1})
r_N	overall rate of nutrient consumption (kg-nutrient h^{-1})
r_P	overall rate of product formation (kg h^{-1})
r_O	overall rate of O_2 consumption (mol-O_2 h^{-1})
r_Q	overall rate of metabolic waste heat production (J h^{-1})
r_W	overall rate of metabolic water production (kg-H_2O h^{-1}
t	time (h)
t_d	time at which inactivation kinetics appear (h)
t_r	time at which inactivation kinetics disappear (h)
T	time for complete particle degradation in Eq. (17.10)
X	total mass of biomass within the bioreactor (kg-dry-biomass)
X_m	maximum possible biomass, logistic equation (kg-dry-biomass)
X_o	initial biomass (kg-dry-biomass)
Y_{AB}	stoichiometric relationship between two species as indicated by subscripts A and B (kg-A kg-B^{-1})
Y_{CX}	yield of CO_2 from biomass (mol-CO_2 kg-dry-$biomass^{-1}$)
Y_{PX}	yield of product from growth (kg-product kg-dry-$biomass^{-1}$)
Y_{QC}	yield of heat from CO_2 production (J kg-CO_2^{-1})
Y_{QX}	yield of heat from the growth reaction (J kg-dry-$biomass^{-1}$)
Y_{WX}	yield of water from the growth reaction (kg-H_2O kg-dry-$biomass^{-1}$)
Y_{XN}	yield of biomass from a nutrient (kg-dry-biomass kg-$nutrient^{-1}$)
Y_{XO}	yield of biomass from O_2 (kg-dry-biomass mol-O_2^{-1})
Y_{XS}	yield of biomass based on overall residual dry substrate (kg-dry-biomass kg-dry-$substrate^{-1}$)
λ	fractional particle length (i.e., l_c/L) in Eq. (17.10) (dimensionless)
λ	time at which product begins to be produced (h), used in Eq. (17.14)
μ	specific growth rate parameter (h^{-1})

Chapter 18

$A_{subscript}$	area of the transfer surface indicated by subscript (m^2)
$a_{wsolid}*$	water activity for solids to be in equilibrium with the gas phase
$a_{w(subscript)}$	water activity of phase or subsystem indicated by subscript
C_{Pbed}	overall heat capacity of the bed (J kg^{-1} °C^{-1})
$C_{Psubscript}$	heat capacity of phase or subsystem indicated by subscript (J kg^{-1} °C^{-1})
D	total mass of dry solids in the bed (kg-dry-solids)
G	mass flux of dry air (kg-dry-air m^{-2} h^{-1})
$h_{subscript}$	heat transfer coefficient as indicated by subscript (J h^{-1} m^{-2} °C^{-1})
hA	global heat transfer coefficient (J h^{-1} °C^{-1})
H_{sat}	saturation humidity (kg-vapor kg-dry-air^{-1})
$H_{subscript}$	humidity of a subsystem or phase as indicated by subscript (kg-vapor kg-dry-air^{-1})
k	thermal conductivity (J m^{-1} h^{-1} °C^{-1})
k_w	mass transfer coefficient for water (kg-H_2O m^{-2} h^{-1})
m_{bed}	mass of the bed (kg)

M_{water}	overall mass of water in the bed (kg)
r_Q	rate of metabolic heat production (J h^{-1})
r_W	rate of metabolic water production (kg h^{-1})
$R_{subscript}$	rate of a mass transfer phenomenon that involves water (kg-H_2O h^{-1})
$Q_{subscript}$	rate of a heat transport phenomenon as indicated by subscript (J h^{-1})
t	time (h)
$T_{subscript}$	temperature of phase or subsystem indicated by subscript (°C)
V_Z	air superficial velocity (m h^{-1})
W	water content of the bed (kg-H_2O kg-dry-solids^{-1})
W_{sat}	water content that the solids would have if they were in equilibrium with the gas phase, dry basis (kg-H_2O kg-dry solid^{-1})
x	distance, usually horizontal distance within the phase (m)
z	distance, usually vertical (axial) distance within the phase (m)
λ	enthalpy of vaporization of water (J kg-H_2O^{-1})
$\rho_{subscript}$	density of phase or subsystem indicated by subscript (kg m^{-3})

Chapter 19

a	fitting parameter of the Antoine equation
a_{wg}	gas phase water activity
a_{ws}	water activity of the solids
b	fitting parameter of the Antoine equation
c	fitting parameter of the Antoine equation
$C_{Psubscript}$	heat capacity of phase or subsystem indicated by subscript (J kg^{-1} °C^{-1})
d	fitting parameter of the Antoine equation
H	humidity (kg-vapor kg-dry-air^{-1})
H	saturation humidity (kg-vapor kg-dry-air^{-1})
M_g	gas molecular weight (kg mol^{-1})
$m_{subscript}$	mass of the item indicated by subscript (g or kg)
n	number of moles (mol)
P	pressure (Pa)
P_w	vapor pressure of water (Pa)
P_{sat}	saturation vapor pressure of water (Pa)
R	universal gas constant (J mol^{-1} K^{-1})
S	shrinkage factor (m^3-dry-bed m^{-3}-moist-bed)
T	temperature (°C)
T_K	temperature (K)
T_s	solids temperature (°C)
V_P	specific packed volume on a dry basis (m^3 kg-dry-matter^{-1})
$V_{subscript}$	volume of phase or subsystem indicated by subscript (L or m^3)
w_i	mass fraction contributed by component "i"
W	solids water content, dry basis (kg- H_2O kg-dry-solids^{-1})
ε	bed porosity (dimensionless)
λ	enthalpy of vaporization of water (J kg-H_2O^{-1})
ρ_b	bed packing density (g L^{-1} or kg m^{-3})
$\rho_{subscript}$	density of phase or subsystem indicated by subscript (g L^{-1} or kg m^{-3})

Chapter 20

A	area for transfer (m^2)
A_g	cross-sectional area of headspace normal to gas flow (m^2)
c_{air}	dimensionless air humidity (as defined by Eq. (20.11))
c_{bed}	dimensionless saturation water vapor concentration
$C_{Psubscript}$	heat capacity of phase or subsystem indicated by subscript (J kg^{-1} $°C^{-1}$)
C_V	dimensionless constant associated with the bed viscosity
d	particle diameter (m)
D	bioreactor diameter (m)
f	porosity factor (dimensionless)
F	inlet air flow rate (kg-dry-air s^{-1})
g	gravitational acceleration (m s^{-2})
G	air flux through the bed (kg-air m^{-2} s^{-1})
h	maximum height of the bed (m)
ha	"volumetric" overall heat transfer coefficient (J s^{-1} m^{-3} $°C^{-1}$)
$h_{subscript}$	heat transfer coefficient, as indicated by subscript (J s^{-1} m^{-2} $°C^{-1}$)
H_{sat}	saturation humidity (kg-vapor kg-dry-air^{-1})
$H_{subscript}$	humidity of phase indicated by subscript (kg-vapor kg-dry-air^{-1})
ka	scaled water mass transfer coefficient (s^{-1})
k_b	thermal conductivity of the bed (J h^{-1} m^{-1} $°C^{-1}$ or J s^{-1} m^{-1} $°C^{-1}$)
k_{wall}	thermal conductivity of the wall (J s^{-1} m^{-1} $°C^{-1}$)
K	secondary variable calculated by Eq. (20.14)
Ka	"volumetric" overall mass transfer coefficient (kg-dry-solids s^{-1} m^{-3})
L	bioreactor length (m)
L_{wall}	wall thickness (m)
M	percentage moisture content, wet basis (% by mass)
N	rotational speed (revolutions per second)
P	pressure (Pa)
Pe_{eff}	effective Peclet number
R_w	scaled overall water transfer rate (s^{-1})
s	mobile layer thickness (m)
S	fraction of the critical speed (dimensionless)
t_c	time of contact between the solid particles and the bioreactor wall (s)
$T_{subscript}$	temperature of phase or subsystem indicated by subscript (°C)
u_P	average particle velocity (m s^{-1})
W	solids water content (kg-H_2O kg-dry-$solids^{-1}$)
α_b	thermal diffusivity of the bed (m^2 h^{-1})
γ	dynamic angle of repose of the solids (degrees)
δ	diffusivity of water vapor in air (m^2 s^{-1})
ρ_b	bed density (kg m^{-3}-bed)

Chapter 22

Also see Tables 22.1 and 22.2.

The model converts all parameters and variables to a consistent set of units.

A	area for heat transfer across bioreactor side wall (m^2)
A_1 to A_4	fitting parameters of the double-Arrhenius equation (Eq. (22.1))

a_{wg}	gas phase water activity
a_{wgin}	inlet air water activity
a_{wgo}	initial gas phase water activity
$a_{wg}*$	outlet gas water activity set point for triggering water addition
a_{ws}	water activity of the solids
a_{wso}	initial water activity of the solids phase
b_o	initial biomass content (kg-biomass kg-initial-dry-solids^{-1})
b_m	maximum biomass content (kg-biomass kg-initial-dry-solids^{-1})
B	mass of bioreactor wall (kg)
C_{Pb}	heat capacity of bioreactor body (J kg^{-1} °C^{-1})
C_{Pg}	heat capacity of dry gas (J kg^{-1} °C^{-1})
C_{Pm}	heat capacity of dry matter (J kg^{-1} °C^{-1})
$C_{Pv,}$	heat capacity of water vapor (J kg^{-1} °C^{-1})
C_{Pw}	heat capacity of liquid water (J kg^{-1} °C^{-1})
D	bioreactor diameter (m)
D_1 to D_4	fitting parameters of Eq. (22.2)
F_{in}	flow rate of dry air at the air inlet (kg-dry-air s^{-1})
$fold$	fold increase in the solids-to-gas heat and mass transfer coefficients
G	mass of dry air held in the inter-particle spaces (kg)
ha	“volumetric” overall heat transfer coefficient (J s^{-1} m^{-3} °C^{-1})
h_{bw}	bioreactor-to-cooling-water heat transfer coefficient (J s^{-1} m^{-2} °C^{-1})
h_{gb}	gas-to-bioreactor heat transfer coefficient (J s^{-1} m^{-2} °C^{-1})
h_{sb}	solids-to-bioreactor heat transfer coefficient (J s^{-1} m^{-2} °C^{-1})
H	gas phase humidity (kg-vapor kg-dry-air^{-1})
H_B	bioreactor height (m)
H_{in}	inlet air humidity (kg-vapor kg-dry-air^{-1})
J	proportional gain (dimensionless)
Ka	“volumetric” overall mass transfer coefficient (kg-dry-solids s^{-1} m^{-3})
L	thickness of the bioreactor wall (mm)
M	total mass of dry solids in the bioreactor (kg)
M_o	initial mass of dry solids in the bioreactor (kg)
P	overall pressure in the bioreactor (mm Hg)
R	universal gas constant (J mol^{-1} °C^{-1})
S_o	initial mass of dry substrate in the bed (kg)
t	time (h)
$Type$	type of relation of growth with solids water activity
T_b	bioreactor body temperature (°C)
T_g	gas phase temperature (°C)
T_{in}	inlet air temperature (°C)
T_{opt}	optimum temperature for growth (°C)
T_s	solids temperature (°C)
$T_{setpoint}$	set point temperature for the cooling water control scheme (°C)
T_{sys}	initial temperature of the system (°C)
T_w	cooling water temperature (°C)
V_{bed}	volume of the bed within the bioreactor (m^3)
vvm	volumes of air per bed volume per minute (m^3-air (m^3-bed)$^{-1}$ min^{-1})