

Contents

About the Authors	v
Foreword	vii
Preface	ix
CHAPTER 1 Introduction	1
1.1 Dimensions	1
1.2 Engineering Units	2
1.2.1 Base Units	2
1.2.2 Derived Units	3
1.2.3 Supplementary Units	4
1.3 System	10
1.4 State of a System	11
1.4.1 Extensive Properties	12
1.4.2 Intensive Properties	13
1.5 Density	13
1.6 Concentration	15
1.7 Moisture Content	17
1.8 Temperature	20
1.9 Pressure	22
1.10 Enthalpy	26
1.11 Equation of State and Perfect Gas Law	26
1.12 Phase Diagram of Water	27
1.13 Conservation of Mass	29
1.13.1 Conservation of Mass for an Open System	30
1.13.2 Conservation of Mass for a Closed System	32
1.14 Material Balances	32
1.15 Thermodynamics	41
1.16 Laws of Thermodynamics	42
1.16.1 First Law of Thermodynamics	42
1.16.2 Second Law of Thermodynamics	42
1.17 Energy	43
1.18 Energy Balance	45
1.19 Energy Balance for a Closed System	45
1.19.1 Heat	45
1.19.2 Work	46
1.20 Energy Balance for an Open System	55
1.20.1 Energy Balance for Steady Flow Systems	56
1.21 A Total Energy Balance	56
1.22 Power	59

1.23	Area	59
	Problems	60
	List of Symbols	62
	Bibliography	63
CHAPTER 2	Fluid Flow in Food Processing.....	65
2.1	Liquid Transport Systems.....	66
2.1.1	Pipes for Processing Plants	67
2.1.2	Types of Pumps	68
2.2	Properties of Liquids	71
2.2.1	Terminology Used in Material Response to Stress	72
2.2.2	Density.....	72
2.2.3	Viscosity.....	73
2.3	Handling Systems for Newtonian Liquids.....	81
2.3.1	The Continuity Equation.....	81
2.3.2	Reynolds Number	84
2.3.3	Entrance Region and Fully Developed Flow.....	88
2.3.4	Velocity Profile in a Liquid Flowing Under Fully Developed Flow Conditions	90
2.3.5	Forces Due to Friction.....	96
2.4	Force Balance on a Fluid Element Flowing in a Pipe—Derivation of Bernoulli Equation.....	100
2.5	Energy Equation for Steady Flow of Fluids	107
2.5.1	Pressure Energy	110
2.5.2	Kinetic Energy	110
2.5.3	Potential Energy.....	112
2.5.4	Frictional Energy Loss.....	112
2.5.5	Power Requirements of a Pump.....	115
2.6	Pump Selection and Performance Evaluation	119
2.6.1	Centrifugal Pumps	119
2.6.2	Head	121
2.6.3	Pump Performance Characteristics	121
2.6.4	Pump Characteristic Diagram	125
2.6.5	Net Positive Suction Head.....	126
2.6.6	Selecting a Pump for a Liquid Transport System	129
2.6.7	Affinity Laws.....	135
2.7	Flow Measurement	136
2.7.1	The Pitot Tube	140
2.7.2	The Orifice Meter	142
2.7.3	The Venturi Meter.....	146
2.7.4	Variable-Area Meters	146
2.7.5	Other Measurement Methods	147

2.8	Measurement of Viscosity.....	148
2.8.1	Capillary Tube Viscometer	148
2.8.2	Rotational Viscometer	150
2.8.3	Influence of Temperature on Viscosity	153
2.9	Flow Characteristics of Non-Newtonian Fluids	155
2.9.1	Properties of Non-Newtonian Fluids	155
2.9.2	Velocity Profile of a Power Law Fluid	161
2.9.3	Volumetric Flow Rate of a Power Law Fluid.....	162
2.9.4	Average Velocity in a Power Law Fluid.....	163
2.9.5	Friction Factor and Generalized Reynolds Number for Power Law Fluids	163
2.9.6	Computation of Pumping Requirement of Non-newtonian Liquids.....	166
2.10	Transport of solid foods	169
2.10.1	Properties of Granular Materials and Powders	170
2.10.2	Flow of Granular Foods.....	175
	Problems	178
	List of Symbols.....	183
	Bibliography	185

CHAPTER 3 Energy and Controls in Food Processes 187

3.1	Generation of Steam	187
3.1.1	Steam Generation Systems.....	188
3.1.2	Thermodynamics of Phase Change	190
3.1.3	Steam Tables.....	194
3.1.4	Steam Utilization	200
3.2	Fuel Utilization	204
3.2.1	Systems	206
3.2.2	Mass and Energy Balance Analysis.....	207
3.2.3	Burner Efficiencies	209
3.3	Electric Power Utilization	210
3.3.1	Electrical Terms and Units	212
3.3.2	Ohm's Law	213
3.3.3	Electric Circuits	214
3.3.4	Electric Motors	216
3.3.5	Electrical Controls.....	217
3.3.6	Electric Lighting	218
3.4	Process Controls in Food Processing.....	220
3.4.1	Processing Variables and Performance Indicators.....	222
3.4.2	Input and Output Signals to Control Processes.....	224
3.4.3	Design of a Control System.....	224
3.5	Sensors.....	232

3.5.1	Temperature	232
3.5.2	Liquid Level in a Tank.....	234
3.5.3	Pressure Sensors.....	235
3.5.4	Flow Sensors.....	236
3.5.5	Glossary of Terms Important in Data Acquisition	237
3.6	Dynamic Response Characteristics of Sensors	237
	Problems	241
	List of Symbols	244
	Bibliography	245
CHAPTER 4	Heat Transfer in Food Processing.....	247
4.1	Systems for Heating and Cooling Food Products.....	248
4.1.1	Plate Heat Exchanger.....	248
4.1.2	Tubular Heat Exchanger.....	252
4.1.3	Scraped-surface Heat Exchanger.....	253
4.1.4	Steam-infusion Heat Exchanger.....	255
4.1.5	Epilogue.....	256
4.2	Thermal Properties of Foods.....	257
4.2.1	Specific Heat.....	257
4.2.2	Thermal Conductivity.....	260
4.2.3	Thermal Diffusivity.....	262
4.3	Modes of Heat Transfer	264
4.3.1	Conductive Heat Transfer.....	264
4.3.2	Convective Heat Transfer.....	267
4.3.3	Radiation Heat Transfer.....	269
4.4	Steady-State Heat Transfer.....	270
4.4.1	Conductive Heat Transfer in a Rectangular Slab.....	271
4.4.2	Conductive Heat Transfer through a Tubular Pipe	274
4.4.3	Heat Conduction in Multilayered Systems.....	277
4.4.4	Estimation of Convective Heat-Transfer Coefficient.....	285
4.4.5	Estimation of Overall Heat-Transfer Coefficient.....	302
4.4.6	Fouling of Heat Transfer Surfaces	306
4.4.7	Design of a Tubular Heat Exchanger	312
4.4.8	The Effectiveness-NTU Method for Designing Heat Exchangers.....	320
4.4.9	Design of a Plate Heat Exchanger	325
4.4.10	Importance of Surface Characteristics in Radiative Heat Transfer	332
4.4.11	Radiative Heat Transfer between Two Objects	334
4.5	Unsteady-State Heat Transfer.....	337
4.5.1	Importance of External versus Internal Resistance to Heat Transfer.....	339

4.5.2 Negligible Internal Resistance to Heat Transfer ($N_{Bi} < 0.1$)—A Lumped System Analysis	340
4.5.3 Finite Internal and Surface Resistance to Heat Transfer ($0.1 < N_{Bi} < 40$)	345
4.5.4 Negligible Surface Resistance to Heat Transfer ($N_{Bi} > 40$)	348
4.5.5 Finite Objects.....	348
4.5.6 Procedures to Use Temperature–Time Charts.....	350
4.5.7 Use of f_h and j Factors in Predicting Temperature in Transient Heat Transfer	358
4.6 Electrical Conductivity of Foods.....	366
4.7 Ohmic Heating	369
4.8 Microwave Heating.....	371
4.8.1 Mechanisms of Microwave Heating.....	372
4.8.2 Dielectric Properties	373
4.8.3 Conversion of Microwave Energy into Heat	374
4.8.4 Penetration Depth of Microwaves	375
4.8.5 Microwave Oven	377
4.8.6 Microwave Heating of Foods	378
Problems	380
List of Symbols.....	397
Bibliography	399
CHAPTER 5 Preservation Processes	403
5.1 Processing Systems.....	403
5.1.1 Pasteurization and Blanching Systems.....	404
5.1.2 Commercial Sterilization Systems.....	406
5.1.3 Ultra-High Pressure Systems.....	410
5.1.4 Pulsed Electric Field Systems	412
5.1.5 Alternative Preservation Systems	413
5.2 Microbial Survivor Curves.....	413
5.3 Influence of External Agents	418
5.4 Thermal Death Time F	422
5.5 Spoilage Probability	423
5.6 General Method for Process Calculation	424
5.6.1 Applications to Pasteurization.....	426
5.6.2 Commercial Sterilization	429
5.6.3 Aseptic Processing and Packaging	432
5.7 Mathematical Methods	440
5.7.1 Pouch Processing.....	444
Problems	447
List of Symbols	450
Bibliography	451

CHAPTER 6 Refrigeration	455
6.1 Selection of a Refrigerant.....	456
6.2 Components of a Refrigeration System.....	460
6.2.1 Evaporator	461
6.2.2 Compressor	463
6.2.3 Condenser	466
6.2.4 Expansion Valve.....	468
6.3 Pressure–Enthalpy Charts	470
6.3.1 Pressure–Enthalpy Tables	474
6.3.2 Use of Computer-Aided Procedures to Determine Thermodynamic Properties of Refrigerants.....	475
6.4 Mathematical Expressions Useful in Analysis of Vapor-Compression Refrigeration	478
6.4.1 Cooling Load.....	478
6.4.2 Compressor.....	480
6.4.3 Condenser	480
6.4.4 Evaporator	481
6.4.5 Coefficient of Performance.....	481
6.4.6 Refrigerant Flow Rate.....	481
6.5 Use of Multistage Systems.....	490
6.5.1 Flash Gas Removal System	491
Problems	495
List of Symbols.....	498
Bibliography.....	498
CHAPTER 7 Food Freezing	501
7.1 Freezing Systems.....	502
7.1.1 Indirect Contact Systems.....	502
7.1.2 Direct-Contact Systems.....	507
7.2 Frozen-Food Properties	510
7.2.1 Density.....	510
7.2.2 Thermal Conductivity.....	511
7.2.3 Enthalpy	511
7.2.4 Apparent Specific Heat	513
7.2.5 Apparent Thermal Diffusivity.....	513
7.3 Freezing Time.....	514
7.3.1 Plank's Equation	516
7.3.2 Other Freezing-Time Prediction Methods	520
7.3.3 Pham's Method to Predict Freezing Time.....	520
7.3.4 Prediction of Freezing Time of Finite-Shaped Objects	524
7.3.5 Experimental Measurement of Freezing Time.....	528

7.3.6	Factors Influencing Freezing Time	528
7.3.7	Freezing Rate	529
7.3.8	Thawing Time.....	529
7.4	Frozen-Food Storage.....	530
7.4.1	Quality Changes in Foods during Frozen Storage.....	530
	Problems	534
	List of Symbols.....	538
	Bibliography	539
CHAPTER 8	Evaporation	543
8.1	Boiling-Point Elevation.....	545
8.2	Types of Evaporators	547
8.2.1	Batch-Type Pan Evaporator	547
8.2.2	Natural Circulation Evaporators.....	548
8.2.3	Rising-Film Evaporator.....	548
8.2.4	Falling-Film Evaporator.....	549
8.2.5	Rising/Falling-Film Evaporator	550
8.2.6	Forced-Circulation Evaporator.....	551
8.2.7	Agitated Thin-Film Evaporator.....	551
8.3	Design of a Single-Effect Evaporator	554
8.4	Design of a Multiple-Effect Evaporator	559
8.5	Vapor Recompression Systems.....	565
8.5.1	Thermal Recompression	565
8.5.2	Mechanical Vapor Recompression.....	566
	Problems	566
	List of Symbols.....	569
	Bibliography	569
CHAPTER 9	Psychrometrics.....	571
9.1	Properties of Dry Air.....	571
9.1.1	Composition of Air.....	571
9.1.2	Specific Volume of Dry Air	572
9.1.3	Specific Heat of Dry Air	572
9.1.4	Enthalpy of Dry Air.....	572
9.1.5	Dry Bulb Temperature	573
9.2	Properties of Water Vapor	573
9.2.1	Specific Volume of Water Vapor.....	573
9.2.2	Specific Heat of Water Vapor.....	573
9.2.3	Enthalpy of Water Vapor.....	574
9.3	Properties of Air-Vapor Mixtures	574
9.3.1	Gibbs-Dalton Law	574
9.3.2	Dew-Point Temperature.....	574

9.3.3	Humidity Ratio (or Moisture Content)	575
9.3.4	Relative Humidity	576
9.3.5	Humid Heat of an Air–Water Vapor Mixture.....	576
9.3.6	Specific Volume	577
9.3.7	Adiabatic Saturation of Air	577
9.3.8	Wet Bulb Temperature.....	579
9.4	The Psychrometric Chart.....	582
9.4.1.	Construction of the Chart.....	582
9.4.2	Use of Psychrometric Chart to Evaluate Complex Air-conditioning Processes	584
	Problems.....	589
	List of Symbols.....	592
	Bibliography	593
CHAPTER 10	Mass Transfer.....	595
10.1	The Diffusion Process.....	596
10.1.1	Steady-State Diffusion of Gases (and Liquids) through Solids	599
10.1.2	Convective Mass Transfer.....	600
10.1.3	Laminar Flow over a Flat Plate	604
10.1.4	Turbulent Flow Past a Flat Plate.....	608
10.1.5	Laminar Flow in a Pipe.....	608
10.1.6	Turbulent Flow in a Pipe	609
10.1.7	Mass Transfer for Flow over Spherical Objects	609
10.2	Unsteady-State Mass Transfer.....	610
10.2.1	Transient-State Diffusion	611
10.2.2	Diffusion of Gases.....	616
	Problems	613
	List of Symbols	621
	Bibliography	622
CHAPTER 11	Membrane Separation	623
11.1	Electrodialysis Systems.....	625
11.2	Reverse Osmosis Membrane Systems.....	629
11.3	Membrane Performance.....	636
11.4	Ultrafiltration Membrane Systems	637
11.5	Concentration Polarization	633
11.6	Types of Reverse-Osmosis and Ultrafiltration Systems	645
11.6.1	Plate and Frame.....	646
11.6.2	Tubular.....	646
11.6.3	Spiral-Wound	646
11.6.4	Hollow-Fiber	649

Problems	649
List of Symbols	650
Bibliography	651
CHAPTER 12 Dehydration	653
12.1 Basic Drying Processes	653
12.1.1 Water Activity.....	654
12.1.2 Moisture Diffusion.....	657
12.1.3 Drying-Rate Curves.....	658
12.1.4 Heat and Mass Transfer.....	658
12.2 Dehydration systems	660
12.2.1 Tray or Cabinet Dryers	660
12.2.2 Tunnel Dryers	661
12.2.3 Puff-Drying	662
12.2.4 Fluidized-Bed Drying	663
12.2.5 Spray Drying	663
12.2.6 Freeze-Drying.....	664
12.3 Dehydration System Design.....	665
12.3.1 Mass and Energy Balance.....	665
12.3.2 Drying-Time Prediction	670
Problems	680
List of Symbols	685
Bibliography	686
CHAPTER 13 Supplemental Processes.....	689
13.1 Filtration	689
13.1.1 Operating Equations	689
13.1.2 Mechanisms of Filtration	695
13.1.3 Design of a Filtration System.....	696
13.2 Sedimentation	699
13.2.1 Sedimentation Velocities for Low-Concentration Suspensions	699
13.2.2 Sedimentation in High-Concentration Suspensions.....	702
13.3 Centrifugation	705
13.3.1 Basic Equations.....	705
13.3.2 Rate of Separation	705
13.3.3. Liquid-Liquid Separation	707
13.3.4 Particle-Gas Separation	709
13.4 Mixing	709
13.4.1 Agitation Equipment.....	711
13.4.2 Power Requirements of Impellers.....	714

Problems	718
List of Symbols	719
Bibliography	720
CHAPTER 14 Extrusion Processes for Foods.....	721
14.1 Introduction and Background.....	721
14.2 Basic Principles of Extrusion.....	722
14.3 Extrusion Systems.....	729
14.3.1 Cold Extrusion.....	730
14.3.2 Extrusion Cooking	731
14.3.3 Single Screw Extruders	732
14.3.4 Twin-Screw Extruders.....	734
14.4 Extrusion System Design.....	735
14.5 Design of More Complex Systems.....	740
Problems	741
List of Symbols	742
Bibliography.....	742
CHAPTER 15 Packaging Concepts	745
15.1 Introduction.....	745
15.2 Food Protection	746
15.3 Product Containment	747
15.4 Product Communication	748
15.5 Product Convenience	748
15.6 Mass Transfer in Packaging Materials.....	748
15.6.1 Permeability of Packaging Material to "Fixed" Gases	751
15.7 Innovations in Food Packaging.....	754
15.7.1 Passive Packaging.....	755
15.7.2 Active Packaging.....	755
15.7.3 Intelligent Packaging.....	756
15.8 Food Packaging and Product Shelf-life.....	758
15.8.1 Scientific Basis for Evaluating Shelf Life.....	758
15.9 Summary.....	766
Problems	766
List of Symbols	767
Bibliography	768
Appendices.....	771
A.1 SI System of Units and Conversion Factors.....	771
A.1.1 Rules for Using SI Units	771
Table A.1.1. SI Prefixes	771
Table A.1.2 Useful Conversion Factors	774
Table A.1.3: Conversion Factors for Pressure.....	776

A.2	Physical Properties of Foods.....	777
	Table A.2.1: Specific Heat of Foods.....	777
	Table A.2.2: Thermal Conductivity of Selected Food Products	778
	Table A.2.3. Thermal Diffusivity of Some Foodstuffs	780
	Table A.2.4. Viscosity of Liquid Foods.....	781
	Table A.2.5: Properties of Ice as a Function of Temperature	782
	Table A.2.6: Approximate Heat Evolution Rates of Fresh Fruits and Vegetables When Stored at Temperatures Shown	782
	Table A.2.7. Enthalpy of Frozen Foods	784
	Table A.2.8. Composition Values of Selected Foods	785
	Table A.2.9. Coefficients to Estimate Food Properties	786
A.3	Physical Properties of Nonfood Materials	787
	Table A.3.1: Physical Properties of Metals	787
	Table A.3.2: Physical Properties of Nonmetals.....	788
	Table A.3.3. Emissivity of Various Surfaces.....	790
A.4	Physical Properties of Water and Air.....	792
	Table A.4.1: Physical Properties of Water at the Saturation Pressure.....	792
	Table A.4.2. Properties of Saturated Steam.....	793
	Table A.4.3: Properties of Superheated Steam	795
	Table A.4.4: Physical Properties of Dry Air at Atmospheric Pressure	796
A.5	Psychrometric Charts	797
	Figure A.5.1: Psychrometric chart for high temperatures.....	797
	Figure A.5.2. Psychrometric chart for low temperatures.....	798
A.6	Pressure-Enthalpy Data	799
	Figure A.6.1: Pressure–enthalpy diagram for Refrigerant 12.....	799
	Table A.6.1: Properties of Saturated Liquid and Vapor R-12	800
	Figure A.6.2: Pressure–enthalpy diagram of superheated R-12 vapor	803
	Table A.G.2: Properties of Saturated Liquid and Vapor R-717 (Ammonia).....	804
	Figure A.6.3: Pressure-enthalpy diagram of superheated R-717 (ammonia) vapor	807
	Table A.6.3. Properties of Saturated Liquid and Vapor R-134a	808
	Figure A.6.4: Pressure–enthalpy diagram of R-134a	811
	Figure A.6.5: Pressure–enthalpy diagram of R-134a (expanded scale)	812
A.7	Symbols for Use in Drawing Food Engineering Process Equipment.....	813

A.8 Miscellaneous.....	818
Table A.8.1: Numerical Data, and Area/Volume of Objects.....	818
Figure A.8.1: Temperature at geometric center of a sphere (expanded scale)	819
Figure A.8.2: Temperature at the axis of an infinitely long cylinder (expanded scale)	820
Figure A.8.3: Temperature at the midplane of an infinite slab (expanded scale).....	821
A.9 Dimensional Analysis.....	822
Table A.9.1: Dimensions of selected experimental variables	823
Bibliography.....	826
Index	829
Food Science and Technology: International Series.....	839