Chemical Engineering for the Food Industry

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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 required 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 professionals 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 $\mathrm{kJ\,kg^{-1}K^{-1}}$ are the same numerically as $\mathrm{J\,kg^{-1}\,{}^{\circ}C^{-1}}$ 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	$J\,kg^{-1}K^{-1}$
c_P	specific heat capacity at constant pressure	$J\,kg^{-1}K^{-1}$

Symbol	Definition	Units
c_V	specific heat capacity at constant volume	$\mathrm{J\,kg^{-1}\,K^{-1}}$
D	decimal reduction time	min
D	large diameter, such as pipe; common distance scale in dimensionless calculations	m
$\mathcal{D}$	diffusion coefficient	$\mathrm{m^2\,s^{-1}}$
D_a	axial diffusion coefficient	$\mathrm{m^2\,s^{-1}}$
D_e	effective diffusion coefficient	$\mathrm{m^2\,s^{-1}}$
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	$\mathrm{V\,m^{-1}}$
E	energy (Chapter 1)	J
E	extract flowrate	$\mathrm{kg\,s^{-1}}$
E_a	activation energy	$\mathrm{J\,kmol^{-1}\,K^{-1}}$
$E(t)$	residence time distribution	–
e	equivalent roughness size	m
e	error signal	
F	F-value: integrated lethality	min
F	flow rate	$\mathrm{m^3\,s^{-1}}$
F	force	N
F	imposed forcing function	
F	fouling factor	$\mathrm{K\,m^2\,W^{-1}}$
F_j	molar flowrate of compound j	$\mathrm{kmol\,s^{-1}}$
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	$\mathrm{m\,s^{-2}}$
H	closed-loop transfer function	
H,h	height	m
H	Henry's law constant	$\mathrm{Pa\,m^3\,kg^{-1}}$
$\mathcal{H}$	humidity	kg/kg
ΔH	loss of head	m
ΔH_f	standard heat of formation	$\mathrm{J\,kmol^{-1}}$
$\Delta H^\circ_\mathrm{R}$	standard heat or enthalpy of reaction	$\mathrm{J\,kmol^{-1}}$

Symbol	Definition	Units
h	film heat transfer coefficient	$\mathrm{W\,m^{-2}\,K^{-1}}$
h	specific enthalpy (Chapter 1)	$\mathrm{J\,kg^{-1}}$
h_{fi}	latent heat of fusion	$\mathrm{J\,kg^{-1}}$
h_{fg}	latent heat of evaporation	$\mathrm{J\,kmol^{-1}}$
I	current (electrical)	A
i	fractional interest or discount rate	–
J	mass transfer rate	$\mathrm{kmol\,s^{-1}}$
j	mass flux	$\mathrm{kg\,m^{-2}\,s^{-1}}$
j_D	j-factor for mass transfer	
j_H	j-factor for heat transfer	
K	equilibrium constant	
K	overall mass transfer coefficient	$\mathrm{m\,s^{-1}}$
K	partition coefficient	
K	power law consistency index (Chapter 5)	$\mathrm{Pa\,s}^{n}$
K_c	controller gain	
K_m	Michaelis constant for enzyme-catalysed reaction	$\mathrm{kmol\,m^{-3}}$ or $\mathrm{kg\,m^{-3}}$
K_o	Monod constant	$\mathrm{kmol\,m^{-3}}$ or $\mathrm{kg\,m^{-3}}$
K_p	static gain (Chapter 7)	
k	film mass transfer coefficient	$\mathrm{m\,s^{-1}}$
k_L	liquid mass transfer coefficient	$\mathrm{m\,s^{-1}}$
k_r	rate constant	$\mathrm{s^{-1}}$
k_n	rate constant for reaction of order n	
k_s	solid mass transfer coefficient	$\mathrm{m\,s^{-1}}$
L	Open loop transfer function	–
L_d	detector length scale	m
L_E	energy lost per unit mass	$\mathrm{J\,kg^{-1}}$
L, l	length	m
M	flux of momentum	$\mathrm{kg\,m\,s^{-2}}$
M	mass	kg
M	mean molecular mass	
M	mixing index	–
m	Distribution coefficient	–
m_0	initial mass	kg
N	total molar flux	$\mathrm{kmol\,m^{-2}\,s^{-1}}$
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	$\mathrm{kg\,m^{-3}\,s^{-1}}$
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)	$\mathrm{kg\,m^{-3}\,s^{-1}}$
Q_C	process cooling (Chapter 6)	W
Q_c	heat content	J
Q_G	heat generation rate (Chapter 9)	$\mathrm{W\,m^{-3}}$
Q_T	Total heat (Chapter 1)	J
Q_g	gas volumetric flowrate	$\mathrm{m^3\,s^{-1}}$
Q_H	process heating (Chapter 6)	W
Q_L	liquid volumetric flowrate	$\mathrm{m^3\,s^{-1}}$
q	heat flux	$\mathrm{W\,m^{-2}}$
R	large radius	m
R	rate of oxygen consumption or demand	$\mathrm{kg\,s^{-1}}$
R	electrical resistance (Chapter 9)	Ω
R_F	fouling resistance	$\mathrm{K\,m^{-2}\,W^{-1}}$
R_g	gas constant	$\mathrm{J\,mol^{-1}\,K^{-1}}$
R_s	radius of sphere	m
r_A	rate of reaction per unit volume (described in terms of production of A)	$\mathrm{kmol\,m^{-3}\,s^{-1}}$
r	small radius	m
Re	Reynolds number = $\rho u_m D/\mu$ (different types defined in text)	
S	selectivity	
S	solvent flowrate	$\mathrm{kg\,s^{-1}}$
s	pressure gradient	$\mathrm{Pa\,m^{-1}}$
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)	$\mathrm{J\,kg^{-1}}$
U	overall heat transfer coefficient	$\mathrm{W\,m^{-2}\,K^{-1}}$
U°	clean heat transfer coefficient	$\mathrm{W\,m^{-2}\,K^{-1}}$
u	velocity of flow through a quasitubular reactor	
V	voltage (Chapter 9)	V
V	volume	$\mathrm{m^3}$
V_m	maximum reaction rate for an enzyme-catalysed reaction	$\mathrm{kmol\,m^{-3}\,s^{-1}}$
V_r	volume of liquid in reactor	$\mathrm{m^3}$
v	velocity	$\mathrm{m\,s^{-1}}$
v_1	centreline velocity	
v_m	mean velocity	$\mathrm{m\,s^{-1}}$
v_∞	terminal velocity	$\mathrm{m\,s^{-1}}$
v_p	velocity of particle	$\mathrm{m\,s^{-1}}$
v_r	velocity ratio	–
W	blade width (Chapter 10)	m
W	work	J
W_g	additional resistance of gel layer (Chapter 4)	$\mathrm{m\,s^{-1}}$
W_m	hydraulic resistance of membrane (Chapter 4)	$\mathrm{m\,s^{-1}}$
w	mass flowrate (Chapter 1)	$\mathrm{kg\,s^{-1}}$
w_1, w_2	total material flows or flowrates (Chapter 1)	$\mathrm{kg\,s^{-1}}$
w_L	volumetric flowrate	$\mathrm{m^3\,s^{-1}}$
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 = $\lambda/\rho c_P$	$\mathrm{m^2\,s^{-1}}$
β	shear rate constant	–
Γ	torque	N m
$\dot{\gamma}$	shear rate or strain rate	$\mathrm{s^{-1}}$
γ	strain	–
δ	disturbance (Chapter 7)	
δ	thickness	m
δ	loss angle	rad
ε'	dipole density	
$\dot{\varepsilon}$	elongational strain rate	$\mathrm{s^{-1}}$
ε	gas volume fraction	–
ζ	damping coefficient	
η_∞	upper Newtonian viscosity	Pa s
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	$\mathrm{s\,m^{-1}}$
λ	relaxation time = μ/G (Chapter 5)	s
λ	thermal conductivity	$\mathrm{W\,m^{-1}\,K^{-1}}$
μ_m	maximum growth rate for a microbial fermentation	$\mathrm{h^{-1}}$
μ	viscosity	Pa s
μ_a	apparent viscosity	Pa s
μ_E	elongational viscosity	Pa s
μ_0	lower Newtonian viscosity	Pa s
$\lvert\mu^*\rvert$	magnitude of complex viscosity	Pa s
ν	kinematic viscosity = μ/ρ	$\mathrm{m^2\,s^{-1}}$
ρ	density	$\mathrm{kg\,m^{-3}}$
σ^2	variance	–

Symbol	Definition	Units
σ	normal stress	Pa
σ	surface tension (Chapter 10)	$\mathrm{N\,m^{-1}}$
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	$\mathrm{rad\,s^{-1}}$