

Food Science Text Series

P. G. Smith

Introduction to Food Process Engineering

Second Edition

 Springer

Food Science Text Series

The Food Science Text Series provides faculty with the leading teaching tools. The Editorial Board has outlined the most appropriate and complete content for each food science course in a typical food science program and has identified textbooks of the highest quality, written by the leading food science educators.

Series Editor

Dennis R. Heldman

Editorial Board

David A. Golden, Ph.D., Professor of Food Microbiology, Department of Food Science and Technology, University of Tennessee

Richard W. Hartel, Professor of Food Engineering, Department of Food Science, University of Wisconsin

Hildegard Heymann, Professor of Food Sensory Science, Department of Food Science and Technology, University of California-Davis

Joseph H. Hotchkiss, Professor, Institute of Food Science and Institute for Comparative and Environmental Toxicology, and Chair, Food Science Department, Cornell University

Michael G. Johnson, Ph.D., Professor of Food Safety and Microbiology, Department of Food Science, University of Arkansas

Joseph Montecalvo, Jr., Professor, Department of Food Science and Nutrition, California Polytechnic and State University-San Luis Obispo

S. Suzanne Nielsen, Professor and Chair, Department of Food Science, Purdue University

Juan L. Silva, Professor, Department of Food Science, Nutrition and Health Promotion, Mississippi State University

For further volumes:

<http://www.springer.com/series/5999>

P.G. Smith

Introduction to Food Process Engineering

Second Edition

 Springer

P.G. Smith
School of Natural and Applied Sciences
University of Lincoln
Brayford Pool
LN6 7TS Lincoln
United Kingdom

ISSN 1572-0330
ISBN 978-1-4419-7661-1 e-ISBN 978-1-4419-7662-8
DOI 10.1007/978-1-4419-7662-8
Springer New York Dordrecht Heidelberg London

© Springer Science+Business Media, LLC 2011

All rights reserved. This work may not be translated or copied in whole or in part without the written permission of the publisher (Springer Science+Business Media, LLC, 233 Spring Street, New York, NY 10013, USA), except for brief excerpts in connection with reviews or scholarly analysis. Use in connection with any form of information storage and retrieval, electronic adaptation, computer soft-ware, or by similar or dissimilar methodology now known or hereafter developed is forbidden.

The use in this publication of trade names, trademarks, service marks, and similar terms, even if they are not identified as such, is not to be taken as an expression of opinion as to whether or not they are subject to proprietary rights.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface to the First Edition

There are now a large number of food-related first-degree courses offered at universities in Britain and elsewhere in the world which either specialise in, or contain a significant proportion of, food technology or food engineering. This is a new book on food process engineering which treats the principles of processing in a scientifically rigorous yet concise manner, which can be used as a lead-in to more specialised texts for higher study and which is accessible to students who do not necessarily possess a traditional science A-level background. It is equally relevant to those in the food industry who desire a greater understanding of the principles of the processes with which they work. Food process engineering is a quantitative science and this text is written from a quantitative and mathematical perspective and is not simply a descriptive treatment of food processing. The aim is to give readers the confidence to use mathematical and quantitative analyses of food processes and most importantly there are a large number of worked examples and problems with solutions. The mathematics necessary to read this book is limited to elementary differential and integral calculus and the simplest kind of differential equation.

This book is the result of 15 years experience of teaching food processing technology and food engineering to students on a variety of diploma, first degree and postgraduate courses. It is designed, *inter alia*, to

- emphasise the importance of thermodynamics and heat transfer as key elements in food processing
- stress the similarity of heat, mass and momentum transfer and make the fundamentals of these essential concepts readily accessible
- develop the theory of mass transfer, which is underused in studies of food processing and little understood in a useful and readily applicable way
- widen the usual list of unit operations treated in textbooks for undergraduates to include the use of membranes
- introduce a proper treatment of the characterisation of food solids and of solids processing and handling

Chapters 1 and 2 set out the background for a quantitative study of food processing by defining the objectives of process engineering, by describing the mathematical and analytical approach to the design and operation of processes and by establishing the use of SI units. Much of what follows in the book is made easier by a thorough understanding of the SI system. Important thermodynamics concepts are introduced in Chapter 3 which underpins the sections on energy balances and heat transfer, itself so central to food processing. Chapter 4 is concerned with material and energy balances and concentrates upon the techniques required to solve problems. Most of the chapter is devoted to numerical examples drawn from a wide range of operations.

In Chapter 5 the concepts of heat, mass and momentum transfer are introduced; the similarity between heat, mass and momentum transfer is stressed. This acts as an introduction to the material

of the following three chapters. These cover first, the flow of food fluids, in which the importance of laminar flow in food processing is emphasised, and food rheology, where the objective is to enable the reader to apply rheological models to experimental data and to understand their significance in mechanistic and structural terms. Second, heat transfer, which is at the heart of many food processing operations. The basic principles are covered in detail and illustrated with numerous worked examples. Third, mass transfer, which is often perceived as a difficult topic and indeed is poorly treated in many food texts. As a consequence, mass transfer theory is underused in the analysis of food processes. Chapter 8 is intended to redress this imbalance, and the treatment of mass transfer is extended in Chapter 9, where the principles of psychrometry are explained.

The principal preservation operations are covered in Chapters 10, 11 and 12. These include the commercial sterilisation of foods, where the bases of the general and mathematical models are outlined and emphasis is given to a clear explanation of calculation procedures; low-temperature preservation, including coverage of the principles of the refrigeration cycle; evaporation and drying. The processing of food particulates is often overlooked and Chapter 13 is an attempt to address this oversight. It considers the characterisation of individual particles and the development of relationships for particle – fluid interaction, and fluidisation is included at this point because it is a fundamental processing technique with wide application to many unit operations. Finally, Chapter 14 covers mixing and physical separation processes, including the increasingly important area of separation using ultrafiltration and reverse osmosis.

Preface to the Second Edition

In this second edition two chapters have been added. Chapter 15 covers some of the mass transfer operations used in the food industry but which are not always considered to be core food processes: distillation (including both batch and continuous operation), leaching (or solid–liquid extraction) and supercritical fluid extraction, a process of increasing importance in the food industry. In the case of distillation and leaching the outline of the relevant theory is supported by detailed worked examples to illustrate the common graphical methods which are used to determine the number of ideal or equilibrium stages.

The growing demand for safer food of ever higher quality has led to the investigation of a range of techniques which may together be labelled as minimum processing technologies. The principles of some of these techniques are outlined in Chapter 16, including ohmic heating, pulsed electric field heating (PEF), radio frequency heating (RF), high-pressure processing, irradiation and ultrasound.

The content of a number of other chapters has been updated or amended. Methods of temperature measurement, especially the details of various types of thermocouples in use, have been included in Chapter 7. A new section on the application of mass transfer to food packaging has been added to Chapter 8; data on the permeability of packaging films are presented. The coverage of freeze drying (Chapter 12) has been extended considerably to include the use of heat and mass transfer models in the prediction of drying time. The section on fluidisation in Chapter 13 has been rewritten to include more information on the estimation of heat and mass transfer coefficients in fluidised beds used in food processes.

In addition to these changes, the opportunity has been taken to review all the worked examples and problems in the book and to correct a number of errors in the first edition. The reading lists at the end of each chapter have been updated where appropriate.

Lincoln, UK
June 2010

P.G. Smith

Contents

1	An Introduction to Food Process Engineering	1
2	Dimensions, Quantities and Units	5
2.1	Dimensions and Units	5
2.2	Definitions of Some Basic Physical Quantities	7
2.2.1	Velocity and Speed	7
2.2.2	Acceleration	7
2.2.3	Force and Momentum	8
2.2.4	Weight	8
2.2.5	Pressure	9
2.2.6	Work and Energy	10
2.2.7	Power	11
2.3	Dimensional Analysis	11
2.3.1	Dimensional Consistency	11
2.3.2	Dimensional Analysis	13
3	Thermodynamics and Equilibrium	15
3.1	Introduction	16
3.1.1	Temperature and the Zeroth Law of Thermodynamics	16
3.1.2	Temperature Scale	17
3.1.3	Heat, Work and Enthalpy	17
3.1.4	Other Definitions	18
3.2	The Gaseous Phase	18
3.2.1	Kinetic Theory of Gases	19
3.2.2	Perfect Gases	19
3.2.3	Pure Component Vapour Pressure	23
3.2.4	Partial Pressure and Pure Component Volume	24
3.3	The Liquid-Vapour Transition	27
3.3.1	Vaporisation and Condensation	27
3.3.2	Isotherms and Critical Temperature	28
3.3.3	Definition of Gas and Vapour	29
3.3.4	Vapour-Liquid Equilibrium	30
3.4	First Law of Thermodynamics	34
3.5	Heat Capacity	36
3.5.1	Heat Capacity at Constant Volume	37
3.5.2	Heat Capacity at Constant Pressure	37
3.5.3	The Relationship Between Heat Capacities for a Perfect Gas	39
3.5.4	The Pressure, Volume, Temperature Relationship for Gases	40

3.6	Second Law of Thermodynamics	41
3.6.1	The Heat Pump and Refrigeration	42
3.6.2	Consequences of the Second Law	43
4	Material and Energy Balances	47
4.1	Process Analysis	48
4.2	Material Balances	48
4.2.1	Overall Material Balances	49
4.2.2	Concentration and Composition	49
4.2.3	Component Material Balances	51
4.2.4	Recycle and Bypass	54
4.3	The Steady-Flow Energy Equation	56
4.4	Thermochemical Data	58
4.4.1	Heat Capacity	59
4.4.2	Latent Heat of Vaporisation	65
4.4.3	Latent Heat of Fusion	65
4.4.4	Steam Tables	65
4.5	Energy Balances	67
5	The Fundamentals of Rate Processes	73
5.1	Introduction	73
5.2	Heat Transfer	74
5.3	Momentum Transfer	75
5.4	Mass Transfer	75
5.5	Transport Properties	76
5.5.1	Thermal Conductivity	76
5.5.2	Viscosity	76
5.5.3	Diffusivity	77
5.6	Similarities Between Heat, Momentum and Mass Transfer	77
6	The Flow of Food Fluids	79
6.1	Introduction	80
6.2	Fundamental Principles	80
6.2.1	Velocity and Flow Rate	80
6.2.2	Reynolds' Experiment	81
6.2.3	Principle of Continuity	84
6.2.4	Conservation of Energy	86
6.3	Laminar Flow in a Pipeline	87
6.4	Turbulent Flow in a Pipeline	90
6.5	Pressure Measurement and Fluid Metering	93
6.5.1	The Manometer	93
6.5.2	The Orifice Meter	94
6.5.3	The Venturi Meter	97
6.6	Pumping of Liquids	99
6.6.1	The Centrifugal Pump	101
6.6.2	Positive Displacement Pumps	103
6.6.3	Net Positive Suction Head	103
6.6.4	Hygienic Design	104
6.7	Non-Newtonian Flow	104
6.7.1	Introduction	104
6.7.2	Stress, Strain and Flow	105

6.8	Time-Independent Rheological Models	107
6.8.1	Hookean Solids	107
6.8.2	Newtonian Fluids	107
6.8.3	Bingham Fluids	108
6.8.4	The Power Law	109
6.8.5	Laminar Flow of Power Law Fluids	112
6.8.6	Other Time-Independent Models	115
6.9	Time-Dependent Rheological Models	116
6.10	Visco-Elasticity	117
6.10.1	Introduction	117
6.10.2	Mechanical Analogues	118
6.11	Rheological Measurements	122
6.11.1	Measurement of Dynamic Viscosity	122
6.11.2	Rheological Measurements for Non-Newtonian Fluids	124
7	Heat Processing of Foods	129
7.1	Introduction	131
7.2	Conduction	131
7.2.1	Steady-State Conduction in a Uniform Slab	131
7.2.2	Conduction in a Composite Slab	134
7.2.3	Radial Conduction	136
7.2.4	Conduction in a Composite Cylinder	138
7.2.5	Conduction Through a Spherical Shell	140
7.3	Convection	140
7.3.1	Film Heat Transfer Coefficient	140
7.3.2	Simultaneous Convection and Conduction	142
7.3.3	Radial Convection	144
7.3.4	Critical Thickness of Insulation	146
7.3.5	Correlations for Film Heat Transfer Coefficients	146
7.3.6	Overall Heat Transfer Coefficient	149
7.4	Heat Exchangers	152
7.4.1	Types of Industrial Heat Exchanger	152
7.4.2	Sizing of Heat Exchangers	154
7.5	Boiling and Condensation	164
7.5.1	Boiling Heat Transfer	164
7.5.2	Condensation	168
7.6	Heat Transfer to Non-Newtonian Fluids	169
7.7	Principles of Radiation	172
7.7.1	Absorption, Reflection and Transmission	173
7.7.2	Black Body Radiation	174
7.7.3	Emissivity and Real Surfaces	175
7.7.4	Radiative Heat Transfer	177
7.7.5	View Factors	178
7.8	Microwave Heating of Foods	180
7.8.1	Microwaves	180
7.8.2	Generation of Microwaves	181
7.8.3	Energy Conversion and Heating Rate	181
7.8.4	Microwave Ovens and Industrial Plant	183
7.8.5	Advantages and Applications of Microwave Heating	184
7.9	Temperature Measurement	185

7.9.1	Principles of Temperature Measurement	185
7.9.2	Expansion Thermometers	185
7.9.3	Electrical Methods	186
7.9.4	Radiation Pyrometry	188
8	Mass Transfer	193
8.1	Introduction	194
8.2	Molecular Diffusion	195
8.2.1	Fick's Law	195
8.2.2	Diffusivity	196
8.2.3	Concentration	197
8.3	Convective Mass Transfer	198
8.3.1	Whitman's Theory	198
8.3.2	Film Mass Transfer Coefficients	199
8.3.3	Overall Mass Transfer Coefficients	201
8.3.4	Addition of Film Mass Transfer Coefficients	202
8.3.5	Resistances to Mass Transfer in Food Processing	204
8.3.6	Effect of Solubility on Mass Transfer Coefficients	204
8.3.7	Alternative Units for Mass Transfer Coefficients	205
8.3.8	Units of Henry's Constant	208
8.4	Binary Diffusion	208
8.4.1	General Diffusion Equation	208
8.4.2	Other Forms of the General Diffusion Equation	209
8.4.3	Diffusion Through a Stagnant Gas Film	210
8.4.4	Particles, Droplets and Bubbles	212
8.5	Correlations for Mass Transfer Coefficients	216
8.6	Mass Transfer and Food Packaging	218
9	Psychrometry	221
9.1	Introduction	221
9.2	Definitions of Some Basic Quantities	222
9.2.1	Absolute Humidity	222
9.2.2	Saturated Humidity	223
9.2.3	Percentage Saturation	223
9.2.4	Relative Humidity	223
9.2.5	Relationship Between Percentage Saturation and Relative Humidity	224
9.2.6	Humid Heat	224
9.2.7	Humid Volume	225
9.2.8	Dew Point	225
9.3	Wet Bulb and Dry Bulb Temperatures	225
9.3.1	Definitions	225
9.3.2	The Wet Bulb Equation	226
9.3.3	Adiabatic Saturation Temperature	227
9.3.4	Relationship Between Wet Bulb Temperature and Adiabatic Saturation Temperature	227
9.4	The Psychrometric Chart	228
9.4.1	Principles	228
9.4.2	Mixing of Humid Air Streams	231
9.5	Application of Psychrometry to Drying	232
10	Thermal Processing of Foods	235

10.1	Unsteady-State Heat Transfer	236
10.1.1	Introduction	236
10.1.2	The Biot Number	236
10.1.3	Lumped Analysis	237
10.2	Unsteady-State Conduction	240
10.2.1	Fourier's First Law of Conduction	240
10.2.2	Conduction in a Flat Plate	240
10.2.3	The Fourier Number	242
10.2.4	Gurney–Lurie Charts	242
10.2.5	Heisler Charts	248
10.3	Food Preservation Techniques Using Heat	249
10.3.1	Introduction to Thermal Processing	249
10.3.2	Pasteurisation	250
10.3.3	Commercial Sterilisation	250
10.4	Kinetics of Microbial Death	251
10.4.1	Decimal Reduction Time and Thermal Resistance Constant	251
10.4.2	Process Lethality	253
10.4.3	Spoilage Probability	255
10.5	The General Method	256
10.6	The Mathematical Method	259
10.6.1	Introduction	259
10.6.2	The Procedure to Find Total Process Time	260
10.6.3	Heat Transfer in Thermal Processing	263
10.6.4	Integrated F Value	265
10.7	Retorts for Thermal Processing	268
10.7.1	The Batch Retort	268
10.7.2	Design Variations	268
10.7.3	Continuous Retorts	269
10.8	Continuous Flow Sterilisation	269
10.8.1	Principles of UHT Processing	269
10.8.2	Process Description	270
11	Low-Temperature Preservation	275
11.1	Principles of Low Temperature Preservation	276
11.2	Freezing Rate and Freezing Point	276
11.3	The Frozen State	279
11.3.1	Physical Properties of Frozen Food	279
11.3.2	Food Quality During Frozen Storage	281
11.4	Freezing Equipment	282
11.4.1	Plate Freezer	282
11.4.2	Blast Freezer	283
11.4.3	Fluidised Bed Freezer	284
11.4.4	Scraped Surface Freezer	284
11.4.5	Cryogenic and Immersion Freezing	284
11.5	Prediction of Freezing Time	285
11.5.1	Plank's Equation	285
11.5.2	Nagaoka's Equation	289
11.5.3	Stefan's Model	290
11.5.4	Plank's Equation for Brick-Shaped Objects	291
11.6	Thawing	293

11.7	Principles of Vapour Compression Refrigeration	294
11.7.1	Introduction	294
11.7.2	The Refrigerant	294
11.7.3	The Evaporator	295
11.7.4	The Compressor	295
11.7.5	The Condenser	296
11.7.6	The Valve or Nozzle	296
11.7.7	The Refrigeration Cycle	296
12	Evaporation and Drying	299
12.1	Introduction to Evaporation	300
12.2	Equipment for Evaporation	301
12.2.1	Natural Circulation Evaporators	301
12.2.2	Forced Circulation Evaporators	302
12.2.3	Thin Film Evaporators	303
12.3	Sizing of a Single Effect Evaporator	303
12.3.1	Material and Energy Balances	304
12.3.2	Evaporator Efficiency	306
12.3.3	Boiling Point Elevation	308
12.4	Methods of Improving Evaporator Efficiency	309
12.4.1	Vapour Recompression	309
12.4.2	Multiple Effect Evaporation	310
12.4.3	An Example of Multiple Effect Evaporation: The Concentration of Tomato Juice	312
12.5	Sizing of Multiple Effect Evaporators	312
12.6	Drying	316
12.6.1	Introduction	316
12.6.2	Water Activity	317
12.6.3	Effect of Water Activity on Microbial Growth	318
12.6.4	Moisture Content	318
12.6.5	Isotherms and Equilibrium	319
12.7	Batch Drying	320
12.7.1	Rate of Drying	320
12.7.2	Batch Drying Time	321
12.8	Types of Drier	325
12.8.1	Batch and Continuous Operation	325
12.8.2	Direct and Indirect Driers	325
12.8.3	Cross-Circulation and Through-Circulation	326
12.8.4	Tray Drier	326
12.8.5	Tunnel Drier	327
12.8.6	Rotary Drier	328
12.8.7	Fluidised Bed Drier	328
12.8.8	Drum Drier	328
12.8.9	Spray Drier	328
12.9	Freeze-Drying	329
12.9.1	Stages in the Freeze-Drying Process	330
12.9.2	Prediction of Freeze-Drying Time	330

13	Solids Processing and Particle Manufacture	335
13.1	Characterisation of Particulate Solids	336
13.1.1	Particle Size Distribution	336
13.1.2	Mean Particle Size	338
13.1.3	Particle Shape	341
13.1.4	Methods of Determining Particle Size	342
13.1.5	Mass Distributions	343
13.1.6	Other Particle Characteristics	346
13.2	The Motion of a Particle in a Fluid	347
13.2.1	Terminal Falling Velocity	347
13.2.2	Particle Drag Coefficient	350
13.2.3	Effect of Increasing Reynolds Number	351
13.3	Packed Beds: The Behaviour of Particles in Bulk	355
13.4	Fluidisation	358
13.4.1	Introduction	358
13.4.2	Minimum Fluidising Velocity in Aggregative Fluidisation	359
13.4.3	Gas-Solid Fluidised Bed Behaviour	365
13.4.4	Bubbles and Particle Mixing	366
13.4.5	Heat and Mass Transfer in Fluidisation	368
13.4.6	Applications of Fluidisation to Food Processing	371
13.4.7	Spouted Beds	373
13.4.8	Particulate Fluidisation	374
13.5	Two-Phase Flow: Pneumatic Conveying	376
13.5.1	Introduction	376
13.5.2	Mechanisms of Particle Movement	376
13.5.3	Pneumatic Conveying Regimes	376
13.5.4	Pneumatic Conveying Systems	377
13.5.5	Safety Issues	378
13.6	Food Particle Manufacturing Processes	378
13.6.1	Classification of Particle Manufacturing Processes	378
13.6.2	Particle-Particle Bonding	382
13.6.3	Fluidised Bed Granulation	383
13.6.4	Other Particle Agglomeration Methods	385
13.7	Size Reduction	387
13.7.1	Mechanisms and Material Structure	387
13.7.2	Size Reduction Equipment	387
13.7.3	Operating Methods	388
13.7.4	Energy Requirement for Size Reduction	389
14	Mixing and Separation	397
14.1	Mixing	398
14.1.1	Definitions and Scope	398
14.1.2	Mixedness	399
14.1.3	Mixing Index and Mixing Time	400
14.1.4	Mixing of Liquids	405
14.1.5	Power Consumption in Liquid Mixing	408
14.1.6	Correlations for the Density and Viscosity of Mixtures	412
14.1.7	Mixing of Solids	413
14.1.8	Equipment for Solids Mixing	414

14.2	Filtration	415
14.2.1	Introduction	415
14.2.2	Analysis of Cake Filtration	416
14.2.3	Constant Pressure Filtration	417
14.2.4	Filtration Equipment	419
14.2.5	Filter Aids	422
14.3	Membrane Separations	422
14.3.1	Introduction	422
14.3.2	Osmosis and Reverse Osmosis	423
14.3.3	General Membrane Equation	424
14.3.4	Osmotic Pressure	425
14.3.5	Ultrafiltration	426
14.3.6	Membrane Properties and Structure	426
14.3.7	Membrane Configurations	427
14.3.8	Permeate Flux	428
14.3.9	Prediction of Permeate Flux	430
14.3.10	Some Applications of Membrane Technology	434
15	Mass Transfer Operations	437
15.1	Introduction to Distillation	438
15.2	Batch Distillation	438
15.2.1	Linear Equilibrium Relationship	440
15.2.2	Constant Relative Volatility	441
15.3	Ideal Stages and Equilibrium	442
15.4	Continuous Fractionation: The McCabe–Thiele Method	444
15.4.1	Material and Energy Balances	444
15.4.2	Derivation of Operating Lines	446
15.4.3	Minimum Reflux Ratio	450
15.5	Steam Distillation	451
15.6	Leaching	453
15.6.1	Introduction	453
15.6.2	Process Description	454
15.6.3	Types of Equipment	455
15.6.4	Counter-Current Leaching: Representation of Three-Component Systems	456
15.6.5	Procedure to Calculate the Number of Ideal Stages	458
15.7	Supercritical Fluid Extraction	462
15.7.1	Introduction	462
15.7.2	The Supercritical State	462
15.7.3	Process Description	462
15.7.4	Advantages of SCFE	464
15.7.5	Food Applications of SCFE	464
16	Minimal Processing Technology	467
16.1	Introduction	467
16.2	Ohmic Heating	468
16.3	Radio Frequency Heating	470
16.4	Pulsed Electric Field Heating	471
16.5	High-Pressure Processing	473
16.6	Food Irradiation	475
16.7	Ultrasound	477

Appendix A
List of Unit Prefixes; Greek Alphabet 479

Appendix B
Fundamental and derived SI Units; Conversion Factors 481

Appendix C
Derivation of a Dimensionless Correlation for Film Heat Transfer Coefficients 483

Appendix D
Properties of Saturated Water and Water Vapour 487

Appendix E
Derivation of Logarithmic Mean Temperature Difference 489

Appendix F
Derivation of Fourier’s First Law of Conduction 491

Answers to Problems 495

Index 501

Chapter 1

An Introduction to Food Process Engineering

A process may be thought of as a sequence of operations which take place in one or more pieces of equipment, giving rise to a series of physical, chemical or biological changes in the feed material and which results in a useful or desirable product. More traditional definitions of the concept of *process* would not include the term *biological* but, because of the increasing sophistication, technological advance and economic importance of, the food industry, and the rise of the biotechnology industries, it is ever more relevant to do so.

Process engineering is concerned with developing an understanding of these operations and with the prediction and quantifying of the resultant changes to feed materials (such as composition and physical behaviour). This understanding leads in turn to the specification of the dimensions of process equipment and the temperatures, pressures and other conditions required to achieve the necessary output of product. It is a quantitative science in which accuracy and precision, measurement, mathematical reasoning, modelling and prediction are all important. Food process engineering is about the operation of processes in which food is manufactured, modified and packaged. Two major categories of process might be considered; those which ensure food safety, that is the preservation techniques such as freezing or sterilisation, which usually involve the transfer of heat and induce changes to microbiological populations, and those which may be classified as food manufacturing steps. Examples of the latter include the addition of components in mixing, the separation of components in filtration or centrifugation or the formation of particles in spray drying. Classification in this way is rather artificial and by no means conclusive but serves to illustrate the variety of reasons for processing food materials.

Although foods are always liquid or solid in form, many foods are aerated (e.g. ice cream), many processes utilise gases or vapours (e.g. steam as a heat source) and many storage procedures require gases of a particular composition. Thus it is important for the food technologist or the food engineer to understand in detail the properties and behaviour of gases, liquids and solids. In other words the transfer of heat, mass and momentum in fluids and an understanding of the behaviour of solids, especially particulate solids, form the basis of food processing technology. At the heart of process engineering is the concept of the unit operation. Thus the principles which underlie drying, extraction, evaporation, mixing and sterilisation are independent of the material which is being processed. Once understood, these principles can be applied to a wide range of products.

The overall purpose of food process engineering then is to design processes which result in safe food products with specific properties and structure. Foods, of course, have their own particular and peculiar properties: most food liquids are non-Newtonian; structures are often complex and multiphase; non-isotropic properties are common. In addition to this, hygiene is of paramount importance in all manufacturing steps. The correct design of such processes is possible only as a result of the development of mathematical models which incorporate the relevant mechanisms. Thus it is important to understand the chemical, structural and microbiological aspects of food in so far as they contribute