

Overall conclusions

We noted at the outset that this book was neither an attempt to describe all, nor indeed many, of the processes which are used in the food industry, nor to describe the whole of chemical engineering. Instead, we have tried to outline the key physical and physico-chemical principles which underpin food processes, and we have then tried to show how simple (for the most part) mathematical descriptions – models – can be developed and interpreted on the basis of these principles. The overall intention has been to demonstrate how quantitative understanding is important for process selection, design and operation.

We have laid great stress on the development and use of simplified models. There are several reasons for this emphasis. First, we believe, and have tried to show, that simplified models can provide a very good first basis for assessing processes and their efficiency. Often, a good estimate is sufficient to answer a technical question about the feasibility of a particular process or the advantages of one process technology over another. Even where simplified descriptions are no longer adequate you will find it useful to be able to produce order of magnitude estimates as a check. This is perhaps even more important today when highly sophisticated computer programmes are used routinely for process design and analysis: apparent sophistication or impressively presented results are, in themselves, no guarantee of reliability. Second, there are many food processes where the data available – such as physical properties – are poor. Models are no better than the data they rely on. On the other hand, rough models which recognize the limitations of their data can be very useful. Finally, recognizing that often mathematics can be off-putting, we have tried to minimize the amount of mathematics used in the text. We hope that those who persevere with the mathematics will find that this book gives them a set of tools with which food processes can be analysed.

Having said all that, we hope that the text will prove useful not only to students and professionals in the food industry, but also to chemical engineers. For the latter group we hope that the book will awaken an interest in the problems and challenges posed by food processing, which is after all the largest sector of manufacturing industry and, arguably, the one with most direct impact on our quality of life.

We will be very pleased to receive comments and suggestions on the text. Even though the process of bringing the book to completion has been desperately slow, we are conscious of the many inadequacies that still remain.

Index

Page numbers appearing in **bold** refer to figures and page numbers appearing in *italics* refer to tables.

- 12D cook 304
- Absolute pressure 69
- Aerated impeller power consumption 407–11
- Aeration 184–8
- Algebraic representation in process design 23
- Apparent viscosity 199
- Arrhenius equation 305–6
- Aseptic packaging 342–3

- Ball mill **423**, 424
- Batch reactors 296, 309–11
- Bernoulli's equation 68–9
- Bingham plastic fluids 204
- Biot number
 - of a can 337
 - definition 139
- Blasius correlation, definition 93
- Blending
 - dimensional analysis of liquid blend times 402–5
 - of low-viscosity liquids 400–2
 - of non-Newtonian liquids 405–6
 - of viscous liquids 404
- Buckingham's theorem 85–91
- Bulk convection and diffusion 167, 174–7

- C-curve 322–3
- C-value 305, 335
- Canning 336–9
- Capillary flow viscometers 217–19
- Cascade control 257
- Cash-flow diagram **46**
- Casson fluid 205
- Cheese plant, design exercise 435–44
- Chemical and biochemical reactions 34–42
- Cleaning
 - cleaning fouled surfaces 376–7
 - kinetics of cleaning 377–9
 - monitoring fouling and cleaning 380–1
 - single-stage commercial cleaners 377
 - stages of cleaning 377–9, **378**
 - two-stage acid and alkali cleaners 376–7
- Closed system 26, **27**
- Composition measures 57
- Computer simulation
 - cheese production 445–6
 - dynamics and feedback control 451–3
 - heat exchanger 446–8
 - mass and energy balance over spray drier 450–1
 - process dynamics and control 445
 - spreadsheets 444–5
 - steady-state bioreactor 448–9
 - steady-state bioreactor with cell recycle 449–50
- Concentration polarization 174
- Concentric cylinder viscometer 213–17, 230–1
- Concentric tube heat exchanger 142–9
- Conduction, heat
 - Fourier's law 106–8
 - in hollow sphere with thick walls 112–14
 - modelling 358–60
 - steady-state heat conduction 108–14
 - thawing and freezing foods 114–16
 - in thick-walled tube 110–11, 134–7
 - in thin-walled tube 131–4
 - unsteady-state heat conduction 116–20
- Cone and plate viscometer 21, 231–2
- Conservation of energy
 - in ideal fluids 68–9, 70–7
 - in process design 26–9
- Conservation of mass in ideal fluids 68, 70–7
- Conservation of momentum in ideal fluids 69–77
- Continuity equation 68
- Continuous stirred tank reactor (CSTR) 298, 315–19
- Contraction coefficient 71
- Control, *see* Process control
- Control system design 291–3
- Controller action
 - adaptive control 288
 - derivative action 286–7

- Controller action *contd*
 eliminating offset 285–6
 integral action 285–6
 multivariable control 288–91
 on–off control 284–5
 speeding up response 286–7
 three-term controller 287–8
- Convection
 bulk convection 167
 mechanism of mass transfer 155
 modelling 358–60
- Convective mixers 428–30
- Cooking, kinetics of 334–6
- Costs
 capital and operating 47–8
 estimating 48–9
 fixed and variable 47–8, 54–6
 unit cost of production 54
- Coupled heat and mass balances 42–4
- Critical Reynolds numbers 64–5
- CSTR, *see* Reactor types
- Cumulative residence time
 distribution 325
- Dalton's law 58
- Damkohler number 191
- Darcy's law 82
- Decimal reduction time 300
- Definitions
 composition measures 57
 ideal and non-ideal mixtures 57–60
- Depreciation 53
- Design, *see* Process design
- Design principles for heat transfer
 equipment 346–9
- Diffusion
 bulk diffusion 167
 effective diffusion coefficient 160
 mechanism of mass transfer 154
 molecular diffusion 159–60
 steady diffusion from a sphere 162–4
 transport across a film 161–2, 164–5
- Dimensional analysis
 applied to flowing systems 169–70
 applied to heat transfer 121–3
 Buckingham's theorem 85–8
 examples 88–91
 liquid blend times 402–5
 power consumption in stirred tanks 396–9
- Discharge coefficient 71
- Discounting 50–1
- Dispersion mill 424
- Dynamics, *see* Process dynamics
- Dynamic similarity, definition 87
- Economics, *see* Process economics
- Effective diffusion coefficient 160
- Elastic loss modulus 221
- Elastic storage modulus 221
- Electrical heating 351–3
- Elongational viscosity 212–13
- Emulsions 414–16
- Energy
 in chemical reactions 34–42
 conservation 26–9
 datum levels 25
 stored or internal energy 29–34
 units 24–6
- Energy balance
 chemical and biochemical reactions 34–42
 conservation of energy 26–9
 coupled heat and mass balances 42–4
 enthalpy 29–31
 enthalpy of mixtures 34
 example 31–4
 stored or potential energy 29–30
 units and datum levels 24–6
- Engineering in food preservation 332–3
- Enthalpy
 definition 29, 36
 of mixtures 34
 in process design 29–34, 36–7
- Enzyme-catalysed reactions 13–17, 308
- Equilibrium
 equilibrium coefficient 155
 equilibrium stage 156–8
 multistage processes 158–9
- Equilibrium vapour pressure 58
- Equivalent roughness size 96
- Ergun correlation 83
- Evaporators 348–9
- Examples
 fat extractor 5–7
 glucose isomerization 13–17
 juice extractor 7–10
 two-stage separation 11–13
- F-curve 323–5
- F-value 304
- Fanning's friction factor 92
- Fanning's friction formula 94
- Fat separator 4
- Feedback, *see* Feedforward and feedback control
- Feedforward and feedback control
 block diagram representation 278–81
 closed loops 278–81
 dynamics and control 275–8
 feedback blender control 255–7, 273–5, 276–7
 feedback cancellation and stability 282–4
 feedback control 272–5
 feedforward control 270–2

- feedforward control of blender 254–5
 - proportional feedforward 271
 - system sensitivity 281–2
- Fermentation 307–8
- Fick's law 160, 162
- Film model of heat transfer 123–5
- Fixed and variable costs 54–6
- Flowing systems
 - around bend 75–7, 98–101
 - bulk convection and diffusion 167
 - bulk flow and diffusion 174–7
 - in circular pipes 79–82, 98–101, 170–1
 - concentration polarization 174–7
 - dimensionless groups 169–70
 - external transfer coefficient 172
 - film theory 167–9
 - flow patterns in mixing equipment 393–6
 - in fluid mixer operations 386–7
 - of food materials 353–8
 - heat transfer in 120–31
 - in ideal fluids 67–77
 - internal transfer coefficient 172
 - non-ideal flow and mixing in continuous reactors 320–9
 - rough and non-circular ducts 96–8
 - spheres, pellets and bubbles 171–2
 - through orifice 70–4
 - through packed beds 82–4
 - velocity profiles 65–6
- Fluid-mixing equipment
 - flow patterns 393–6
 - standard geometry stirred tanks 389–93
- Force on pipe bend 75–7
- Fouling
 - chemistry of 368–70
 - cleaning fouled surfaces 376–7
 - fouling period 371–4
 - fouling problem 365–8
 - fouling resistance (or factor) 366
 - in heat exchangers 137
 - implications of fouling model 374–6
 - induction period 371
 - from milk 368–70
 - monitoring fouling and cleaning 380–1
 - in reaction engineering 371–4
- Fourier's law 106–8
- Fractional conversion 309
- Freezing
 - beef burger **138**
 - of foods 114–16, 334
- Freezing times 137–9
- Frequency domain methods 253
- Friction factor 92–4
- Froude number 355
- Gas void fraction 411–13
- Gas–liquid mass transfer 413–14
 - Gas–liquid mixing
 - aerated impeller power consumption 407–11
 - gas voidage fraction in stirred tanks 411–13
 - gas–liquid mass transfer 413–14
 - interfacial area in stirred tanks 411–13
 - surface aeration phenomena in stirred tanks 406–7
 - Gauge pressure 69
 - Geometric similarity, definition 87
 - Glucose isomerization process **14**, 40–2
 - Grashof number, definition 170
 - Heat exchanger simulation 446–8
 - Heat exchangers
 - concentric tube exchangers 142–9
 - plate heat exchangers 347
 - scraped-surface exchangers 150, 348
 - tubular exchangers 149, 348
 - Heat generation, modelling 361–5
 - Heat integration, in process design
 - design of process plant 234–47
 - in the food industry 247–8
 - introduction 234
 - second-law analysis 237–47
 - Heat transfer
 - conduction 106–20
 - design principles for heat transfer equipment 346–9
 - effect of fouling 137
 - equipment for heat transfer 149–50
 - Fourier's law 106–8
 - freezing and thawing 114–16, 137–9
 - heat exchangers 142–50, 347–8
 - heat transfer coefficients 109, 131–7
 - in hollow sphere with thick walls 112–14
 - introduction 105–6
 - modelling 358–65
 - practical aspects 131–50
 - steady-state conduction 108–14
 - and sterilization 336–40
 - in thick-walled tube 110–11, 134–7
 - in thin-walled tube 121–3, 131–4
 - with turbulent flow 121–31
 - unsteady-state heat transfer 116–20, 139–42
 - Heat transfer coefficient
 - definition 109
 - for thick-walled tube 134–7
 - for thin-walled tube 131–4
 - Heat transfer in flowing systems
 - dimensional analysis 121–3
 - experimental measurements 127–8
 - film model 123–5
 - j*-factor analogy 126–7
 - in other geometries 130–1

- Heat transfer in flowing systems *contd*
 Reynolds analogy 125–6
 in smooth tube 128–30
- Heating and cooling in the food industry 333–4
- Henry's law 59
- Herschel–Bulkley equation 205–6
- High-temperature short time (HTST)
 process
 definition 340
 engineering implications 341–6
 modelling 360–1
 problems 345–6
- Hopper mixers 431
- HTST, *see* High-temperature short time
 process
- Humidity 59
- Hydraulic mean diameter 96
- Ideal and non-ideal mixtures 57–60
- Ideal fluids
 Bernoulli's equation 68–9
 conservation of energy 68–9
 conservation of momentum 69–70
 continuity equation 68
 definition 67
 example calculations 70–7
- In-line static mixer 425–6
- Inflation 53
- Integrated lethality 305, 335
- Internal energy 29–30
- Internal rate of return (IRR) 52
- Interphase transfer
 limiting resistances 184
 overall resistances and coefficients 177–80
 two-film theory 180–4
- Inverse Peclet number 326
- Isothermal 'ideal' reactor systems
 batch reactors 309–11
 continuous stirred tank reactors 315–19
 fractional conversion 309
 plug flow tubular reactors 313–15
- j*-factor model of heat transfer 126–7
- Juice extractor 8
- Laminar flow
 in circular cross-section tube 79–82
 critical Reynolds number 64–5
 definition 64, 65, 78
 through packed beds 82–4
 velocity profiles 65–6
- Limiting reagent 20
- Linear viscoelastic fluids 208–11
- Linear viscoelastic Maxwell element 229–30
- Liquid–liquid dispersions 414–16
- Loops, closed 278–81
- Mass balance
 coupled heat and mass balances 42–4
 in process design 3–10
- Mass transfer
 aeration 184–8
 diffusion 159–65
 equilibrium 155–9
 flowing systems 167–77
 gas–liquid mass transfer 415–16
 interphase transfer 177–84
 introduction 153–4
 mass transfer from a sphere 171
 mass transfer limitations 188–93
 mechanisms 154–5
 in solid–liquid mixtures 416–20
 in solid suspension 416–20
 transient behaviour 165–7
 why does transfer occur? 154
- Mass transfer coefficient 163
- Mass transfer limitations
 oxygen transfer in a fermenter 188–93
- Material requirements and flows
 algebraic representation 23
 choosing a basis 5
 examples 5–10
 mass balances 3–5
 reaction stoichiometry 17–18
 recycles 13–17
 stoichiometric and yield coefficients 19–23
 system boundary 11–13
- Maximum energy recovery (MER)
 definition 238
 design for MER 244–7
- Mean residence time 314, 325
- MER, *see* Maximum energy recovery
- Microwave processing 350–1
- Milk, fouling from 368–70
- Miscible liquid blending operations
 blending non-Newtonian liquids 405–6
 blending of low-viscosity liquids 400–2
 blending of viscous liquids 404
 dimensional analysis of liquid blend times 402–5
- Mixing
 alternative mixing devices 422–6
 emulsions, creation of 414–16
 flow regimes for fluid mixer operations 386–7
 fluid-mixing equipment 389–96
 gas–liquid mixing 406–14
 laminar mixing mechanisms 387–8
 liquid–liquid dispersions 414–16
 miscible liquid blending operations 400–6

- mixing of particulate materials 426–31
 - mixing processes 383–4
 - power consumption in stirred tanks 396–400
 - scale of scrutiny 384–6
 - scale-up of mixers 420–2
 - solid–liquid mass transfer 416–20
 - solids suspension 416–20
 - turbulent mixing mechanisms 388–9
- Mixtures
 - enthalpies of 34
 - ideal and non-ideal 57–60
 - processing solid–liquid food mixtures 349–53
- Modelling
 - conduction and convection 358–60
 - in design process 444–52
 - heat generation 361–5
 - HTST processes 360–1
- Molecular diffusion coefficient 160
- Momentum equation in ideal fluid 69–77
- Monod equation 308
- Nutamix 429
- Net present value 51
- Newton's law of fluid friction 197
- Newtonian fluids
 - definition 78
 - dimensional analysis 85–91
 - ideal fluids 67–77
 - introduction 63
 - laminar and turbulent flow 64–7
 - laminar flows 78–84
 - power consumption in stirred tanks 396–9
 - turbulent flow 91–103
- No-slip condition 78
- Non-ideal flow and mixing in continuous reactors 320–9
 - analysis of residence time distributions 325–8
 - experimental characterization 322–5
 - experimental characterization of non-ideal flow 322–5
 - predicting conversion using RTDs 328–9
 - residence time distributions 320–2, 325–8, 328–9
- Non-isothermal reactions 319–20
- Non-Newtonian fluids
 - blending 405–6
 - complex fluid flow problems 229
 - elongation viscosity effects 212–13
 - linear viscoelastic fluids 208–11
 - linear viscoelastic Maxwell element 229–30
 - non-Newtonian pipe flows 226–9
 - normal stress differences 211–12
 - power consumption in stirred tanks 399–400
 - time-dependent non-Newtonian fluids 206–8
 - time-independent shear-thickening fluids 200–6
 - time-independent shear-thinning fluids 200–6
- Nusselt number 109
- One-seventh power law 65, 101–3
 - see also* Power-law parameter for various foods
- Open system 26, 27, 28, 28
- Opportunity cost 52
- Oxygen transfer in a fermenter 188–93
- Parallel plate viscometer 219
- Particulate materials
 - nature 427–8
 - solids mixers 428–31
- Pasteurization 333
- Payback time 53
- Permeability, definition 83
- Physical chemistry of food reactions
 - enthalpies of reaction 300
 - kinetic data for some processes 301
 - reaction rates 300–5
 - types of reaction 299–300
- Pipe flows, non-Newtonian 226–9
- Plate heat exchangers 347–8
- Plug flow tubular reactor 297, 313–15, 316–19
- Power consumption in stirred tanks
 - non-Newtonian liquids 399–400
 - single Newtonian liquid phase 396–9
- Power-law parameters for various foods 203
- Prandtl number
 - definition 122
 - values 122
- Preservation
 - engineering in 332–3
- Pressure
 - absolute pressure 69
 - definition 66
 - gauge pressure 69
 - measurement 66–7
- Pressure losses in bends and pipe fittings 98–101
- Process control
 - basic control structures 253–9
 - control objectives 252–3
 - control problem 251–9
 - control system design for complete plants 291–3
 - controller action, types 284–91

- Process control *contd*
 feedforward and feedback control 270–84
 frequency response 269–70
 introduction 250–1
 multiple inputs and linearization 265–9
 process dynamics 260–5
- Process design
 basis for design 5
 cheese plant exercise 435–44
 computer simulation of cheese plant 444–52
 energy balances 24–44
 exercise 435–41
 heat integration 234–49
 introduction 1–3
 material requirements and flows 3–23
 process economic 56–9
- Process design, exercise and simulation
 examples
 cheese plant 435–44
 computer simulations 444–53
 introduction 434–5
- Process dynamics
 computer simulation 445
 dead times 263
 first-order systems 261–2
 holding tank 267–9
 second-order lags 263–5
 series of lags 263
 transportation lags 262–3
- Process economics
 capital and operating costs 47–8
 depreciation 53
 design study, ethanol plant 48–9
 discounting 50–1
 estimating costs 48–9
 fixed and variable costs 47–8, 54–6
 inflation 53
 internal rate of return 52
 payback time 53
 processes, products and time 45–7
 risk 53
 time value of money 50–1
 unit cost of production 54
- Proportional feedforward control 271
- Rabinowitch correction control 217
- Ratio control 257
- Reaction rates 300–5
- Reactions in food industry
 biological reactions 307–8
 energy balance in chemical reactions 34–42
 enthalpies of reaction 29–34, 300
 enzyme-catalysed reactions 308
 fermentations 307
 non-isothermal reactions 319–20
 physical chemistry of food reactions 299–308
 reaction rates 300–5
 reaction stoichiometrics 17–18
 stoichiometric and yield coefficients 19
 types of reaction 299–300
 variation of reaction rates with temperature 304–7
- Reactor types
 back-mix reactor 298
 batch reactors 296, 309–11
 choice of reactor type 298–9
 continuous stirred tank reactors (CSTR) 298, 315–19
 fixed bed reactor 297
 isothermal 'ideal' reactor 308–19
 packed bed reactor 297
 plug flow tubular reactors 297, 313–15, 316–19
 tube reactor 296–8
- Recycles
 numerical solution of recycle problem 16–17
 in process design 13–17
- Regulator problem 252
- Residence time distributions
 analysis of 325–8
 definition 320–2
 in UHT process 343–5
 use to predict reactor conversion 328–9
- Resistances
 limiting resistances 184
 in mass transfer 177–80
- Reynolds analogy 125–6
- Reynolds number
 critical 64–5
 definition 64
- Rheology, food
 application to engineering problems 226–9
 characteristics of non-Newtonian fluids 199–213
 characterization 196
 engineering processes 196–7
 shear forces and viscosity 197–9
 shear rates for food operations 200
 shear-thickening fluids 200–6
 shear-thinning fluids 200–6
 viscometric flows 213–26
- Rheopectic behaviour 207
- Ribbon blender 428–9
- Risk 53
- Root locus methods 253
- Rough and non-circular ducts 96–7
- Scale-up of mixers from pilot trials 420–2
- Schmidt number 169, 403

- Scraped-surface heat exchangers 348
 Screw extruder 424–5
 Second-law analysis 237–47
 Segregation
 intensity of 385
 scale of 385
 Semi-batch extraction with supercritical
 carbon dioxide **2**
 Servo problem 252
 Shear rates for food operations 200
 Shear stress, definition 79
 Shear thickening fluids 200–6
 Shear thinning fluids 200–6
 Shear viscosity
 measurement of shear viscosity 213–19
 shear forces 197–9
 Sherwood number 162
 Similarity, definition 87
 Simulation, *see* Computer simulation
 Single input single output (SISO)
 systems 253
 Solid–liquid food mixtures
 heat generation processes 350–3
 separate processing of solids and
 liquids 349
 Solid–liquid mass transfer 416–20
 Solids mixers
 convective mixers 428–30
 hopper mixers 431
 selection of powder mixers 430
 tumble mixers 428
 Solids suspension mass transfer 416–20
 Spray drier **3**, **4**, 42–4
 Spreadsheet simulations 444–5
 Standard geometry stirred tanks
 high-viscosity applications 392–3
 low-viscosity applications 389–2
 Stanton number 122
 Steady diffusion from a sphere 162–4
 Steady-state bioreactor simulation 448–50
 Steady-state heat conduction 108–14
 Sterilization
 commercial sterility 303–7
 heat transfer and 333, 336–40
 high-temperature short time (HTST)
 process 340–6
 ideal sterilization process 340–1
 steam sterilization 31–4, **31**, **33**
 ultra-high temperature (UHT) process
 340
 Stoichiometric coefficients 19–23
 Stored and internal energy 29–30
 Surface aeration phenomena in stirred
 tanks 406–7
 Symbols used xii–xvi
 System boundary
 examples 11–13
 in process design 11
 Tanks-in-series model 327–8
 Taylor vortices 215
 Thawing of foods 114–16
 Thermal conductivity
 definition 106
 values 107
 Thermal death time 304
 Thermal diffusivity 117
 Thermal treatment of foods
 continuous processing, problems and
 solutions 346–65
 engineering in food preservations
 332–3
 engineering principles 336–46
 fouling and cleaning 365–81
 heating and cooling 333–4
 introduction 331–6
 kinetics of cooking 334–6
 Thixotropic behaviour 207
 Time domain methods 253
 Time value of money 50–1
 Transfer across a film 161–2, 164–5
 Transfer function 278
 Transient behaviour in mass transfer
 165–7
 Transient period 167
 Transport across a film 161–2, 164–5
 Tubular heat exchangers 348
 Tubular reactors 296–8
 Tumbler mixers 428
 Turbulent flow
 critical Reynolds number 64–5
 definition 64, **65**
 Fanning's friction formula 94–6
 friction factor 92–4
 heat transfer in 123–31
 one-seventh power law 101–3
 pressure losses in bends and pipe
 fittings 98–101
 rough and non-circular ducts 96–7
 Two-film theory of interphase mass
 transfer 180–4
 Two-stage separation **11**
 U-tube manometer 66–7
 UHT, *see* Ultra-high temperature process
 Ultra-high temperature (UHT) process
 340, 343
 Unit cost of production 54
 Units, energy 24–6
 Unsteady-state heat conduction 116–20,
 139–42
 Variable costs 54–6
 Velocity coefficient 71
 Velocity profiles (of flowing fluids) 65–6
 Vena contracta 71
 Venturi tube 75

- Vessel dispersion number 326
- Viscoelastic fluids
 - linear viscoelastic fluids 208–11
 - properties 219–26
- Viscometric flows
 - capillary flow viscometers 217–19
 - concentric cylinder viscometer 213–17, 230–1
 - cone and plate oscillatory viscometers 219, 231–2
 - measurement of shear viscosity 213–26
 - measurement of viscoelastic properties 219–26
 - parallel plate viscometer 219
- Viscosity
 - apparent viscosity 199
 - complex viscosity 221
 - definition 78
- Voigt model 209
- Vortex cavities 410
- Weber number 415
- Weissenberg effect 208, 212
- Yeast fermenter 37–9, **38**
- Yield coefficient 19–23