

Chemical Engineering for the Food Industry

JOIN US ON THE INTERNET VIA WWW, GOPHER, FTP OR EMAIL:

WWW: <http://www.thomson.com>
GOPHER: <gopher.thomson.com>
FTP: <ftp.thomson.com>
EMAIL: findit@kiosk.thomson.com

A service of **ITP**

Chemical Engineering for the Food Industry

Edited by

P.J. FRYER
School of Chemical Engineering
University of Birmingham
Birmingham, UK

D.L. PYLE
Department of Food Science and Technology
University of Reading
Reading, UK

and

C.D. RIELLY
Department of Chemical Engineering
University of Cambridge
Cambridge, UK



SPRINGER-SCIENCE+BUSINESS MEDIA, B.V.

© 1997 Springer Science+Business Media Dordrecht
Originally published by Chapman & Hall in 1997

Typeset in 10 on 12 pt Times by Best-set Typesetter Ltd., Hong Kong

ISBN 978-1-4613-6724-6 ISBN 978-1-4615-3864-6 (eBook)

DOI 10.1007/978-1-4615-3864-6

Apart from any fair dealing for the purposes of research or private study, or criticism or review, as permitted under the UK Copyright Designs and Patents Act, 1988, this publication may not be reproduced, stored, or transmitted, in any form or by any means, without the prior permission in writing of the publishers, or in the case of reprographic reproduction only in accordance with the terms of the licences issued by the Copyright Licensing Agency in the UK, or in accordance with the terms of licences issued by the appropriate Reproduction Rights Organization outside the UK. Enquiries concerning reproduction outside the terms stated here should be sent to the publishers at the London address printed on this page.

The publisher makes no representation, express or implied, with regard to the accuracy of the information contained in this book and cannot accept any legal responsibility or liability for any errors or omissions that may be made.

A catalogue record for this book is available from the British Library

Library of Congress Catalog Card Number: 96-85315



Printed on acid-free text paper, manufactured in accordance with ANSI/NISO Z39.48-1992
(Permanence of Paper)

Contents

List of contributors	viii
Preface	ix
List of symbols	xii
1 Introduction to process design	1
D.L. PYLE	
Introduction	1
1.1 Material requirements and flows	3
1.2 Energy balances	24
1.3 Process economics	45
Appendix 1.A: Some basic definitions	57
Conclusions	60
Further reading	61
2 Newtonian fluid mechanics	63
R.M. NEDDERMAN	
Introduction	63
2.1 Laminar and turbulent flow	64
2.2 Ideal fluids	67
2.3 Laminar flows	78
2.4 Dimensional analysis	85
2.5 Turbulent flow	91
Conclusions	103
Further reading	104
3 Introduction to heat transfer	105
A.N. HAYHURST	
Introduction	105
3.1 Heat conduction	106
3.2 Heat transfer in flowing systems	120
3.3 Heat exchange: more practical aspects	131
Conclusions	151
Further reading	151
4 Mass transfer in food and bioprocesses	153
D.L. PYLE, K. NIRANJAN and J. VARLEY	
Introduction	153
4.1 Why does transfer occur?	154
4.2 Mechanisms	154

4.3	Equilibrium	155
4.4	Diffusion	159
4.5	Transient behaviour	165
4.6	Flowing systems	167
4.7	Interphase transfer	177
4.8	Aeration	184
4.9	Mass transfer limitations	188
	Conclusions	193
	Further reading	194
5	Food rheology	195
	C.D. RIELLY	
	Introduction	195
5.1	Characteristics of non-Newtonian fluids	199
5.2	Viscometric flows	213
5.3	Application to engineering problems	226
	Appendix 5.A: Linear viscoelastic Maxwell element	229
	Appendix 5.B: Concentric cylinder viscometer	230
	Appendix 5.C: Cone and plate viscometer	231
	Conclusions	232
	References and further reading	232
6	Process design: heat integration	234
	P.J. FRYER	
	Introduction	234
6.1	Design of process plant	234
6.2	Second-law analysis: heat integration	237
6.3	Heat and process integration in the food industry	247
	Conclusions	248
7	Process control	250
	D.L. PYLE and C.A. ZAROR	
	Introduction	250
7.1	What is the control problem?	251
7.2	Block diagrams	260
7.3	Process dynamics	260
7.4	Multiple inputs and linearization	265
7.5	Frequency response	269
7.6	Feedforward and feedback control	270
7.7	Types of controller action	284
7.8	Control system design for complete plants	291
	Conclusions	293
	Further reading	294
8	Reactors and reactions in food processing	295
	H.A. CHASE	
	Introduction	295
8.1	Reactor types	296
8.2	Physical chemistry of food reactions	299

8.3	Analysis of isothermal 'ideal' reactor systems	308
8.4	Non-isothermal reactions	319
8.5	Non-ideal flow and mixing in continuous reactors	320
	Conclusions	329
	References and further reading	329
9	Thermal treatment of foods	331
	P.J. FRYER	
	Introduction	331
9.1	Engineering principles	336
9.2	Continuous processing: problems and solutions	346
9.3	Fouling and cleaning in food process plant	365
	Conclusions	381
	References and further reading	382
10	Mixing in food processing	383
	C.D. RIELLY	
	Introduction	383
10.1	Fundamentals of mixing	383
10.2	Fluid-mixing equipment	389
10.3	Power consumption in stirred tanks	396
10.4	Miscible liquid blending operations	400
10.5	Gas-liquid mixing	406
10.6	Liquid-liquid dispersions and the creation of emulsions	414
10.7	Solids suspension and solid-liquid mass transfer	416
10.8	Scale-up of mixers from pilot trials	420
10.9	Alternative mixing devices	422
10.10	Mixing of particulate materials	426
	Conclusions	431
	References and further reading	431
11	Process design: an exercise and simulation examples	434
	C.A. ZAROR and D.L. PYLE	
	Introduction	434
11.1	An integrated cheese plant: a design exercise	435
11.2	Computer simulations	444
	Conclusions	453
	Overall conclusions	454
	Index	455

Contributors

- H.A. Chase Department of Chemical Engineering, University of Cambridge, Pembroke Street, Cambridge CB2 3RA, UK.
- P.J. Fryer School of Chemical Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK.
- A.N. Hayhurst Department of Chemical Engineering, University of Cambridge, Pembroke Street, Cambridge CB2 3RA, UK.
- R.M. Nedderman Department of Chemical Engineering, University of Cambridge, Pembroke Street, Cambridge CB2 3RA, UK.
- D.L. Pyle Department of Food Science and Technology, University of Reading, Whiteknights, PO Box 226, Reading RG6 6AP, UK.
- C.D. Rielly Department of Chemical Engineering, University of Cambridge, Pembroke Street, Cambridge CB2 3RA, UK.
- J. Varley Department of Food Science and Technology, University of Reading, Whiteknights, PO Box 226, Reading RG6 6AP, UK.
- C.A. Zaror Department of Chemical Engineering, University of Concepcion, Casilla 53-C, Correo 3, Concepcion, Chile.

Preface

Industrial food processing involves the production of added value foods on a large scale; these foods are made by mixing and processing different ingredients in a prescribed way. The food industry, historically, has not designed its processes in an engineering sense, i.e. by understanding the physical and chemical principles which govern the operation of the plant and then using those principles to develop a process. Rather, processes have been 'designed' by purchasing equipment from a range of suppliers and then connecting that equipment together to form a complete process. When the process being run has essentially been scaled up from the kitchen then this may not matter. However, there are limits to the approach.

- As the industry becomes more sophisticated, and economies of scale are exploited, then the size of plant reaches a scale where systematic design techniques are needed.
- The range of processes and products made by the food industry has increased to include foods which have no kitchen counterpart, such as low-fat spreads.
- It is vital to ensure the quality and safety of the product.
- Plant must be flexible and able to cope with the need to make a variety of products from a range of ingredients. This is especially important as markets evolve with time.
- The traditional design process cannot readily handle multi-product and multi-stream operations.
- Processes must be energetically efficient and meet modern environmental standards.

The problems of the food industry at the moment are very similar to those faced by the chemical process industries forty years ago. Design techniques which had proved able to cope with a small number of processes, based on well-tried plant units, were not able to cope with the requirements for new materials and more efficient production techniques. Chemical engineering is the profession which evolved to solve the design problems of the process industries. Chemical engineers have developed design techniques for continuous process plant, both individual plant items such as heat exchangers and reactors, and whole flowsheets. Although the materials used by the food industry are more complex than those commonly used in the chemical industry and the product safety requirements are different from those re-

quired of chemical plant, the principles used in the analysis and design of food and chemical plant are the same.

Once a process has been designed, it must be operated and controlled in an efficient way. Chemical engineers have developed ways to monitor and analyse the behaviour of process plant. In conjunction with modern developments in information technology, these concepts can be used to optimize the running of process plant.

An increasing number of chemical engineers are being employed by the food industry, and thus a large number of people working in the industry are coming into contact with chemical engineering design techniques. The aim of this book is to outline the basic principles on which chemical engineering works and to develop those ideas into ways of studying food process plant.

The book has its origin in a successful course which has been run in the Chemical Engineering Department at Cambridge since 1989, designed to give an introduction to chemical engineering principles to people working in the food industry but without a degree in chemical engineering. Over the years, the material in the book, first given as lectures and examples on the course, has evolved in response to the needs of the industry and to specific comments from the individuals on the course.

There are two things that this book does **not** set out to do.

- It does not aim to give a list of the processes used by the food industry and the equipment used to carry out those processes. Such a list is always out of date, as equipment is modified, and, more importantly, as novel processes are introduced. **Rather, we seek to outline the physical principles which underpin processing, such as heat, mass and momentum transfer and reaction engineering.**
- It does not describe the whole of chemical engineering. It is no longer possible to put the whole of chemical engineering into one book! Each chapter introduces topics on which whole books have been based. **By reading this book and doing the worked examples, a good basic understanding will be obtained; references are included so that those with specific needs can go further.**

The book is aimed at two groups: it will be useful both for those who are not chemical engineers and who are working in the food industry, and as a refresher for chemical engineers in the food industry. Using the written material, it is possible to examine food processing plant and to understand the design principles involved in heat transfer, mass transfer, mixing and reaction, which can be found in all plants. The aim of engineering, however, is efficient and economic design. We have included at the end a lengthy worked design example, which develops a flowsheet and plant items from an outline of a process. The example comes with supporting information on computer disk; increasingly, all design is computer based, and all profes-

sionals in the food industry must be computer literate. The programs which come with this book allow a further demonstration of the physical principles which we are trying to get over and reinforce the practical aspects of the subject.

A note on units

We have tried wherever possible throughout this text to conform to the SI system of units. Sometimes data has come in such a form that we have fallen below the standards which are imposed by the 'strict' SI system, and we have justified that to ourselves by noting that the 'real world' often appears ignorant of the SI system. Note that $\text{kJ kg}^{-1} \text{K}^{-1}$ are the same numerically as $\text{J kg}^{-1} \text{°C}^{-1}$ etc. The important point is to be consistent and, above all, **always** to check that equations and formulae are dimensionally correct.

Acknowledgements

This book has been developed over a number of years by the authors of the individual chapters in response to discussions with the many people in the food industry who have been on our course. We are deeply grateful for the feedback given, which has enabled us to improve the relevance of the material to industry needs.

The Editors wish to thank all of the authors for spending so much time developing this course, and transferring a vague idea into first a successful course, and then this book. They also thank all those who have suffered during its preparation.

List of symbols

Symbol	Definition	Units
A	area	m^2
A_o	area of orifice	
A	area under C -curve	kmol s m^{-3}
A	pre-exponential factor	–
a	specific area per unit volume	m^2/m^3
B	baffle width	m
Bi	Biot number	–
b	thickness	m
C	annual cash flow (Chapter 1)	£/yr
C	constant of integration	
C	cook value	min
C	impeller clearance (Chapter 10)	m
C_c	contraction coefficient	
C_D	discharge coefficient	
C_{\max}	maximum cook value	min
C_v	velocity coefficient	
c	concentration	kmol m^{-3}
\bar{c}	mean concentration	kmol m^{-3}
c_A	concentration of species A	kmol m^{-3}
c_b	bulk concentration	kmol m^{-3}
c_e	concentration of tracer in exit stream from reactor	kmol m^{-3}
c_{film}	solubility in film	kmol m^{-3}
c_i	interfacial concentration	kmol m^{-3}
c_{in}	concentration of tracer in inlet stream to reactor	kmol m^{-3}
c_s	surface concentration	kmol m^{-3}
c^*	dimensionless concentration	–
c_∞	final concentration	kmol m^{-3}
c_0	initial concentration	kmol m^{-3}
c_D	drag coefficient	
c_f	friction factor	
\bar{c}_p	mean specific heat capacity	$\text{J kg}^{-1} \text{K}^{-1}$
c_p	specific heat capacity at constant pressure	$\text{J kg}^{-1} \text{K}^{-1}$

Symbol	Definition	Units
c_V	specific heat capacity at constant volume	$\text{J kg}^{-1} \text{K}^{-1}$
D	decimal reduction time	min
D	large diameter, such as pipe; common distance scale in dimensionless calculations	m
\mathcal{D}	diffusion coefficient	$\text{m}^2 \text{s}^{-1}$
D_a	axial diffusion coefficient	$\text{m}^2 \text{s}^{-1}$
D_e	effective diffusion coefficient	$\text{m}^2 \text{s}^{-1}$
D_H	hydraulic mean diameter	m
d	small diameter, such as particle	m
d_{\max}	maximum bubble size	m
d_{32}	Sauter mean diameter	m
Da	Damköhler number	–
E	electric field strength	V m^{-1}
E	energy (Chapter 1)	J
E	extract flowrate	kg s^{-1}
E_a	activation energy	$\text{J kmol}^{-1} \text{K}^{-1}$
$E(t)$	residence time distribution	–
e	equivalent roughness size	m
e	error signal	
F	F-value: integrated lethality	min
F	flow rate	$\text{m}^3 \text{s}^{-1}$
F	force	N
F	imposed forcing function	
F	fouling factor	$\text{Km}^2 \text{W}^{-1}$
F_j	molar flowrate of compound j	kmol s^{-1}
F_P	required process integrated lethality	min
$F(t)$	cumulative residence time distribution	
Fr	Froude number	–
FV	future value	
G	shear modulus for elastic deformation	Pa
G	transfer function	
G'	storage modulus	Pa
G''	loss modulus	Pa
Gr	Grashof number = $\rho \Delta \rho g L^3 / \mu^2$	–
g	acceleration due to gravity	m s^{-2}
H	closed-loop transfer function	
H, h	height	m
H	Henry's law constant	$\text{Pa m}^3 \text{kg}^{-1}$
\mathcal{H}	humidity	kg/kg
ΔH	loss of head	m
ΔH_f	standard heat of formation	J kmol^{-1}
ΔH°_R	standard heat or enthalpy of reaction	J kmol^{-1}

Symbol	Definition	Units
h	film heat transfer coefficient	$\text{W m}^{-2} \text{K}^{-1}$
h	specific enthalpy (Chapter 1)	J kg^{-1}
h_{fi}	latent heat of fusion	J kg^{-1}
h_{fg}	latent heat of evaporation	J kmol^{-1}
I	current (electrical)	A
i	fractional interest or discount rate	–
J	mass transfer rate	kmols^{-1}
j	mass flux	$\text{kg m}^{-2} \text{s}^{-1}$
j_{D}	j -factor for mass transfer	
j_{H}	j -factor for heat transfer	
K	equilibrium constant	
K	overall mass transfer coefficient	m s^{-1}
K	partition coefficient	
K	power law consistency index (Chapter 5)	Pa s^n
K_{c}	controller gain	
K_{m}	Michaelis constant for enzyme-catalysed reaction	kmol m^{-3} or kg m^{-3}
K_{o}	Monod constant	kmol m^{-3} or kg m^{-3}
K_{p}	static gain (Chapter 7)	
k	film mass transfer coefficient	m s^{-1}
k_{L}	liquid mass transfer coefficient	m s^{-1}
k_{r}	rate constant	s^{-1}
k_{r}	rate constant for reaction of order n	
k_{s}	solid mass transfer coefficient	m s^{-1}
L	Open loop transfer function	–
L_{d}	detector length scale	m
L_{E}	energy lost per unit mass	J kg^{-1}
L, l	length	m
M	flux of momentum	kg m s^{-2}
M	mass	kg
M	mean molecular mass	
M	mixing index	–
m	Distribution coefficient	–
m_0	initial mass	kg
N	total molar flux	$\text{kmol m}^{-2} \text{s}^{-1}$
N	impeller speed	rps
N_{A}	aeration number	
N_{po}	ungassed power number	–
NPV	Net Present Value	£
N_{Q}	flow number	–
N_1	first normal stress difference	Pa

Symbol	Definition	Units
N_2	second normal stress difference	Pa
Nu	Nusselt number = hL/λ	–
n	number	–
n	power-law exponent in eqn (5.7)	–
P	power input	W
P	productivity	$\text{kg m}^{-3}\text{s}^{-1}$
P	total pressure	Pa
P	wetted perimeter of duct	m
P_a	atmospheric pressure	Pa
P_o	ungassed power unit	W
ΔP	pressure drop	Pa
Pr	Prandtl number = $\mu c_p/\lambda$	–
PV	present value	
p	partial pressure	Pa
p°	equilibrium vapour pressure	Pa
Q	heat flow	W
Q	Oxygen transfer rate (Chapter 4)	$\text{kg m}^{-3}\text{s}^{-1}$
Q_c	process cooling (Chapter 6)	W
Q_c	heat content	J
Q_G	heat generation rate (Chapter 9)	W m^{-3}
Q_T	Total heat (Chapter 1)	J
Q_g	gas volumetric flowrate	m^3s^{-1}
Q_H	process heating (Chapter 6)	W
Q_L	liquid volumetric flowrate	m^3s^{-1}
q	heat flux	W m^{-2}
R	large radius	m
R	rate of oxygen consumption or demand	kg s^{-1}
R	electrical resistance (Chapter 9)	Ω
R_F	fouling resistance	$\text{K m}^{-2}\text{W}^{-1}$
R_g	gas constant	$\text{J mol}^{-1}\text{K}^{-1}$
R_s	radius of sphere	m
r_A	rate of reaction per unit volume (described in terms of production of A)	$\text{kmol m}^{-3}\text{s}^{-1}$
r	small radius	m
Re	Reynolds number = $\rho u_m D/\mu$ (different types defined in text)	
S	selectivity	
S	solvent flowrate	kg s^{-1}
s	pressure gradient	Pa m^{-1}
Sc	Schmidt number = $\mu/\rho D$	
Sh	Sherwood number = kd/θ	–
St	Stanton number = $h/\rho u_m c_p$	

Symbol	Definition	Units
T	tank diameter (Chapter 10)	m
T	temperature	K or °C
T_0	initial temperature	K
T_i	interface temperature	K
T_L	liquid temperature	K
T_m	mean temperature of fluid	K
T_{ref}	reference temperature	K
T_s	surface temperature	K
T_w	wall or water temperature	K
ΔT_{lm}	logarithmic mean temperature difference	K
ΔT_{min}	minimum approach temperature	K
ΔT	temperature difference	K
T_D	derivative action time (Chapter 7)	
T_i	integral action time (Chapter 7)	s
t	time	s
\bar{t}	average of the residence time distribution	s
t_o	residence time along the axis	s
U	internal energy (Chapter 1)	Jkg ⁻¹
U	overall heat transfer coefficient	Wm ⁻² K ⁻¹
U^o	clean heat transfer coefficient	Wm ⁻² K ⁻¹
u	velocity of flow through a quasitubular reactor	
V	voltage (Chapter 9)	V
V	volume	m ³
V_m	maximum reaction rate for an enzyme-catalysed reaction	kmolm ⁻³ s ⁻¹
V_r	volume of liquid in reactor	m ³
v	velocity	ms ⁻¹
v_1	centreline velocity	
v_m	mean velocity	ms ⁻¹
v_∞	terminal velocity	ms ⁻¹
v_p	velocity of particle	ms ⁻¹
v_r	velocity ratio	–
W	blade width (Chapter 10)	m
W	work	J
W_g	additional resistance of gel layer (Chapter 4)	ms ⁻¹
W_m	hydraulic resistance of membrane (Chapter 4)	ms ⁻¹
w	mass flowrate (Chapter 1)	kg s ⁻¹
w_1, w_2	total material flows or flowrates (Chapter 1)	kg s ⁻¹
w_L	volumetric flowrate	m ³ s ⁻¹
w	width	m
We	Weber number	–

Symbol	Definition	Units
X	mixedness fraction	–
X_A	fractional conversion of component A	
x, y, z	deviation/perturbation variable (Chapter 7)	
x, y, z	distance	m
x, y, z	mass or mole fraction or concentration (Chapters 1 and 4)	
x	output (Chapter 7)	
Y	yield coefficient	kg/kg
z_c, z_F	Z value: slope of the lethality or cooking curve	K
α	solids volume fraction	–
α	thermal diffusivity = $\lambda/\rho c_p$	m ² s ⁻¹
β	shear rate constant	–
Γ	torque	N m
$\dot{\gamma}$	shear rate or strain rate	s ⁻¹
γ	strain	–
δ	disturbance (Chapter 7)	
δ	thickness	m
δ	loss angle	rad
ϵ'	dipole density	
$\dot{\epsilon}$	elongational strain rate	s ⁻¹
ϵ	gas volume fraction	–
ζ	damping coefficient	
η_∞	upper Newtonian viscosity	Pas
θ	angle	rad
θ	controller output (Chapter 7)	
θ	temperature	K
θ_w	fraction of water in the material	
ϑ	dimensionless time	
κ	electrical conductivities in the x and y directions	s m ⁻¹
λ	relaxation time = μ/G (Chapter 5)	s
λ	thermal conductivity	W m ⁻¹ K ⁻¹
μ_m	maximum growth rate for a microbial fermentation	h ⁻¹
μ	viscosity	Pas
μ_a	apparent viscosity	Pas
μ_E	elongational viscosity	Pas
μ_0	lower Newtonian viscosity	Pas
$ \mu^* $	magnitude of complex viscosity	Pas
ν	kinematic viscosity = μ/ρ	m ² s ⁻¹
ρ	density	kg m ⁻³
σ^2	variance	–

Symbol	Definition	Units
σ	normal stress	Pa
σ	surface tension (Chapter 10)	Nm^{-1}
τ	shear stress	Pa
τ	system time constant	s
τ_w	wall sheer stress	Pa
τ_y	yield stress (Chapter 5)	Pa
Φ	constant value of N_{po}	–
$\phi_{C,F}$	cook and sterility ratio	
ϕ	dispersed phase volume fraction	
ϕ	phase shift	
ω	frequency	rad s^{-1}