

Index

- absorbing media, in radiation heat transfer, 205–210
 - between plane parallel walls, 206 f
 - cold media surrounded by hot walls, 205–206
 - gas radiation, 207–208
 - nonuniform temperatures, 209–210
 - uniform temperature hot medium, 207
- absorptivity, 172, 175–177
 - typical values, 177 t
- accuracy, 5
- adiabatic lines, 34 f , 37 f
- adiabatic wall temperature, 120, 141, 219–220
- analogies, 38–39
- art of engineering, 1–3
- automobile
 - air conditioning, 126
 - drum brake, 104–105
- Biot number, 39, 59–65, 70 f , 95
- black bodies, *see also* nonblack bodies
 - as part of built up wall, 178 f
 - cavity, 173 f
 - definition of, 172
 - electrical analogy, 193 f
 - emissive power, 172, 175, 184
 - fraction of total black body radiation, 174–175
 - heat transfer between, 178–180
 - intensity, 184
 - laboratory, 186–187
 - monochromatic emissive power of, 173–178
 - radiation heat transfer between, 24, 192–194
 - radiative heat transfer coefficient, 25 t
- boundary layers
 - buoyant flow, 142
 - flat plate, 116–117, 119
 - growth in channel inlet, 115
 - high speed in gases, 221
 - laminar, 111–117, 123–124
 - laminar fully developed b.l. thickness, 115
 - laminar momentum b.l. thickness, 116
 - laminar thermal b.l. thickness, 116
- temperature distribution in, 112 f , 118 f
 - turbulent, 117–120, 122–123
 - turbulent effective thermal b.l. thickness, 120
- brace, 37 f
- brick, refractory, 102
- Brinkman number, 135, 137, 220
- bulk enthalpy, 131
- bulk flow model, 129–138
 - bulk enthalpy, 131
 - bulk entropy, 218–219
 - bulk temperature, 132–133
 - bulk temperature variation, streamwise, 135–138
 - bulk velocity, 130
 - dissipation of mechanical energy, 133–135, 219–221
 - energy conservation, 130–133
 - kinetic energy transport, 131–132
 - streamwise bulk temperature variation, 135–138
- bulk temperature, 120, 132–133
 - dissipative heating in journal bearing, 136–137
 - equation for ideal gas, 135–136
 - equation for incompressible liquid, 135
 - solutions for, 137–138
 - streamwise variation, 135–138
 - with significant dissipative heating, 219–221
- bulk velocity, 130
- buoyancy-driven flows, 110–111, 141–143
 - coexisting with forced flow, 127, 143
 - enhanced or impaired heat transfer, 126–128
- buoyant velocity, 142
- capacitance, *see* thermal capacitance
- carbon dioxide
 - air conditioning cycle, 127 f
 - emissivity, 208 f
 - infrared radiation, absorption of, 174–175
 - refrigerants, 125–127
- Carnot efficiency, 11
- casting, *see* sand casting

- Chvorinov's Rule, 86–87
- coefficient of performance, 126
- combined experiments/analysis, 13
- combustion, 154–155
- compressible flow, one-dimensional, 132
- condensation, heat transfer coefficient, 24*t*
- condenser, air-cooled, 29–30
- conduction, *see topical headings*, steady-state
 - conduction, transient conduction
- conduction resistance, 21–22, *see also* thermal resistance
- conduction shape factors, 47–49
- conductivity, *see* thermal conductivity
- configuration factor, 181–188
 - equations for two finite size bodies, 222–223
 - two-dimensional approximations, 188–190
- convection
 - Biot number, 39, 59–60
 - buoyancy-driven flows, 141–143
 - coefficient, *see* heat transfer coefficient
 - defined, 110
 - heat transfer, 23–24, 110–155
 - laminar boundary layer, 111–117
 - mass transfer, 143–146
 - models, 110–155
 - bulk flow energy conservation, 129–138
 - integral energy conservation, 138–139
 - surface renewal, 139–141
 - resistance, 24
 - turbulent boundary layer, 117–120
 - convective mass transfer, 143–146
 - analogy to heat transfer, 145–146
 - coefficient, 144
 - in flowing medium, 144–146
 - convective resistance, 24
 - copying machine, 2–3
 - counterflow heat exchanger, 159, 162
 - critical point temperature, 125
 - crossflow heat exchanger, 12, 163*f*
 - cross-strings method, 189–190
 - cylinder
 - one-dimensional series solutions for, 71–75
 - semi-infinite body solutions, 82, 87–88
 - steady conduction shape factors, 48*t*
 - Darcy friction factor
 - laminar flow, 134–135
 - turbulent flow, 122
 - deflagration, 154
 - diffuse reflection, 197
 - diffusion coefficient, 6, 144
 - diffusive mass flux, 144
 - dissipation
 - bulk temperature with significant dissipation, 219–221
 - in developing laminar flow, 134
 - in fully developed pipe flow, 133–134
 - in journal bearing, 136–137
 - of mechanical energy, 133–135
 - neglecting, 134–135
 - dissipative heating, 136–137
 - Dittus-Boelter equation, 217, 218*f*
 - double skin facade, 190*f*
 - dropwise condensation, 27
 - duct, non-circular, 121, 123
 - Duhamel's theorem, 78
 - Eckert number, 221
 - effectiveness, heat exchanger, 161–162
 - eigenvalue, 71
 - electrical analogy for radiation, 201–202
 - electrical analogy for heat conduction, 21–22
 - electromagnetic radiation, 171
 - emissive power, 172, 183
 - emissivity, 175, 196
 - cases where emissivity and absorptivity are equal, 176
 - energy balance, 8–9
 - fin, 40
 - glass fiber drawing, 45
 - grey body radiation, 199–200
 - heat exchangers, 157–159
 - internal flow, 129–137
 - liquid-vapor interface, 88, 91
 - sand casting, 86
 - unsteady conduction, 67–69
 - energy conservation, 130–133
 - bulk flow, 129–138
 - bulk temperature, 132–133
 - integral, 138–139
 - mechanical energy, dissipation of, 133–135
 - energy equation, 32, 90, 130–136, 145, *see also* heat equation
 - engineering approach in modeling, 4–5
 - art of, 1–3
 - enthalpy
 - bulk, 131
 - function of *s* and *p*, 218
 - function of *T* and *p*, 132
 - thermodynamic fundamental equation, 218
 - entry length, 115, 124
 - error function, 78
 - estimates of magnitude, 22–32
 - graphical estimates, 34
 - evacuated panel, 30*f*
 - external resistance, 61–62
 - extruded cross section, 188*f*, 189*f*
 - filament, light bulb, 103
 - fins, 39–42, 95–98
 - efficiency, 40, 43*f*
 - thermal resistance, 41–42
 - two-dimensional, 39*f*
 - unsteady, scaling of, 95–98
 - upper/lower limits to performance, 42
 - Fick's Law, 144

- First Law of Thermodynamics, 61, 62, 67, *see also*
 energy equation
 flame, laminar, 154–155
 fluidized bed, circulating, 152, 168–169
 flux diffusion depth, 85
 time-mean, 140
 foam, 6, 20, 26, 38, 51, 57, 58*f*, 214
 forced convection, 24, 60, *see also* convection
 Fourier number, 69–70, 95
 freezing, 86–88
 Fourier series, 64, 70–77
 one-dimensional forms, 71, 73–75
 Fourier's Law, 19–20, 112, 144, 217
 fuel rods, *see* nuclear fuel rods
 friction factor, *see* Darcy friction factor
 furnace, 184–185
 fuser roll, copying machines, 3*f*
- gas coolers, 126
 gas radiation, 207–208
 gas turbine blade cooling, 27–28
 glaciers, 80–82
 glass fiber
 cooling, 12
 cross section, 45*f*
 insulation, 28–29
 specific heat capacity of, 58–59
 spinning, 8–9, 166–167
 heat transfer during, 43–47
 glass globes, cooling, 75–77
 initial contact of glass and mold, 83
 Gnielinski correlation for turbulent internal flow, 122
 comparison to old power law correlations, 217, 218*f*
 power law approximations, 119, 123, 146
 governing equations, 13
 nondimensional form, 42–47
 graphical approximations, 13–14, 34–38
 Grashof number, 142
 gray body
 definition of, 176
 electrical analogy for fuel rod surfaces, 202–204
 multiple gray surfaces, 202–204
 one-bounce approximation, 194
 radiation, diffuse, 199–202
 spacecraft heat sink, 203–204
- HCFC-134a, 126
 heat capacity, 157, *see also* specific heat capacity
 heat capacity rate, 157
 heat diffusivity, 78
 heat equation, 70, 92, *see also* energy equation
 heat exchangers, 156–170
 balanced flow, 159
 compact, 157*f*
 counterflow, 156, 159, 159*f*, 162*f*
 crossflow, 12, 156, 163*f*
 defined, 156
- design, 163–167
 cooler with separate tube bundlers, 165*f*
 glass fiber spinning, 166–167
 heat recovery loop, 164*f*
 instability under imbalance, 166, 170
 liquid coupled, 163–164
 nonuniform flow, 165–166
 differential area for heat transfer, 160*f*
 effectiveness, 161–162
 at low NTU, 162
 energy balance, limiting cases, 157–159
 flow arrangement, 156
 functions of, 156
 geometry, 156
 heat capacity, heat capacity rate, 157
 number of transfer units (NTU), 12, 158
 overall heat transfer coefficient, 158, 159
 parallel flow, 156, 159*f*
 performance relationships, 159–163
 plate and frame, 157*f*
 rating, 156
 rotary, 157, 167
 schematic diagram, 157*f*
 shell and tube, 150–151, 156, 157*f*
 single-stream limit ($C_{\text{MIN}}/C_{\text{MAX}} = 0$), 161–162
- heat transfer
 between black bodies, 178–180
 convection, 23–24, 110–155
 during glass fiber spinning, 43–47
 electrical analogy for, 25*f*
 enhanced or impaired, 126–128
 Poiseuille flow, 117
 radiation, 24–26
 rate of, 19
 scraped surface, 139–141
 slug flow, 117
 through windows, 22–23
 total, 72–73
 transient conduction, 56–109
- heat transfer coefficient
 basic concepts for convection, 23, 111–120
 black body radiation, 24–25, 179–180
 boundary layer thickness effect on, 113, 115, 117, 120
 bulk temperature effect on, 124*f*
 channel inlet, 115*f*
 cooling time and, 62–65
 flat plate, 116, 119
 fluid velocity effect on, 113, 116, 119
 internal flow, 115–116, 120–129
 fully developed, 115, 117
 microchannel, 122
 overall heat transfer coefficient, 158, 159
 typical values
 black bodies, 25*t*
 convection, 24*t*
 wall boundary condition effect on, 113–114, 118–119
- hydraulic diameter, 121, 123

- ideal gas, 132, 135–136, 220–221
- incompressible substance model, 57, 132, 135, 219
 - bulk temperature variation for, 135
 - validity of, 135
- integral energy conservation models, 138–139
- integral methods, 14, 67–68, 138–139
- internal energy, 57, 61, 66–68, 130, 172, 219
- internal flow
 - choice of T and p as independent variables, 217–218
 - heat transfer coefficients, 120–129
 - developing flow and axially varying boundary conditions, 123–124
 - enhanced and impaired heat transfer, 128 f
 - flows with varying physical properties, 124–125
 - fully developed, 121–123
 - supercritical flow in tubes, 125–129
 - kinetic energy, 131–134, 221
 - laminar, 121
 - turbulent, 122–123
- internal resistance, 62–64
- irradiance, 199
- isotherms, 34 f , 37 f
- Jakob, Max, 89
- Jakob number, 89
- Jepson surface renewal model, 140
- journal bearing, 136–137
- kinetic energy for internal flow
 - mass-average, 131, 151
 - transport, 131–132
- Kirchhoff's Law, 177
- KISS (Keep it simple, stupid) rule, 7
- laminar boundary layer, *see* boundary layer
- laminar flow
 - boundary layer, 111–117, 141–142
 - dissipation, 134–5, 220
 - flame, 154–155
 - internal, 115–117, 120–122, 123–4, 131, 138, 149
 - modeling, 110
- Laplacian, 93
- lateral conductivity, 30, 31 f
- length scale, 44–47, 79, 90, 92–96
- liquid coupled heat exchanger, 163–164
- liquid sodium, 122
- lower bound, 9–11
- lumped capacity, 56, 61–62, 64–66, 70 f , 97
 - general solution, 61
 - time constant, 61
- Mach number, 221
- mass average, *see* bulk
- mass fraction, 143
- mass transfer, convective, *see* convective mass transfer
- mass transfer coefficient, 144
- maximum/minimum bounds, 9–11
- Maxwell, James C., 38
- mean beam length, 206
- mean temperature, 24–26, 72–73, 178–180
- mechanical energy, dissipation of, 133–135
- microchannel heat transfer, 121–122
- microprocessor chip, 10
- microturbine, 11
- mixtures, 143–144
- modeling techniques, 7–14
 - analogies, 12
 - combined experiments/analysis, 13
 - energy balance, 8–9
 - engineering approach, 4–5
 - governing equations, 13
 - graphical approximations, 13–14
 - integral methods, 14
 - known solutions, simplification to, 13
 - maximum/minimum bounds, 9–11
 - numerical solutions, 14
 - order of magnitude estimates, 7
 - real-world problems, 1–17
 - Second Law of Thermodynamics, 11
- monochromatic properties, 173–178
- natural convection, 24, 141–143
- nonblack bodies, *see also* black bodies
 - diffuse gray body radiation, 199–202
 - multiple gray surfaces, 202–204
 - nondiffuse reflection, 204–205
 - one-bounce, 196–199
 - one-way energy flux, 194
 - radiation heat transfer between, 194–205
- nondimensional equations
 - convective mass transfer, 145–146
 - general rules for, 42–43
 - steady state, 43–47
 - unsteady conduction, 91–98
 - nondiffuse reflection, 204–205
 - nonuniform flow, 165–166
 - nonuniform temperatures, 209–210
 - nuclear fuel rods, 192–194
 - electrical analogy, 193 f , 202 f
 - transport container with nonblack rods, 201–202
- number of transfer units (NTU), 12, 158
- numerical solutions, 14
- Nusselt number, 117, 119–120, 142, 146
 - laminar flow past flat plate, 114, 116
 - laminar fully developed flow, 121
 - natural convection on vertical flat plate, 142
 - slug flow, fully developed, 117
 - turbulent flow past flat plate, 119
 - turbulent internal flow, 122
 - variable property correction, turbulent internal flow, 125

- Ohm's Law, 21
- oil cooler, 166
- one-bounce approximation, 196–199
 - for extruded rectangular object, 198–199
 - for parallel gray surfaces, 197–198
- one-term solutions, 73–75
- one-way energy flux, 181–182, 194
- order of magnitude estimates, 7
- order of magnitude of derivatives, 46–47, 93–94
- packed beds, 148, 152–153
- Péclet number, 46
- pipe, frozen, 101
- photocopiers, 2–3
- Planck, M., 173
- plastic melter, 100
- plate and frame heat exchanger, 157*f*
- Poiseuille flow, heat transfer in, 117
- polyurethane foam, *see* foam
- Prandtl number, 116, 119–120, 123, 128, 145
- property values
 - importance in modeling, 15, 19–20, 57–59
 - simplified approximation to radiation, 177, 178
- pseudocritical temperature, 126
- quenching, 107–109
- radiation
 - electromagnetic, 171
 - intensity of, 182–184
 - natural, 59
 - thermal, 6, 11, 13, 29, 171–172
- radiation energy balance, 11
- radiation heat transfer, 24–26, 171–215
 - absorbing media, 205–210
 - between plane parallel walls, 206*f*
 - cold media surrounded by hot walls, 205–206
 - diffusion limit, 209
 - gas radiation, 207–208
 - nonuniform temperatures, 209–210
 - uniform temperature hot medium, 207
 - between black bodies, 178–180, 192–194
 - between nonblack bodies, 194–205
 - diffuse gray body radiation, 199–202
 - multiple gray surfaces, 202–204
 - nondiffuse reflection, 204–205
 - one-bounce approximation, 196–199
 - configuration factor, 184–191
 - crossed strings, 189
 - equations for two finite size bodies, 222–223
 - limiting case, 190–191
 - numerical approximation, 191
 - two-dimensional approximations, 188–190
 - electrical analogy, 201–202
 - emissive power, 172, 183
 - fraction of black body energy, 174
 - fundamental concepts, 172–173
 - heat transfer coefficient, 24–25, 179–180
 - geometry, 181–184
 - linearized formation, 178–180
 - monochromatic properties, 173–178
 - one-way radiant energy flux, 181–182
 - radiation properties approximation, 177–178
 - radiosity, 199
 - Rankine cycle, 11
 - Rayleigh number, 143
 - reciprocity, 184–188, 197, 200
 - redesign, 14
 - reflection, nondiffuse, 204–205
 - reflooding, 107–109
 - refrigerants, 125–126
 - resistance
 - electrical analogy, 21–22
 - thermal, *see* thermal resistance
 - Reynolds number, 116, 119–120, 128, 142, 145
 - Rosseland equation, 209–210
 - sand casting, 84–88
 - cylindrical, 87–88
 - heat transfer, 84–85
 - planar, 85*f*
 - spherical, 87–88
 - thermal circuit for, 85*f*
 - thermal resistance, 85
 - Schmidt number, 145
 - scraped surface heat transfer, 139–141
 - Second Law of Thermodynamics, 11
 - semi-infinite body solutions, 66–69, 70*f*, 77–91
 - convection resistance, 83–84
 - cylindrical problem, 82
 - heat flux, 79*t*, 140
 - modeling, 83
 - penetration depth, 66–69, 79*t*, 85
 - periodically varying wall temperature, 79–82
 - planar, 79*t*
 - sand casting, 84–88
 - spherical problem, 82
 - step change in environmental temperature with convection resistance, 79*t*, 80, 81*f*, 83–84
 - step change in wall heat flux, 78–80
 - step change in wall temperature, 66–69, 78, 79*t*
 - table of solutions, 79*t*
 - time average, 140
 - two isothermal bodies brought into contact, 79*t*, 82
 - series solutions, *see* Fourier series, transient conduction
 - shape factors, conduction, 47–49
 - shell and tube heat exchanger, 150, 151*f*, 157*f*
 - Sherwood number, 146
 - side wall conduction resistance, 31
 - singular perturbation problem, 98
 - slab
 - one-dimensional series solutions for, 64, 70–76
 - semi-infinite body solutions for, 77–87
 - transient conduction, 66–70

- slug flow, 117, 148
- solar thermal collectors, 185–186
- solid angles, 181
- spacecraft heat sink, 203–204
- space shuttle, 106 and front cover
- species conservation equation, 144
- specific heat capacity, 57–59
 - constant pressure vs. constant volume, 57
 - near critical temperature, 126–129
 - per unit volume, 57–59
 - porous materials, 57–59
- specular reflectors, 204f
- sphere
 - one-dimensional series solutions for, 71–75
 - semi-infinite body solutions, 82, 87–89
 - steady conduction shape factors, 48f
- spherical casting, 87–88
- sputtering, 107–109
- steady-state conduction, 18–54
 - approximate estimates of magnitude, 22–32
 - conduction shape factors, 47–49
 - electrical analogy, 21–22
 - estimation, graphical, 34–35
 - fins, 39–42
 - general steady-state equation, 32–33
 - governing differential equation, nondimensional form, 42–47
 - property values, 19–20
 - shape factors, 47–49
 - two- and three-dimensional steady conduction, 32–38
 - estimation, graphical, 34–35
 - upper limit, 35–39
 - vacuum insulation, 30f
- steel envelope, 30
- Stefan–Boltzmann constant, 24, 173
- supercritical flow in tubes, 125–129
- surface renewal models, 110, 139–141
- swamp coolers, 156
- Teflon, 27
- temperature
 - bulk, 132–133, *see also* bulk temperature
 - changes, propagation of, 66–69
 - critical point, 125
 - mean, 72–73
 - pseudocritical, 126
- temperature response charts, 71–72
- thermal capacitance, 59–70
 - short time scales, 66–68
 - two or more, 66
- thermal circuits, 21–22, 25f, 31f, 32f, 41f, 62–63, 65–66, 85f
 - in radiation, 201–202
- thermal conductivity, 6, 13, 19–20, 21f, 58f
- evacuated powder, 30
- porous materials, 38–39
- test apparatus, 32–37
 - values of, 21f, 58f
- thermal diffusivity, 57, 58f
- thermal effusivity, 78, 140
- thermal energy storage, 57
- thermal expansion coefficient, volumetric, 132, 141
- thermal inertia, 3
- thermal penetration depth, *see* semi-infinite body solutions
- thermal radiation, 6, 11, 13, 29, 171–172, *see also* radiation heat transfer
- thermal resistance, 21–22, 24, 25–26, 59–70, 73, 193
 - conduction, 21–22
 - convection, 83–84
 - electrical analogy, 21–22
 - fin, 41–42
 - internal, 62–63
 - series resistances, 22f
 - short time scales, 66–69
 - radiation, 24–25, 193
 - time dependent, 69, 80, 83, 84, 85
- thermodynamic fundamental equation, 218
- thermodynamics
 - First Law of, 11, 66
 - Second Law of, 11
- three-dimensional steady conduction, 32–38
- time scales, 62–66, 69–70, 94–95
- total heat transfer, 72–73
- transient conduction, 56–109
 - lumped capacity, *see* lumped capacity
 - modeling tactics, 73, 83
 - nondimensionalization and scaling in, 91–98
 - characteristic lengths, 92–94
 - characteristic temperatures, 90–91
 - characteristic times, 62–66, 69–70, 94–95
 - physical properties in unsteady conduction, 57–59
 - scaling of unsteady fin, 95–97
 - semi-infinite body solutions, *see* semi-infinite body solutions
 - series solutions for unsteady conduction, 64, 70–78
 - mean temperature, 72–73
 - one-term solutions, 73–75
 - total heat transfer, 72–73
 - thermal capacitance, 59–70
 - thermal circuit, 62–63, 65–66, 85
 - thermal resistance, 59–70
 - time constant, 62–66
 - unsteady fin, 95–98
 - tube furnace, 184f
 - turbulent boundary layer, *see* boundary layer
 - turbulent internal flow, *see* internal flow
 - two-dimensional steady conduction, 32–38

Index 231

- uncertainty, 5–6
unsteady conduction, *see* transient conduction
upper bound, 9–11
- vacuum insulation, evacuated panel, 30–32,
 41–42
vapor bubble growth, 88–91
- velocity, buoyant, 142
volumetric heat generation, 32, 70, 72, 92,
 103
- wire-heated plate, 10*f*
Zel'dovich number, 155