

Table of Contents

Preface	13
Acknowledgements	15
1 Units and Dimensions	
1.1 Introduction	17
1.2 Fundamental units	18
1.3 Mass [M] (kg)	18
1.3.1 Mass balances	19
1.3.1.1 Example of mass balance	19
1.3.1.2 Mass balances (hourly basis)	20
1.4 Length [L] (m)	22
1.5 Time [T] (s)	22
1.6 Temperature [Θ] (K)	22
1.6.1 Food-processing temperatures	26
1.7 Other fundamental units	27
1.7.1 Electric current (A)	27
1.7.2 Luminous intensity (cd)	27
1.7.3 Amount of substance (mol)	28
1.8 Prefixes in common use	28
1.9 Derived units	28
1.10 Area [L ²] (m ²)	29
1.11 Volume [L ³] (m ³)	31
1.11.1 Surface-area-to-volume ratio	32
1.12 Density [ML ³] (kg m ⁻³)	32
1.12.1 Specific gravity	32
1.13 Velocity [LT ⁻¹] (m s ⁻¹)	33
1.13.1 Angular velocity	34
1.14 Momentum [MLT ⁻¹] (kg m s ⁻¹)	34
1.15 Acceleration [LT ⁻²] (m s ⁻²)	35
1.16 Force [MLT ⁻²] (kg m s ⁻² or N)	36
1.16.1 Centrifugal force	38
1.17 Pressure [ML ⁻¹] (kg m ⁻¹ s ⁻² or N m ⁻²)	38
1.17.1 Vacuum measurement	40
1.17.2 Pressures used in food-processing operations	40

1.18	Work $[\text{ML}^2\text{T}^{-2}]$ ($\text{kg m}^2 \text{s}^{-2}$ or J)	42
1.19	Power $[\text{ML}^2\text{T}^{-3}]$ ($\text{kg m}^2 \text{s}^{-3}$ or W).	43
1.19.1	Pumping power	44
1.20	Energy $[\text{ML}^2\text{T}^{-2}]$ (J)	45
1.21	Summary of the main fundamental and derived units.	45
1.22	Dimensional analysis	45
1.23	Concentration	47
1.24	Symbols	49
1.24.1	Greek symbols.	49
1.24.2	Dimensionless groups.	50
2	Density and Specific Gravity	
2.1	Introduction	51
2.2	Solid density	53
2.3	Bulk density.	55
2.3.1	Relationship between porosity, bulk density and solid density.	57
2.4	Liquid density and specific gravity.	58
2.4.1	Density bottles	59
2.4.2	Hydrometers and hydrometer scales	60
2.4.2.1	Hydrometer scales.	60
2.4.3	Liquid density values	62
2.4.4	Density of milk	64
2.5	Gases and vapours	65
2.6	Density of aerated products: over-run	66
2.7	Symbols	68
2.7.1	Greek symbols	68
3	Properties of Fluids, Hydrostatics and Dynamics	
3.1	Introduction	69
3.2	Hydrostatics	69
3.2.1	Pressure measurement	70
3.2.2	Vacuum measurement	73
3.3	Archimedes' principle.	74
3.4	Factors affecting frictional losses.	74
3.5	Streamline and turbulent flow	75
3.5.1	Further distinctions between streamline and turbulent flow	77
3.5.1.1	Streamline flow	77
3.5.1.2	Turbulent flow	78
3.6	Reynolds number in agitated vessels	78
3.7	The continuity equation	79
3.8	Bernoulli's equation	80
3.9	Pressure drop as a function of shear stress at a pipe wall.	82
3.10	Frictional losses.	82
3.10.1	Frictional losses in straight pipes	82
3.10.2	Frictional losses in other fittings	85
3.10.2	Total system losses.	86
3.11	Relative motion between a fluid and a single particle.	86
3.12	Fluid flow through packed and fluidized beds.	89
3.12.1	Fluidization	92
3.13	Fluid flow measurement	92
3.13.1	Variable-head measurement	92
3.13.1.1	Pitot tube.	94
3.13.2	Variable-area meters	95
3.14	Fluid transportation and pumping	96

3.14.1	Positive-displacement pumps	96
3.14.2	Centrifugal pumps	97
3.14.3	Other characteristics of pumps	99
3.14.4	Flow control	100
3.14.5	Special types of pump	101
3.15	Vacuum operations	102
3.16	Aseptic operations	102
3.17	Average residence time	102
3.18	Distribution of residence times	103
3.19	Continuous stirred tank reactor	105
3.20	Flowability of powders	106
3.21	Symbols	106
3.21.1	Greek symbols	107
3.21.2	Dimensionless groups	107
4	Viscosity	
4.1	Introduction	108
4.2	Ideal solids and liquids	109
4.3	Shear stress and shear rate	109
4.4	Newtonian fluids and dynamic viscosity	110
4.4.1	Temperature effects	112
4.5	Kinematic viscosity	112
4.6	Relative and specific viscosities	113
4.7	Non-Newtonian behaviour	114
4.8	Time-independent fluids	115
4.8.1	Plastic fluids	117
4.9	Time-dependent fluids	117
4.10	The power law equation	119
4.11	Methods for determining viscosity	121
4.11.1	Streamline flow methods	121
4.11.2	Capillary flow viscometers	123
4.11.3	Falling-sphere viscometers	125
4.12	Rotational viscometers	127
4.12.1	Concentric-cylinder viscometers	128
4.12.2	Cone-and-plate viscometers	129
4.12.3	Single-spindle viscometers	129
4.13	Viscometer selection	130
4.14	Viscosity data	130
4.14.1	Milk and milk products	131
4.14.2	Oils and fats	132
4.14.3	Sugar solutions	133
4.14.4	Hydrocolloids	133
4.15	Some sensory aspects	135
4.16	Symbols	135
5	Solid Rheology and Texture	
5.1	Introduction	137
5.2	The perception of texture	137
5.3	Texture assessment by sensory methods	138
5.4	Texture evaluation by instrumental methods	139
5.4.1	Fundamental methods	141
5.4.2	Imitative methods	141
5.4.3	Empirical methods	141
5.4.4	Chemical and microscopic methods	142
5.5	Fundamental properties	143

5.5.1	Young's modulus	145
5.5.2	Shear modulus	147
5.5.3	Poisson's ratio	147
5.5.4	Bulk modulus	148
5.5.5	Relationship between these properties	148
5.6	Viscoelastic behaviour	149
5.6.1	Deformation-time relationships	150
5.6.2	Stress relaxation experiments	150
5.6.3	Weissenberg effect	152
5.6.4	Oscillatory methods	153
5.6.5	Empirical methods	154
5.6.5.1	The Brabender system	154
5.6.5.2	Extensometer or extensograph	155
5.7	Gelation	155
5.8	Model systems	157
5.9	Objective texture measurement: empirical testing	158
5.9.1	Penetrometer	158
5.9.2	Extrusion and extruders	159
5.9.3	General Foods texturometer	161
5.9.4	Instron universal testing machine	161
5.9.5	Other instrumental methods	162
5.10	Size reduction and grinding	162
5.11	Expression	165
5.12	Symbols	165
5.12.1	Greek symbols	166
6	Surface Properties	
6.1	Introduction	167
6.2	Surface tension	169
6.3	Surface activity	171
6.4	Temperature effects	173
6.5	Methods for measuring surface tension	173
6.5.1	Capillary rise	174
6.5.2	Bubble methods	176
6.5.3	Drop-weight techniques	178
6.5.4	Direct measurement of capillary pull	179
6.6	Interfacial tension	180
6.7	Work of adhesion and cohesion	182
6.8	Emulsions	184
6.9	Young's equation (solid-liquid equilibrium)	188
6.10	Detergency	188
6.11	Foaming	191
6.12	Wettability and solubility	194
6.13	Stabilization (dispersion and colour)	195
6.14	Other unit operations	196
6.15	Symbols	198
6.15.1	Greek symbols	199
6.15.2	Dimensionless groups	199
7	Introduction to Thermodynamic and Thermal Properties	
7.1	Introduction	200
7.2	Conservation and conversion of energy	202
7.3	Thermal energy and thermal units	203
7.4	Thermodynamic terms	205
7.4.1	Systems and surroundings	205

7.4.2	Adiabatic and isothermal processes	206
7.4.3	Reversible and irreversible processes	206
7.5	The first law of thermodynamics	207
7.6	Enthalpy	207
7.7	Entropy and the second law of thermodynamics	208
7.8	Diagrammatic representation of thermodynamic changes	210
7.9	The Carnot cycle	211
7.9.1	The reverse Carnot cycle	212
7.10	Heat or energy balances	213
7.11	Energy value of food	214
7.12	Energy conservation in food processing	216
7.13	Symbols	218
7.13.1	Greek symbols	219
8	Sensible and Latent Heat Changes	
8.1	Introduction	220
8.2	Specific heat	220
8.3	Relationship between specific heat and composition	222
8.4	Specific heat of gases and vapours	224
8.5	Determination of specific heats of materials (experimental)	226
8.5.1	Method of mixtures	226
8.5.2	Method of cooling	227
8.5.3	Electrical methods	229
8.6	Latent heat	229
8.7	Behaviour of water in foods during freezing	232
8.8	Latent heat values for foods (fusion)	233
8.9	Enthalpy–composition data	234
8.10	Oils and fats: solid–liquid transitions	237
8.11	Differential thermal analysis and differential scanning calorimetry	240
8.12	Dilatation	243
8.13	Symbols	244
8.13.1	Greek symbols	245
9	Heat Transfer Mechanisms	
9.1	Introduction	246
9.2	Heat transfer by conduction	246
9.3	Steady- and unsteady-state heat transfer	247
9.4	Thermal conductivity	248
9.5	Heat transfer through a composite wall	250
9.6	Thermal conductivity of foods	252
9.6.1	Compositional factors	254
9.6.2	Temperature effects	255
9.6.3	Pressure effects	255
9.7	Determination of thermal conductivity	256
9.8	Thermal diffusivity	257
9.9	Particulate and granular material	258
9.10	Heat transfer by convection (introduction)	258
9.11	Heat film coefficient	259
9.11.1	Evaluation of heat film coefficients	261
9.12	Combination of heat transfer by conduction and convection	262
9.12.1	Overall heat transfer coefficient	263
9.12.2	Limiting resistances	266
9.12.3	Biot number	268
9.12.4	Example of heat exchanger design	268
9.13	Application to heat exchangers	269

9.13.1	Regeneration efficiency	270
9.13.2	Continuous heat exchangers	271
9.14	Direct steam injection	272
9.15	Fouling	274
9.16	Evaporator design	275
9.17	Heat transfer by radiation	277
9.17.1	Characteristics of electromagnetic radiation	277
9.18	Radiation emitted from heated surfaces	279
9.19	Stefan's law	280
9.20	Infrared radiation	282
9.21	Radio-frequency waves	282
9.21.1	Microwave and dielectric heating	282
9.21.2	Absorption of microwave energy	283
9.22	Irradiation	287
9.23	Symbols	290
9.23.1	Greek symbols	290
9.23.2	Dimensionless groups	291
10	Unsteady-state Heat Transfer	
10.1	Introduction	292
10.2	Heat transfer to a well-mixed liquid	292
10.3	Unsteady-state heat transfer by conduction	294
10.4	Heat transfer involving conduction and convection	295
10.5	Thermal processing	301
10.5.1	D and Z values	303
10.7	F_0 evaluation	304
10.7	Commercial sterility and UHT processes	306
10.8	Heat penetration into canned foods (f_h and f_c values)	306
10.9	Freezing and thawing times	309
10.10	Refrigeration methods	312
10.11	Plate freezers	313
10.12	Cold-air freezing	314
10.13	Immersion freezing	315
10.14	Cryogenic freezing	316
10.15	Vacuum cooling and freezing	318
10.16	Chilling	319
10.17	Controlled-atmosphere storage and heat of respiration	320
10.18	Symbols	320
10.18.1	Greek symbols	323
10.18.2	Dimensionless groups	323
11	Properties of Gases and Vapours	
11.1	Introduction	324
11.2	General properties of gases and vapours	324
11.2.1	Distinction between gases and vapours	326
11.3	Properties of saturated vapours	327
11.4	Properties of saturated water vapour (steam tables)	329
11.5	Wet vapours	332
11.6	Superheated vapours	334
11.7	Thermodynamic charts	336
11.8	Diagrammatic representation of some thermodynamic processes	338
11.8.1	Compression	338
11.8.2	Cooling and condensation at a constant pressure	339
11.8.3	Throttling expansion	340
11.8.4	Evaporation at a constant pressure	340

11.9	Vapour compression refrigeration cycle	340
11.10	Introduction to air–water systems	344
11.10.1	Absolute and relative humidity	344
11.10.2	Dew-point temperature	346
11.10.3	Wet-bulb temperature	347
11.10.4	Adiabatic saturation temperature	347
11.11	Humidity charts	349
11.12	Determination of other properties from humidity charts	351
11.13	Example of interpretation of charts	351
11.14	Mixing of air streams	354
11.15	Water in food	355
11.16	Sorption isotherms	357
11.17	Water activity in food	359
11.17.1	Hysteresis	361
11.17.2	Frozen foods	362
11.18	Water activity–moisture relationships	363
11.19	Symbols	364
11.19.1	Subscripts	364
12	Electrical Properties	
12.1	Introduction	366
12.2	Electrical units	366
12.3	Electrical resistance and Ohms' law	368
12.3.1	Electrical conductance	371
12.4	Electrical energy	372
12.5	Magnetic effects associated with an electric current	373
12.6	Measurement of electrical variables	374
12.6.1	Potentiometer	375
12.6.2	Electrical resistance measurement	376
12.7	Resistivity and specific conductance of foods	377
12.8	Electrical sensing elements	380
12.8.1	Thermocouples	380
12.8.2	Resistance thermometers	384
12.8.3	Semiconductors (thermistors)	385
12.8.4	Strain gauge transducer	386
12.8.5	Humidity measurement	387
12.8.6	Other sensors	387
12.9	Process control and automation	387
12.10	Alternating current	389
12.10.1	Introduction	389
12.10.2	Production and characteristics of an alternating EMF	389
12.10.3	Voltage, current and power measurement	391
12.10.4	Electrical heating	392
12.11	AC circuits	392
12.11.1	Inductance	393
12.11.2	Capacitance	394
12.11.3	AC circuits containing resistors, inductors and capacitors	395
12.11.4	Q factor	400
12.11.5	Measurement of capacitance	400
12.12	Dielectric properties	402
12.12.1	Dielectric constant	402
12.12.2	Dielectric loss factor	402
12.13	Dielectric properties of foods	403
12.14	Power factor	407
12.15	Transformer action	408

12.16	Three-phase supply	408
12.17	Electric motors	410
12.18	Symbols	411
12.18.1	Greek symbols	412
12.18.2	Subscripts	412
13	Diffusion and Mass Transfer	
13.1	Introduction	413
13.2	Diffusion	415
13.3	Fick's law	415
13.4	Gaseous diffusion	416
13.4.1	Equimolecular counter-diffusion	416
13.4.2	Diffusion of a gas through a stagnant layer	417
13.4.3	Experimental determination of diffusivity	419
13.5	Diffusivity in liquids	420
13.6	Solid diffusion	421
13.7	Two-film theory	423
13.7.1	Overall mass transfer coefficient	424
13.7.2	Relationship between overall mass transfer coefficients and film coefficients	425
13.7.3	Determination of mass film coefficients	426
13.8	Unsteady-state mass transfer	427
13.9	Simultaneous heat and mass transfer	428
13.9.1	Hot-air drying	428
13.9.2	Spray drying	432
13.9.3	Freeze drying (lyophilization)	434
13.10	Packaging materials	437
13.11	Membrane processes	440
13.12	Symbols	443
13.12.1	Greek symbols	444
13.12.2	Dimensionless groups	444
13.12.3	Subscripts	445
	Bibliography and references	446
	Index	459