

Contents

Nomenclature	xviii
1 Introduction. Technical Applications	1
1.1 The different types of heat transfer	1
1.1.1 Heat conduction	2
1.1.2 Steady, one-dimensional conduction of heat	5
1.1.3 Convective heat transfer. Heat transfer coefficient	10
1.1.4 Determining heat transfer coefficients. Dimensionless numbers	15
1.1.5 Thermal radiation	25
1.1.6 Radiative exchange	27
1.2 Overall heat transfer	31
1.2.1 The overall heat transfer coefficient	31
1.2.2 Multi-layer walls	33
1.2.3 Overall heat transfer through walls with extended surfaces	34
1.2.4 Heating and cooling of thin walled vessels	38
1.3 Heat exchangers	40
1.3.1 Types of heat exchanger and flow configurations	41
1.3.2 General design equations. Dimensionless groups	45
1.3.3 Countercurrent and cocurrent heat exchangers	50
1.3.4 Crossflow heat exchangers	57
1.3.5 Operating characteristics of further flow configurations. Diagrams	64
1.4 The different types of mass transfer	65
1.4.1 Diffusion	67
1.4.1.1 Composition of mixtures	67
1.4.1.2 Diffusive fluxes	68
1.4.1.3 Fick's law	71
1.4.2 Diffusion through a semipermeable plane. Equimolar diffusion	73
1.4.3 Convective mass transfer	77
1.5 Mass transfer theories	81
1.5.1 Film theory	81
1.5.2 Boundary layer theory	85
1.5.3 Penetration and surface renewal theories	87
1.5.4 Application of film theory to evaporative cooling	88

1.6 Overall mass transfer	92
1.7 Mass transfer apparatus	94
1.7.1 Material balances	95
1.7.2 Concentration profiles and heights of mass transfer columns	98
1.8 Exercises	103
2 Heat conduction and mass diffusion	107
2.1 The heat conduction equation	107
2.1.1 Derivation of the differential equation for the temperature field	108
2.1.2 The heat conduction equation for bodies with constant material properties	111
2.1.3 Boundary conditions	113
2.1.4 Temperature dependent material properties	116
2.1.5 Similar temperature fields	117
2.2 Steady-state heat conduction	121
2.2.1 Geometric one-dimensional heat conduction with heat sources	121
2.2.2 Longitudinal heat conduction in a rod	124
2.2.3 The temperature distribution in fins and pins	129
2.2.4 Fin efficiency	133
2.2.5 Geometric multi-dimensional heat flow	136
2.2.5.1 Superposition of heat sources and heat sinks	137
2.2.5.2 Shape factors	141
2.3 Transient heat conduction	142
2.3.1 Solution methods	143
2.3.2 The Laplace transformation	144
2.3.3 The semi-infinite solid	151
2.3.3.1 Heating and cooling with different boundary conditions	151
2.3.3.2 Two semi-infinite bodies in contact with each other	156
2.3.3.3 Periodic temperature variations	158
2.3.4 Cooling or heating of simple bodies in one-dimensional heat flow	161
2.3.4.1 Formulation of the problem	161
2.3.4.2 Separating the variables	163
2.3.4.3 Results for the plate	165
2.3.4.4 Results for the cylinder and the sphere	169
2.3.4.5 Approximation for large times: Restriction to the first term in the series	171
2.3.4.6 A solution for small times	173
2.3.5 Cooling and heating in multi-dimensional heat flow	174
2.3.5.1 Product solutions	175
2.3.5.2 Approximation for small Biot numbers	178
2.3.6 Solidification of geometrically simple bodies	179
2.3.6.1 The solidification of flat layers (Stefan problem)	180
2.3.6.2 The quasi-steady approximation	183
2.3.6.3 Improved approximations	186
2.3.7 Heat sources	187

2.3.7.1	Homogeneous heat sources	188
2.3.7.2	Point and linear heat sources	189
2.4	Numerical solution to heat conduction problems with difference methods	194
2.4.1	The simple, explicit difference method for transient heat conduction problems	195
2.4.1.1	The finite difference equation	195
2.4.1.2	The stability condition	197
2.4.1.3	Heat sources	198
2.4.2	Discretisation of the boundary conditions	199
2.4.3	The implicit difference method from J. Crank and P. Nicolson	205
2.4.4	Noncartesian coordinates. Temperature dependent material properties	208
2.4.4.1	The discretisation of the self-adjoint differential operator	209
2.4.4.2	Constant material properties. Cylindrical coordinates	210
2.4.4.3	Temperature dependent material properties	212
2.4.5	Transient two- and three-dimensional temperature fields	213
2.4.6	Steady-state temperature fields	216
2.4.6.1	A simple finite difference method for plane, steady-state temperature fields	216
2.4.6.2	Consideration of the boundary conditions	219
2.5	Numerical solution to heat conduction problems with the method of Finite elements	224
2.5.1	The finite element method applied to geometrical one-dimensional, steady-state temperature fields	225
2.5.2	The finite element method applied to steady-state plane temperature fields	230
2.5.3	The finite element method applied to transient, geometrical one-dimensional heat conduction problems	236
2.5.4	Extension to transient, geometrical two-dimensional heat conduction problems	241
2.6	Mass diffusion	242
2.6.1	Remarks on quiescent systems	242
2.6.2	Derivation of the differential equation for the concentration field	245
2.6.3	Simplifications	250
2.6.4	Boundary conditions	251
2.6.5	Steady-state mass diffusion with catalytic surface reaction	254
2.6.6	Steady-state mass diffusion with homogeneous chemical reaction	258
2.6.7	Transient mass diffusion	262
2.6.7.1	Transient mass diffusion in a semi-infinite solid	263
2.6.7.2	Transient mass diffusion in bodies of simple geometry with one-dimensional mass flow	264
2.7	Exercises	266

3	Convective heat and mass transfer. Single phase flow	275
3.1	Preliminary remarks: Longitudinal, frictionless flow over a flat plate	275
3.2	The balance equations	280
3.2.1	Reynolds' transport theorem	280
3.2.2	The mass balance	282
3.2.2.1	Pure substances	282
3.2.2.2	Multicomponent mixtures	284
3.2.3	The momentum balance	286
3.2.3.1	The stress tensor	288
3.2.3.2	Cauchy's equation of motion	292
3.2.3.3	The strain tensor	293
3.2.3.4	Constitutive equations for the solution of the momentum equation	295
3.2.3.5	The Navier-Stokes equations	296
3.2.4	The energy balance	297
3.2.4.1	Dissipated energy and entropy	302
3.2.4.2	Constitutive equations for the solution of the energy equation	303
3.2.4.3	Some other formulations of the energy equation	305
3.2.5	Summary	308
3.3	Influence of the Reynolds number on the flow	310
3.4	Simplifications to the Navier-Stokes equations	313
3.4.1	Creeping flows	313
3.4.2	Frictionless flows	314
3.4.3	Boundary layer flows	314
3.5	The boundary layer equations	315
3.5.1	The velocity boundary layer	315
3.5.2	The thermal boundary layer	319
3.5.3	The concentration boundary layer	323
3.5.4	General comments on the solution of boundary layer equations	323
3.6	Influence of turbulence on heat and mass transfer	327
3.6.1	Turbulent flows near solid walls	331
3.7	External forced flow	335
3.7.1	Parallel flow along a flat plate	336
3.7.1.1	Laminar boundary layer	336
3.7.1.2	Turbulent flow	348
3.7.2	The cylinder in crossflow	353
3.7.3	Tube bundles in crossflow	357
3.7.4	Some empirical equations for heat and mass transfer in external forced flow	361
3.8	Internal forced flow	364
3.8.1	Laminar flow in circular tubes	364
3.8.1.1	Hydrodynamic, fully developed, laminar flow	365

3.8.1.2	Thermal, fully developed, laminar flow	367
3.8.1.3	Heat transfer coefficients in thermally fully developed, laminar flow	369
3.8.1.4	The thermal entry flow with fully developed velocity profile	372
3.8.1.5	Thermally and hydrodynamically developing flow	377
3.8.2	Turbulent flow in circular tubes	379
3.8.3	Packed beds	380
3.8.4	Porous bodies	384
3.8.4.1	Fluid flow and momentum balance	384
3.8.4.2	The energy balance	387
3.8.4.3	Heat transfer inside channels	392
3.8.5	Fluidised beds	398
3.8.6	Some empirical equations for heat and mass transfer in flow through channels, packed and fluidised beds	407
3.9	Free flow	411
3.9.1	The momentum equation	413
3.9.2	Heat transfer in laminar flow on a vertical wall	417
3.9.3	Some empirical equations for heat transfer in free flow	421
3.9.4	Mass transfer in free flow	423
3.10	Overlapping of free and forced flow	425
3.11	Compressible flows	426
3.11.1	The temperature field in a compressible flow	426
3.11.2	Calculation of heat transfer	433
3.12	Exercises	437
4	Convective heat and mass transfer. Flows with phase change	443
4.1	Heat transfer in condensation	443
4.1.1	The different types of condensation	444
4.1.2	Nusselt's film condensation theory	446
4.1.3	Deviations from Nusselt's film condensation theory	450
4.1.4	Influence of non-condensable gases	454
4.1.5	Film condensation in a turbulent film	460
4.1.6	Condensation of flowing vapours	464
4.1.7	Dropwise condensation	469
4.1.8	Condensation of vapour mixtures	473
4.1.8.1	The temperature at the phase interface	477
4.1.8.2	The material and energy balance for the vapour	481
4.1.8.3	Calculating the size of a condenser	483
4.1.9	Some empirical equations	484
4.2	Heat transfer in boiling	486
4.2.1	The different types of heat transfer	486
4.2.2	The formation of vapour bubbles	491
4.2.3	Mechanism of heat transfer in natural convection boiling	494

4.2.4	Bubble frequency and departure diameter	498
4.2.5	Boiling in free flow. The Nukijama curve	500
4.2.6	Stability during boiling in free flow	502
4.2.7	Calculation of heat transfer coefficients for boiling in free flow	505
4.2.8	Some empirical equations for heat transfer during nucleate boiling in free flow	509
4.2.9	Two-phase flow	513
4.2.9.1	The different flow patterns	514
4.2.9.2	Flow maps	516
4.2.9.3	Some basic terms and definitions	517
4.2.9.4	Pressure drop in two-phase flow	520
4.2.9.5	The different heat transfer regions in two-phase flow	528
4.2.9.6	Heat transfer in nucleate boiling and convective evaporation	530
4.2.9.7	Critical boiling states	533
4.2.9.8	Some empirical equations for heat transfer in two-phase flow	535
4.2.10	Heat transfer in boiling mixtures	536
4.3	Exercises	542
5	Thermal radiation	545
5.1	Fundamentals. Physical quantities	545
5.1.1	Thermal radiation	546
5.1.2	Emission of radiation	548
5.1.2.1	Emissive power	548
5.1.2.2	Spectral intensity	549
5.1.2.3	Hemispherical spectral emissive power and total intensity	551
5.1.2.4	Diffuse radiators. Lambert's cosine law	555
5.1.3	Irradiation	557
5.1.4	Absorption of radiation	559
5.1.5	Reflection of radiation	564
5.1.6	Radiation in an enclosure. Kirchhoff's law	566
5.2	Radiation from a black body	569
5.2.1	Definition and realisation of a black body	569
5.2.2	The spectral intensity and the spectral emissive power	571
5.2.3	The emissive power and the emission of radiation in a wavelength interval	574
5.3	Radiation properties of real bodies	580
5.3.1	Emissivities	580
5.3.2	The relationships between emissivity, absorptivity and reflectivity. The grey Lambert radiator	582
5.3.2.1	Conclusions from Kirchhoff's law	582
5.3.2.2	Calculation of absorptivities from emissivities	583
5.3.2.3	The grey Lambert radiator	585
5.3.3	Emissivities of real bodies	587

5.3.3.1	Electrical insulators	588
5.3.3.2	Electrical conductors (metals)	590
5.3.4	Transparent bodies	593
5.4	Solar radiation	597
5.4.1	Extraterrestrial solar radiation	598
5.4.2	The attenuation of solar radiation in the earth's atmosphere	600
5.4.2.1	Spectral transmissivity	601
5.4.2.2	Molecular and aerosol scattering	604
5.4.2.3	Absorption	605
5.4.3	Direct solar radiation on the ground	606
5.4.4	Diffuse solar radiation and global radiation	608
5.4.5	Absorptivities for solar radiation	611
5.5	Radiative exchange	612
5.5.1	View factors	613
5.5.2	Radiative exchange between black bodies	619
5.5.3	Radiative exchange between grey Lambert radiators	622
5.5.3.1	The balance equations according to the net-radiation method	623
5.5.3.2	Radiative exchange between a radiation source, a radiation receiver and a reradiating wall	624
5.5.3.3	Radiative exchange in a hollow enclosure with two zones	628
5.5.3.4	The equation system for the radiative exchange between any number of zones	630
5.5.4	Protective radiation shields	633
5.6	Gas radiation	637
5.6.1	Absorption coefficient and optical thickness	638
5.6.2	Absorptivity and emissivity	640
5.6.3	Results for the emissivity	643
5.6.4	Emissivities and mean beam lengths of gas spaces	646
5.6.5	Radiative exchange in a gas filled enclosure	650
5.6.5.1	Black, isothermal boundary walls	650
5.6.5.2	Grey isothermal boundary walls	651
5.6.5.3	Calculation of the radiative exchange in complicated cases	654
5.7	Exercises	655
Appendix A: Supplements		660
A.1	Introduction to tensor notation	660
A.2	Relationship between mean and thermodynamic pressure	662
A.3	Navier-Stokes equations for an incompressible fluid of constant viscosity in cartesian coordinates	663
A.4	Navier-Stokes equations for an incompressible fluid of constant viscosity in cylindrical coordinates	664
A.5	Entropy balance for mixtures	665

A.6	Relationship between partial and specific enthalpy	666
A.7	Calculation of the constants a_n of the Graetz-Nusselt problem (3.245)	667
Appendix B: Property data		669
Appendix C: Solutions to the exercises		683
Literature		701
Index		720