

CONTENTS

| | |
|--|-----------------|
| <i>Preface</i> | <i>page</i> xix |
| <i>Acknowledgments</i> | xxi |
| <i>Study guide</i> | xxiii |
| <i>Nomenclature</i> | xxvii |
| 1 ONE-DIMENSIONAL, STEADY-STATE CONDUCTION • 1 | |
| 1.1 Conduction Heat Transfer | 1 |
| 1.1.1 Introduction | 1 |
| 1.1.2 Thermal Conductivity | 1 |
| <i>Thermal Conductivity of a Gas*</i> (E1) | 5 |
| 1.2 Steady-State 1-D Conduction without Generation | 5 |
| 1.2.1 Introduction | 5 |
| 1.2.2 The Plane Wall | 5 |
| 1.2.3 The Resistance Concept | 9 |
| 1.2.4 Resistance to Radial Conduction through a Cylinder | 10 |
| 1.2.5 Resistance to Radial Conduction through a Sphere | 11 |
| 1.2.6 Other Resistance Formulae | 13 |
| <i>Convection Resistance</i> | 14 |
| <i>Contact Resistance</i> | 14 |
| <i>Radiation Resistance</i> | 16 |
| EXAMPLE 1.2-1: LIQUID OXYGEN DEWAR | 17 |
| 1.3 Steady-State 1-D Conduction with Generation | 24 |
| 1.3.1 Introduction | 24 |
| 1.3.2 Uniform Thermal Energy Generation in a Plane Wall | 24 |
| 1.3.3 Uniform Thermal Energy Generation in Radial Geometries | 29 |
| EXAMPLE 1.3-1: MAGNETIC ABLATION | 31 |
| 1.3.4 Spatially Non-Uniform Generation | 37 |
| EXAMPLE 1.3-2: ABSORPTION IN A LENS | 38 |
| 1.4 Numerical Solutions to Steady-State 1-D Conduction Problems (EES) | 44 |
| 1.4.1 Introduction | 44 |
| 1.4.2 Numerical Solutions in EES | 45 |
| 1.4.3 Temperature-Dependent Thermal Conductivity | 55 |
| 1.4.4 Alternative Rate Models | 60 |
| EXAMPLE 1.4-1: FUEL ELEMENT | 62 |
| 1.5 Numerical Solutions to Steady-State 1-D Conduction Problems using MATLAB | 68 |
| 1.5.1 Introduction | 68 |
| 1.5.2 Numerical Solutions in Matrix Format | 69 |
| 1.5.3 Implementing a Numerical Solution in MATLAB | 71 |

* Section can be found on the website that accompanies this book (www.cambridge.org/nellisandklein)

| | | |
|---|---|-----|
| 1.5.4 | Functions | 77 |
| 1.5.5 | Sparse Matrices | 80 |
| 1.5.6 | Temperature-Dependent Properties | 82 |
| EXAMPLE 1.5-1: THERMAL PROTECTION SYSTEM | | 84 |
| 1.6 | Analytical Solutions for Constant Cross-Section Extended Surfaces | 92 |
| 1.6.1 | Introduction | 92 |
| 1.6.2 | The Extended Surface Approximation | 92 |
| 1.6.3 | Analytical Solution | 95 |
| 1.6.4 | Fin Behavior | 103 |
| 1.6.5 | Fin Efficiency and Resistance | 105 |
| EXAMPLE 1.6-1: SOLDERING TUBES | | 110 |
| 1.6.6 | Finned Surfaces | 113 |
| EXAMPLE 1.6-2: THERMOELECTRIC HEAT SINK | | 117 |
| 1.6.7 | Fin Optimization* (E2) | 122 |
| 1.7 | Analytical Solutions for Advanced Constant Cross-Section Extended Surfaces | 122 |
| 1.7.1 | Introduction | 122 |
| 1.7.2 | Additional Thermal Loads | 122 |
| EXAMPLE 1.7-1: BENT-BEAM ACTUATOR | | 127 |
| 1.7.3 | Moving Extended Surfaces | 133 |
| EXAMPLE 1.7-2: DRAWING A WIRE | | 136 |
| 1.8 | Analytical Solutions for Non-Constant Cross-Section Extended Surfaces | 139 |
| 1.8.1 | Introduction | 139 |
| 1.8.2 | Series Solutions | 139 |
| 1.8.3 | Bessel Functions | 142 |
| 1.8.4 | Rules for Using Bessel Functions | 150 |
| EXAMPLE 1.8-1: PIPE IN A ROOF | | 155 |
| EXAMPLE 1.8-2: MAGNETIC ABLATION WITH BLOOD PERfusion | | 161 |
| 1.9 | Numerical Solution to Extended Surface Problems | 164 |
| 1.9.1 | Introduction | 164 |
| EXAMPLE 1.9-1: TEMPERATURE SENSOR ERROR DUE TO MOUNTING & SELF HEATING | | 165 |
| EXAMPLE 1.9-2: CRYOGENIC CURRENT LEADS | | 171 |
| Problems | | 185 |
| References | | 201 |

2 TWO-DIMENSIONAL, STEADY-STATE CONDUCTION • 202

| | | |
|---|--|-----|
| 2.1 | Shape Factors | 202 |
| EXAMPLE 2.1-1: MAGNETIC ABLATIVE POWER MEASUREMENT | | 205 |
| 2.2 | Separation of Variables Solutions | 207 |
| 2.2.1 | Introduction | 207 |
| 2.2.2 | Separation of Variables | 208 |
| <i>Requirements for using Separation of Variables</i> | | 209 |
| <i>Separate the Variables</i> | | 211 |
| <i>Solve the Eigenproblem</i> | | 212 |
| <i>Solve the Non-homogeneous Problem for each Eigenvalue</i> | | 213 |
| <i>Obtain Solution for each Eigenvalue</i> | | 214 |
| <i>Create the Series Solution and Enforce the Remaining Boundary Conditions</i> | | 215 |
| <i>Summary of Steps</i> | | 222 |

* Section can be found on the website that accompanies this book (www.cambridge.org/nellisandklein)

| | |
|---|-----|
| 2.2.3 Simple Boundary Condition Transformations | 224 |
| EXAMPLE 2.2-1: TEMPERATURE DISTRIBUTION IN A 2-D FIN | 225 |
| EXAMPLE 2.2-2: CONSTRICTION RESISTANCE | 236 |
| 2.3 Advanced Separation of Variables Solutions* (E3) | 242 |
| 2.4 Superposition | 242 |
| 2.4.1 Introduction | 242 |
| 2.4.2 Superposition for 2-D Problems | 245 |
| 2.5 Numerical Solutions to Steady-State 2-D Problems with EES | 250 |
| 2.5.1 Introduction | 250 |
| 2.5.2 Numerical Solutions with EES | 251 |
| 2.6 Numerical Solutions to Steady-State 2-D Problems with MATLAB | 260 |
| 2.6.1 Introduction | 260 |
| 2.6.2 Numerical Solutions with MATLAB | 260 |
| 2.6.3 Numerical Solution by Gauss-Seidel Iteration* (E4) | 268 |
| 2.7 Finite Element Solutions | 269 |
| 2.7.1 Introduction to FEHT* (E5) | 269 |
| 2.7.2 The Galerkin Weighted Residual Method* (E6) | 269 |
| 2.8 Resistance Approximations for Conduction Problems | 269 |
| 2.8.1 Introduction | 269 |
| EXAMPLE 2.8-1: RESISTANCE OF A BRACKET | 270 |
| 2.8.2 Isothermal and Adiabatic Resistance Limits | 272 |
| 2.8.3 Average Area and Average Length Resistance Limits | 275 |
| EXAMPLE 2.8-2: RESISTANCE OF A SQUARE CHANNEL | 276 |
| 2.9 Conduction through Composite Materials | 278 |
| 2.9.1 Effective Thermal Conductivity | 278 |
| EXAMPLE 2.9-1: FIBER OPTIC BUNDLE | 282 |
| Problems | 290 |
| References | 301 |

3 TRANSIENT CONDUCTION • 302

| | |
|--|-----|
| 3.1 Analytical Solutions to 0-D Transient Problems | 302 |
| 3.1.1 Introduction | 302 |
| 3.1.2 The Lumped Capacitance Assumption | 302 |
| 3.1.3 The Lumped Capacitance Problem | 303 |
| 3.1.4 The Lumped Capacitance Time Constant | 304 |
| EXAMPLE 3.1-1: DESIGN OF A CONVEYOR BELT | 307 |
| EXAMPLE 3.1-2: SENSOR IN AN OSCILLATING TEMPERATURE ENVIRONMENT | 310 |
| 3.2 Numerical Solutions to 0-D Transient Problems | 317 |
| 3.2.1 Introduction | 317 |
| 3.2.2 Numerical Integration Techniques | 317 |
| <i>Euler's Method</i> | 318 |
| <i>Heun's Method</i> | 322 |
| <i>Runge-Kutta Fourth Order Method</i> | 326 |
| <i>Fully Implicit Method</i> | 328 |
| <i>Crank-Nicolson Method</i> | 330 |
| <i>Adaptive Step-Size and EES' Integral Command</i> | 332 |
| <i>MATLAB's Ordinary Differential Equation Solvers</i> | 335 |
| EXAMPLE 3.2-1(A): OVEN BRAZING (EES) | 339 |
| EXAMPLE 3.2-1(B): OVEN BRAZING (MATLAB) | 344 |

* Section can be found on the website that accompanies this book (www.cambridge.org/nellisandklein)

| | | |
|--|--|-----|
| 3.3 | Semi-Infinite 1-D Transient Problems | 348 |
| 3.3.1 | Introduction | 348 |
| 3.3.2 | The Diffusive Time Constant | 348 |
| EXAMPLE 3.3-1: TRANSIENT RESPONSE OF A TANK WALL | | 351 |
| 3.3.3 | The Self-Similar Solution | 354 |
| 3.3.4 | Solutions to other Semi-Infinite Problems | 361 |
| EXAMPLE 3.3-2: QUENCHING A COMPOSITE STRUCTURE | | 363 |
| 3.4 | The Laplace Transform | 369 |
| 3.4.1 | Introduction | 369 |
| 3.4.2 | The Laplace Transformation | 370 |
| <i>Laplace Transformations with Tables</i> | | 371 |
| <i>Laplace Transformations with Maple</i> | | 371 |
| 3.4.3 | The Inverse Laplace Transform | 372 |
| <i>Inverse Laplace Transform with Tables and the Method of Partial Fractions</i> | | 373 |
| <i>Inverse Laplace Transformation with Maple</i> | | 376 |
| 3.4.4 | Properties of the Laplace Transformation | 378 |
| 3.4.5 | Solution to Lumped Capacitance Problems | 380 |
| 3.4.6 | Solution to Semi-Infinite Body Problems | 386 |
| EXAMPLE 3.4-1: QUENCHING OF A SUPERCONDUCTOR | | 391 |
| 3.5 | Separation of Variables for Transient Problems | 395 |
| 3.5.1 | Introduction | 395 |
| 3.5.2 | Separation of Variables Solutions for Common Shapes | 396 |
| <i>The Plane Wall</i> | | 396 |
| <i>The Cylinder</i> | | 401 |
| <i>The Sphere</i> | | 403 |
| EXAMPLE 3.5-1: MATERIAL PROCESSING IN A RADIANT OVEN | | 405 |
| 3.5.3 | Separation of Variables Solutions in Cartesian Coordinates | 408 |
| <i>Requirements for using Separation of Variables</i> | | 409 |
| <i>Separate the Variables</i> | | 410 |
| <i>Solve the Eigenproblem</i> | | 411 |
| <i>Solve the Non-homogeneous Problem for each Eigenvalue</i> | | 413 |
| <i>Obtain a Solution for each Eigenvalue</i> | | 414 |
| <i>Create the Series Solution and Enforce the Initial Condition</i> | | 414 |
| <i>Limits of the Separation of Variables Solution</i> | | 417 |
| EXAMPLE 3.5-2: TRANSIENT RESPONSE OF A TANK WALL (REVISITED) | | 420 |
| 3.5.4 | Separation of Variables Solutions in Cylindrical Coordinates* (E7) | 427 |
| 3.5.5 | Non-homogeneous Boundary Conditions* (E8) | 428 |
| 3.6 | Duhamel's Theorem* (E9) | 428 |
| 3.7 | Complex Combination* (E10) | 428 |
| 3.8 | Numerical Solutions to 1-D Transient Problems | 428 |
| 3.8.1 | Introduction | 428 |
| 3.8.2 | Transient Conduction in a Plane Wall | 429 |
| <i>Euler's Method</i> | | 432 |
| <i>Fully Implicit Method</i> | | 438 |
| <i>Heun's Method</i> | | 442 |
| <i>Runge-Kutta 4th Order Method</i> | | 445 |
| <i>Crank-Nicolson Method</i> | | 449 |
| <i>EES' Integral Command</i> | | 452 |
| <i>MATLAB's Ordinary Differential Equation Solvers</i> | | 453 |

* Section can be found on the website that accompanies this book (www.cambridge.org/nellisandklein)

| | |
|---|-----|
| EXAMPLE 3.8-1: TRANSIENT RESPONSE OF A BENT-BEAM ACTUATOR | 457 |
| 3.8.3 Temperature-Dependent Properties | 463 |
| 3.9 Reduction of Multi-Dimensional Transient Problems* (E11) | 468 |
| Problems | 469 |
| References | 482 |
| 4 EXTERNAL FORCED CONVECTION • 483 | |
| 4.1 Introduction to Laminar Boundary Layers | 483 |
| 4.1.1 Introduction | 483 |
| 4.1.2 The Laminar Boundary Layer | 484 |
| <i>A Conceptual Model of the Laminar Boundary Layer</i> | 485 |
| <i>A Conceptual Model of the Friction Coefficient and Heat Transfer Coefficient</i> | 488 |
| <i>The Reynolds Analogy</i> | 492 |
| 4.1.3 Local and Integrated Quantities | 494 |
| 4.2 The Boundary Layer Equations | 495 |
| 4.2.1 Introduction | 495 |
| 4.2.2 The Governing Equations for Viscous Fluid Flow | 495 |
| <i>The Continuity Equation</i> | 495 |
| <i>The Momentum Conservation Equations</i> | 496 |
| <i>The Thermal Energy Conservation Equation</i> | 498 |
| 4.2.3 The Boundary Layer Simplifications | 500 |
| <i>The Continuity Equation</i> | 500 |
| <i>The x-Momentum Equation</i> | 501 |
| <i>The y-Momentum Equation</i> | 502 |
| <i>The Thermal Energy Equation</i> | 503 |
| 4.3 Dimensional Analysis in Convection | 506 |
| 4.3.1 Introduction | 506 |
| 4.3.2 The Dimensionless Boundary Layer Equations | 508 |
| <i>The Dimensionless Continuity Equation</i> | 508 |
| <i>The Dimensionless Momentum Equation in the Boundary Layer</i> | 509 |
| <i>The Dimensionless Thermal Energy Equation in the Boundary Layer</i> | 509 |
| 4.3.3 Correlating the Solutions of the Dimensionless Equations | 511 |
| <i>The Friction and Drag Coefficients</i> | 511 |
| <i>The Nusselt Number</i> | 513 |
| EXAMPLE 4.3-1: SUB-SCALE TESTING OF A CUBE-SHAPED MODULE | 515 |
| 4.3.4 The Reynolds Analogy (revisited) | 520 |
| 4.4 Self-Similar Solution for Laminar Flow over a Flat Plate | 521 |
| 4.4.1 Introduction | 521 |
| 4.4.2 The Blasius Solution | 522 |
| <i>The Problem Statement</i> | 522 |
| <i>The Similarity Variables</i> | 522 |
| <i>The Problem Transformation</i> | 526 |
| <i>Numerical Solution</i> | 530 |
| 4.4.3 The Temperature Solution | 535 |
| <i>The Problem Statement</i> | 535 |
| <i>The Similarity Variables</i> | 536 |
| <i>The Problem Transformation</i> | 536 |
| <i>Numerical Solution</i> | 538 |
| 4.4.4 The Falkner-Skan Transformation* (E12) | 542 |

* Section can be found on the website that accompanies this book (www.cambridge.org/nellisandklein)

| | | |
|------------|--|-----|
| 4.5 | Turbulent Boundary Layer Concepts | 542 |
| 4.5.1 | Introduction | 542 |
| 4.5.2 | A Conceptual Model of the Turbulent Boundary Layer | 543 |
| 4.6 | The Reynolds Averaged Equations | 548 |
| 4.6.1 | Introduction | 548 |
| 4.6.2 | The Averaging Process | 549 |
| | <i>The Reynolds Averaged Continuity Equation</i> | 550 |
| | <i>The Reynolds Averaged Momentum Equation</i> | 551 |
| | <i>The Reynolds Averaged Thermal Energy Equation</i> | 554 |
| 4.7 | The Laws of the Wall | 556 |
| 4.7.1 | Introduction | 556 |
| 4.7.2 | Inner Variables | 557 |
| 4.7.3 | Eddy Diffusivity of Momentum | 560 |
| 4.7.4 | The Mixing Length Model | 561 |
| 4.7.5 | The Universal Velocity Profile | 562 |
| 4.7.6 | Eddy Diffusivity of Momentum Models | 565 |
| 4.7.7 | Wake Region | 566 |
| 4.7.8 | Eddy Diffusivity of Heat Transfer | 567 |
| 4.7.9 | The Thermal Law of the Wall | 568 |
| 4.8 | Integral Solutions | 571 |
| 4.8.1 | Introduction | 571 |
| 4.8.2 | The Integral Form of the Momentum Equation | 571 |
| | <i>Derivation of the Integral Form of the Momentum Equation</i> | 571 |
| | <i>Application of the Integral Form of the Momentum Equation</i> | 575 |
| | EXAMPLE 4.8-1: PLATE WITH TRANSPERSION | 580 |
| 4.8.3 | The Integral Form of the Energy Equation | 584 |
| | <i>Derivation of the Integral Form of the Energy Equation</i> | 584 |
| | <i>Application of the Integral Form of the Energy Equation</i> | 587 |
| 4.8.4 | Integral Solutions for Turbulent Flows | 591 |
| 4.9 | External Flow Correlations | 593 |
| 4.9.1 | Introduction | 593 |
| 4.9.2 | Flow over a Flat Plate | 593 |
| | <i>Friction Coefficient</i> | 593 |
| | <i>Nusselt Number</i> | 598 |
| | EXAMPLE 4.9-1: PARTIALLY SUBMERGED PLATE | 603 |
| | <i>Unheated Starting Length</i> | 606 |
| | <i>Constant Heat Flux</i> | 606 |
| | <i>Flow over a Rough Plate</i> | 607 |
| 4.9.3 | Flow across a Cylinder | 609 |
| | <i>Drag Coefficient</i> | 611 |
| | <i>Nusselt Number</i> | 613 |
| | EXAMPLE 4.9-2: HOT WIRE ANEMOMETER | 615 |
| | <i>Flow across a Bank of Cylinders</i> | 617 |
| | <i>Non-Circular Extrusions</i> | 617 |
| 4.9.4 | Flow past a Sphere | 618 |
| | EXAMPLE 4.9-3: BULLET TEMPERATURE | 620 |
| | Problems | 620 |
| | References | 624 |
| | | 633 |

* Section can be found on the website that accompanies this book (www.cambridge.org/nellisandklein)

| | |
|---|--|
| 5 INTERNAL FORCED CONVECTION • 635 | |
| 5.1 Internal Flow Concepts 635 | |
| 5.1.1 Introduction 635 | |
| 5.1.2 Momentum Considerations 635 | |
| <i>The Mean Velocity</i> 637 | |
| <i>The Laminar Hydrodynamic Entry Length</i> 638 | |
| <i>Turbulent Internal Flow</i> 638 | |
| <i>The Turbulent Hydrodynamic Entry Length</i> 640 | |
| <i>The Friction Factor</i> 641 | |
| 5.1.3 Thermal Considerations 644 | |
| <i>The Mean Temperature</i> 644 | |
| <i>The Heat Transfer Coefficient and Nusselt Number</i> 645 | |
| <i>The Laminar Thermal Entry Length</i> 646 | |
| <i>Turbulent Internal Flow</i> 648 | |
| 5.2 Internal Flow Correlations 649 | |
| 5.2.1 Introduction 649 | |
| 5.2.2 Flow Classification 650 | |
| 5.2.3 The Friction Factor 650 | |
| <i>Laminar Flow</i> 651 | |
| <i>Turbulent Flow</i> 654 | |
| <i>EES' Internal Flow Convection Library</i> 656 | |
| EXAMPLE 5.2-1: FILLING A WATERING TANK 657 | |
| 5.2.4 The Nusselt Number 661 | |
| <i>Laminar Flow</i> 662 | |
| <i>Turbulent Flow</i> 667 | |
| EXAMPLE 5.2-2: DESIGN OF AN AIR HEATER 668 | |
| 5.3 The Energy Balance 671 | |
| 5.3.1 Introduction 671 | |
| 5.3.2 The Energy Balance 671 | |
| 5.3.3 Prescribed Heat Flux 673 | |
| <i>Constant Heat Flux</i> 674 | |
| 5.3.4 Prescribed Wall Temperature 674 | |
| <i>Constant Wall Temperature</i> 674 | |
| 5.3.5 Prescribed External Temperature 675 | |
| EXAMPLE 5.3-1: ENERGY RECOVERY WITH AN ANNULAR JACKET 677 | |
| 5.4 Analytical Solutions for Internal Flows 686 | |
| 5.4.1 Introduction 686 | |
| 5.4.2 The Momentum Equation 686 | |
| <i>Fully Developed Flow between Parallel Plates</i> 687 | |
| <i>The Reynolds Equation* (E13)</i> 689 | |
| <i>Fully Developed Flow in a Circular Tube* (E14)</i> 689 | |
| 5.4.3 The Thermal Energy Equation 689 | |
| <i>Fully Developed Flow through a Round Tube with a Constant Heat Flux</i> 691 | |
| <i>Fully Developed Flow through Parallel Plates with a Constant Heat Flux</i> 695 | |
| 5.5 Numerical Solutions to Internal Flow Problems 697 | |
| 5.5.1 Introduction 697 | |
| 5.5.2 Hydrodynamically Fully Developed Laminar Flow 698 | |
| <i>EES' Integral Command</i> 702 | |

* Section can be found on the website that accompanies this book (www.cambridge.org/nellisandklein)

| | |
|--|-----|
| <i>The Euler Technique</i> | 704 |
| <i>The Crank-Nicolson Technique</i> | 706 |
| <i>MATLAB's Ordinary Differential Equation Solvers</i> | 710 |
| 5.5.3 Hydrodynamically Fully Developed Turbulent Flow | 712 |
| Problems | 723 |
| References | 734 |
| 6 NATURAL CONVECTION • 735 | |
| 6.1 Natural Convection Concepts | 735 |
| 6.1.1 Introduction | 735 |
| 6.1.2 Dimensionless Parameters for Natural Convection | 735 |
| <i>Identification from Physical Reasoning</i> | 736 |
| <i>Identification from the Governing Equations</i> | 739 |
| 6.2 Natural Convection Correlations | 741 |
| 6.2.1 Introduction | 741 |
| 6.2.2 Plate | 741 |
| <i>Heated or Cooled Vertical Plate</i> | 742 |
| <i>Horizontal Heated Upward Facing or Cooled Downward Facing Plate</i> | 744 |
| <i>Horizontal Heated Downward Facing or Cooled Upward Facing Plate</i> | 745 |
| <i>Plate at an Arbitrary Tilt Angle</i> | 747 |
| EXAMPLE 6.2-1: AIRCRAFT FUEL ULLAGE HEATER | 748 |
| 6.2.3 Sphere | 752 |
| EXAMPLE 6.2-2: FRUIT IN A WAREHOUSE | 753 |
| 6.2.4 Cylinder | 757 |
| <i>Horizontal Cylinder</i> | 757 |
| <i>Vertical Cylinder</i> | 758 |
| 6.2.5 Open Cavity | 760 |
| <i>Vertical Parallel Plates</i> | 761 |
| EXAMPLE 6.2-3: HEAT SINK DESIGN | 763 |
| 6.2.6 Enclosures | 766 |
| 6.2.7 Combined Free and Forced Convection | 768 |
| EXAMPLE 6.2-4: SOLAR FLUX METER | 769 |
| 6.3 Self-Similar Solution* (E15) | 772 |
| 6.4 Integral Solution* (E16) | 772 |
| Problems | 773 |
| References | 777 |
| 7 BOILING AND CONDENSATION • 778 | |
| 7.1 Introduction | 778 |
| 7.2 Pool Boiling | 779 |
| 7.2.1 Introduction | 779 |
| 7.2.2 The Boiling Curve | 780 |
| 7.2.3 Pool Boiling Correlations | 784 |
| EXAMPLE 7.2-1: COOLING AN ELECTRONICS MODULE USING NUCLEATE BOILING | 786 |
| 7.3 Flow Boiling | 790 |
| 7.3.1 Introduction | 790 |
| 7.3.2 Flow Boiling Correlations | 791 |
| EXAMPLE 7.3-1: CARBON DIOXIDE EVAPORATING IN A TUBE | 794 |

* Section can be found on the website that accompanies this book (www.cambridge.org/nellisandklein)

| | | |
|-------|--|-----|
| 7.4 | Film Condensation | 798 |
| 7.4.1 | Introduction | 798 |
| 7.4.2 | Solution for Inertia-Free Film Condensation on a Vertical Wall | 799 |
| 7.4.3 | Correlations for Film Condensation | 805 |
| | <i>Vertical Wall</i> | 805 |
| | EXAMPLE 7.4-1: WATER DISTILLATION DEVICE | 807 |
| | <i>Horizontal, Downward Facing Plate</i> | 810 |
| | <i>Horizontal, Upward Facing Plate</i> | 811 |
| | <i>Single Horizontal Cylinder</i> | 811 |
| | <i>Bank of Horizontal Cylinders</i> | 811 |
| | <i>Single Horizontal Finned Tube</i> | 811 |
| 7.5 | Flow Condensation | 812 |
| 7.5.1 | Introduction | 812 |
| 7.5.2 | Flow Condensation Correlations | 813 |
| | Problems | 815 |
| | References | 821 |

8 HEAT EXCHANGERS • 823

| | | |
|-------|---|-----|
| 8.1 | Introduction to Heat Exchangers | 823 |
| 8.1.1 | Introduction | 823 |
| 8.1.2 | Applications of Heat Exchangers | 823 |
| 8.1.3 | Heat Exchanger Classifications and Flow Paths | 824 |
| 8.1.4 | Overall Energy Balances | 828 |
| 8.1.5 | Heat Exchanger Conductance | 831 |
| | <i>Fouling Resistance</i> | 831 |
| | EXAMPLE 8.1-1: CONDUCTANCE OF A CROSS-FLOW HEAT EXCHANGER | 832 |
| 8.1.6 | Compact Heat Exchanger Correlations | 838 |
| | EXAMPLE 8.1-2: CONDUCTANCE OF A CROSS-FLOW HEAT EXCHANGER (REVISITED) | 841 |
| 8.2 | The Log-Mean Temperature Difference Method | 841 |
| 8.2.1 | Introduction | 841 |
| 8.2.2 | <i>LMTD</i> Method for Counter-Flow and Parallel-Flow Heat Exchangers | 842 |
| 8.2.3 | <i>LMTD</i> Method for Shell-and-Tube and Cross-Flow Heat Exchangers | 847 |
| | EXAMPLE 8.2-1: PERFORMANCE OF A CROSS-FLOW HEAT EXCHANGER | 848 |
| 8.3 | The Effectiveness- <i>NTU</i> Method | 851 |
| 8.3.1 | Introduction | 851 |
| 8.3.2 | The Maximum Heat Transfer Rate | 852 |
| 8.3.3 | Heat Exchanger Effectiveness | 853 |
| | EXAMPLE 8.3-1: PERFORMANCE OF A CROSS-FLOW HEAT EXCHANGER (REVISITED) | 858 |
| 8.3.4 | Further Discussion of Heat Exchanger Effectiveness | 861 |
| | <i>Behavior as C_R Approaches Zero</i> | 862 |
| | <i>Behavior as NTU Approaches Zero</i> | 863 |
| | <i>Behavior as NTU Becomes Infinite</i> | 864 |
| | <i>Heat Exchanger Design</i> | 865 |
| 8.4 | Pinch Point Analysis | 867 |
| 8.4.1 | Introduction | 867 |
| 8.4.2 | Pinch Point Analysis for a Single Heat Exchanger | 867 |
| 8.4.3 | Pinch Point Analysis for a Heat Exchanger Network | 872 |
| 8.5 | Heat Exchangers with Phase Change | 876 |

| | | |
|---|---|-----|
| 8.5.1 | Introduction | 876 |
| 8.5.2 | Sub-Heat Exchanger Model for Phase-Change | 876 |
| 8.6 | Numerical Model of Parallel- and Counter-Flow Heat Exchangers | 888 |
| 8.6.1 | Introduction | 888 |
| 8.6.2 | Numerical Integration of Governing Equations | 888 |
| | <i>Parallel-Flow Configuration</i> | 889 |
| | <i>Counter-Flow Configuration*</i> (E17) | 896 |
| 8.6.3 | Discretization into Sub-Heat Exchangers | 897 |
| | <i>Parallel-Flow Configuration</i> | 897 |
| | <i>Counter-Flow Configuration*</i> (E18) | 897 |
| 8.6.4 | Solution with Axial Conduction* (E19) | 902 |
| 8.7 | Axial Conduction in Heat Exchangers | 902 |
| 8.7.1 | Introduction | 903 |
| 8.7.2 | Approximate Models for Axial Conduction | 905 |
| | <i>Approximate Model at Low λ</i> | 907 |
| | <i>Approximate Model at High λ</i> | 907 |
| | <i>Temperature Jump Model</i> | 907 |
| 8.8 | Perforated Plate Heat Exchangers | 909 |
| 8.8.1 | Introduction | 911 |
| 8.8.2 | Modeling Perforated Plate Heat Exchangers | 911 |
| 8.9 | Numerical Modeling of Cross-Flow Heat Exchangers | 913 |
| 8.9.1 | Introduction | 919 |
| 8.9.2 | Finite Difference Solution | 920 |
| | <i>Both Fluids Unmixed with Uniform Properties</i> | 920 |
| | <i>Both Fluids Unmixed with Temperature-Dependent Properties</i> | 927 |
| | <i>One Fluid Mixed, One Fluid Unmixed*</i> (E20) | 936 |
| | <i>Both Fluids Mixed*</i> (E21) | 936 |
| 8.10 | Regenerators | 937 |
| 8.10.1 | Introduction | 937 |
| 8.10.2 | Governing Equations | 939 |
| 8.10.3 | Balanced, Symmetric Flow with No Entrained Fluid Heat Capacity | 942 |
| | <i>Utilization and Number of Transfer Units</i> | 942 |
| | <i>Regenerator Effectiveness</i> | 942 |
| 8.10.4 | Correlations for Regenerator Matrices | 948 |
| | <i>Packed Bed of Spheres</i> | 950 |
| | <i>Screens</i> | 951 |
| | <i>Triangular Passages</i> | 952 |
| EXAMPLE 8.10-1: AN ENERGY RECOVERY WHEEL | | 953 |
| 8.10.5 | Numerical Model of a Regenerator with No Entrained Heat Capacity* (E22) | 962 |
| Problems | | 962 |
| References | | 973 |
| 9 | MASS TRANSFER* (E23) • 974 | |
| Problems | | 974 |
| 10 | RADIATION • 979 | |
| 10.1 | Introduction to Radiation | 979 |
| 10.1.1 | Radiation | 979 |

* Section can be found on the website that accompanies this book (www.cambridge.org/nellisandklein)

| | | |
|--------|--|------|
| 10.1.2 | The Electromagnetic Spectrum | 980 |
| 10.2 | Emission of Radiation by a Blackbody | 981 |
| 10.2.1 | Introduction | 981 |
| 10.2.2 | Blackbody Emission | 982 |
| | <i>Planck's Law</i> | 982 |
| | <i>Blackbody Emission in Specified Wavelength Bands</i> | 985 |
| | EXAMPLE 10.2-1: UV RADIATION FROM THE SUN | 987 |
| 10.3 | Radiation Exchange between Black Surfaces | 989 |
| 10.3.1 | Introduction | 989 |
| 10.3.2 | View Factors | 989 |
| | <i>The Enclosure Rule</i> | 990 |
| | <i>Reciprocity</i> | 991 |
| | <i>Other View Factor Relationships</i> | 992 |
| | <i>The Crossed and Uncrossed String Method</i> | 992 |
| | EXAMPLE 10.3-1: CROSSED AND UNCROSSED STRING METHOD | 993 |
| | <i>View Factor Library</i> | 996 |
| | EXAMPLE 10.3-2: THE VIEW FACTOR LIBRARY | 998 |
| 10.3.3 | Blackbody Radiation Calculations | 1001 |
| | <i>The Space Resistance</i> | 1001 |
| | EXAMPLE 10.3-3: APPROXIMATE TEMPERATURE OF THE EARTH | 1002 |
| | <i>N-Surface Solutions</i> | 1006 |
| | EXAMPLE 10.3-4: HEAT TRANSFER IN A RECTANGULAR ENCLOSURE | 1007 |
| | EXAMPLE 10.3-5: DIFFERENTIAL VIEW FACTORS: RADIATION EXCHANGE BETWEEN PARALLEL PLATES | 1009 |
| 10.4 | Radiation Characteristics of Real Surfaces | 1012 |
| 10.4.1 | Introduction | 1012 |
| 10.4.2 | Emission of Real Materials | 1012 |
| | <i>Intensity</i> | 1012 |
| | <i>Spectral, Directional Emissivity</i> | 1014 |
| | <i>Hemispherical Emissivity</i> | 1014 |
| | <i>Total Hemispherical Emissivity</i> | 1015 |
| | <i>The Diffuse Surface Approximation</i> | 1016 |
| | <i>The Diffuse Gray Surface Approximation</i> | 1016 |
| | <i>The Semi-Gray Surface</i> | 1016 |
| 10.4.3 | Reflectivity, Absorptivity, and Transmittivity | 1018 |
| | <i>Diffuse and Specular Surfaces</i> | 1019 |
| | <i>Hemispherical Reflectivity, Absorptivity, and Transmittivity</i> | 1020 |
| | <i>Kirchoff's Law</i> | 1020 |
| | <i>Total Hemispherical Values</i> | 1022 |
| | <i>The Diffuse Surface Approximation</i> | 1023 |
| | <i>The Diffuse Gray Surface Approximation</i> | 1023 |
| | <i>The Semi-Gray Surface</i> | 1023 |
| | EXAMPLE 10.4-1: ABSORPTIVITY AND EMISSIVITY OF A SOLAR SELECTIVE SURFACE | 1024 |
| 10.5 | Diffuse Gray Surface Radiation Exchange | 1027 |
| 10.5.1 | Introduction | 1027 |
| 10.5.2 | Radiosity | 1028 |
| 10.5.3 | Gray Surface Radiation Calculations | 1029 |
| | EXAMPLE 10.5-1: RADIATION SHIELD | 1032 |
| | EXAMPLE 10.5-2: EFFECT OF OVEN SURFACE PROPERTIES | 1037 |

* Section can be found on the website that accompanies this book (www.cambridge.org/nellisandklein)

| | |
|---|------|
| 10.5.4 The \hat{F} Parameter | 1043 |
| EXAMPLE 10.5-3: RADIATION HEAT TRANSFER BETWEEN PARALLEL PLATES | 1046 |
| 10.5.5 Radiation Exchange for Semi-Gray Surfaces | 1050 |
| EXAMPLE 10.5-4: RADIATION EXCHANGE IN A DUCT WITH SEMI-GRAY SURFACES | 1051 |
| 10.6 Radiation with other Heat Transfer Mechanisms | 1055 |
| 10.6.1 Introduction | 1055 |
| 10.6.2 When Is Radiation Important? | 1055 |
| 10.6.3 Multi-Mode Problems | 1057 |
| 10.7 The Monte Carlo Method | 1058 |
| 10.7.1 Introduction | 1058 |
| 10.7.2 Determination of View Factors with the Monte Carlo Method | 1058 |
| <i>Select a Location on Surface 1</i> | 1060 |
| <i>Select the Direction of the Ray</i> | 1060 |
| <i>Determine whether the Ray from Surface 1 Strikes Surface 2</i> | 1061 |
| 10.7.3 Radiation Heat Transfer Determined by the Monte Carlo Method | 1068 |
| Problems | 1077 |
| References | 1088 |
| Appendices | |
| A.1: <i>Introduction to EES*</i> (E24) | 1089 |
| A.2: <i>Introduction to Maple</i> (E25) | 1089 |
| A.3: <i>Introduction to MATLAB*</i> (E26) | 1089 |
| A.4: <i>Introduction to FEHT*</i> (E27) | 1089 |
| A.5: <i>Introduction to Economics*</i> (E28) | 1090 |
| Index | 1091 |

* Section can be found on the website that accompanies this book (www.cambridge.org/nellisandklein)