

Contents

1	Cryogenic Principles and Applications	1
1.1	Temperature Scale	2
1.2	Historical Background	4
1.3	Applications for Cryogenics	7
1.4	Thermodynamic Laws	9
1.4.1	First and Second Laws of Thermodynamics	9
1.4.2	Third Law of Thermodynamics	14
	Further Readings	16
2	Low-Temperature Materials Properties	17
2.1	Heat Capacity	18
2.1.1	Lattice Heat Capacity	19
2.1.2	Electronic Heat Capacity	23
2.1.3	Heat Capacity of Special Materials	24
2.2	Thermal Contraction	26
2.3	Conductivities: Electrical and Thermal	29
2.3.1	Electrical Resistivity of Metals	30
2.3.2	Magneto-Resistance in Metals	32
2.3.3	Electrical Conductivity of Semiconductors	34
2.3.4	Thermal Conductivity of Metals	34
2.3.5	Lattice Thermal Conductivity	37
2.3.6	Contact Resistance	39
2.4	Mechanical Properties	42
2.5	Superconductivity	44
2.5.1	Type I Superconductivity	45
2.5.2	Type II Superconductivity	50
	References	56
	Further Readings	57

3 Helium as a Classical Fluid	59
3.1 Helium Phase Diagram	59
3.2 Gaseous Helium	61
3.2.1 Intermolecular Interactions	62
3.2.2 Virial Expansion	64
3.2.3 Empirical Equations of State	67
3.3 State Properties of Liquid He I	69
3.3.1 Density	70
3.3.2 Thermal Properties	72
3.3.3 Vapor Pressure	74
3.3.4 Surface Tension	75
3.4 Transport Properties of Gaseous and Liquid He I	76
3.4.1 Modeling Transport Properties	77
3.4.2 Transport Properties	79
References	84
Further Readings	84
4 Classical Helium Fluid Mechanics	85
4.1 Single Phase Internal Flow	86
4.1.1 General Considerations	86
4.1.2 One Dimensional Internal Flow	88
4.2 Supercritical Helium	92
4.2.1 Compressible Fluid Mechanics	92
4.2.2 Experimental Confirmation	94
4.3 Helium Two-Phase Flow	97
4.3.1 Flow Regimes and Transitions	97
4.3.2 Pressure Drop Correlations	100
4.3.3 Natural Circulation Loops	103
4.4 Flow Through Porous Media	108
References	113
Further Readings	114
5 Classical Helium Heat Transfer	115
5.1 Regimes of Heat Transfer	117
5.2 Convective Heat Transfer	120
5.3 Nucleate Boiling Heat Transfer	123
5.3.1 Nucleation Theory	124
5.3.2 Heat Transfer Correlations	127
5.3.3 Maximum Nucleate Boiling Heat Flux	130
5.4 Film Boiling	134
5.4.1 Minimum Film Boiling Heat Flux	135
5.4.2 Heat Transfer Correlations	138
5.5 Surface Effects	139
5.6 Channel Heat Transfer	140

5.7	Forced Convection Heat Transfer	146
5.7.1	General Considerations	146
5.7.2	Heat Transfer Correlations.....	147
5.7.3	Two Phase Flow Heat Transfer.....	150
5.8	Transient Heat Transfer.....	151
5.8.1	Surface Temperature Difference.....	154
5.8.2	Transition to Film Boiling	157
	References.....	159
	Further Readings	161
6	Helium as a Quantum Fluid	163
6.1	Ideal Quantum Gases	165
6.1.1	Density of an Ideal Bose Gas.....	168
6.1.2	Internal Energy of an Ideal Bose Gas	170
6.1.3	Specific Heat of an Ideal Bose Gas.....	171
6.1.4	Vapor Pressure of an Ideal Bose Gas.....	172
6.1.5	Latent Heat of an Ideal Bose Gas.....	174
6.2	Liquid He II Properties	175
6.2.1	State Properties of He II	176
6.2.2	Transport Properties of He II	179
6.2.3	Fountain Effect.....	181
6.3	Excitations in He II	183
6.4	Two-Fluid Model	186
6.4.1	Equations of Motion	188
6.4.2	Thermomechanical Effect.....	191
6.4.3	Sound Propagation	193
6.4.4	Viscous Flow.....	197
6.4.5	Heat Transport	200
6.5	Vortices and Turbulence in He II.....	203
6.5.1	Helium II in Rotation	203
6.5.2	Critical Velocities	207
6.5.3	Mutual Friction.....	213
6.5.4	Steady-State Heat Transport	217
6.5.5	Forced Convection Heat Transport	218
6.5.6	Attenuation of Second Sound.....	219
6.5.7	Development of Turbulence	221
6.5.8	Second Sound Shock.....	222
	References.....	225
	Further Readings	226
7	He II Heat and Mass Transfer	227
7.1	Steady-State He II Heat Transport in Wide Channels.....	229
7.1.1	He II Heat Conductivity Function	230
7.1.2	Peak Heat Flux in Wide Channels.....	232
7.1.3	Peak Heat Flux in Saturated He II.....	335

7.1.4	He II Heat Transfer in Cylindrical Geometries.....	239
7.1.5	Static Bath He II Heat Exchangers	241
7.1.6	He II Two Phase Heat Transfer and Flow.....	247
7.2	Transient Heat Transport in Wide Channels	251
7.2.1	He II Diffusion Equation	253
7.2.2	Analytic Solution Methods	255
7.2.3	Numerical Solution of the He II Diffusion Equation.....	258
7.3	Forced Convection Heat Transport in Wide Channels	261
7.3.1	He II Energy Equation	262
7.3.2	Steady State Heat Transport: Analytic Solution.....	263
7.3.3	Pressure Drop in Turbulent He II.....	265
7.3.4	He II Joule Thomson Effect	267
7.3.5	Transient Heat Transport in Forced Flow He II: Numerical Solution	268
7.4	Heat and Mass Transfer in Porous Media	270
7.4.1	Steady Laminar Heat Transport in He II	270
7.4.2	He II Heat and Mass Transfer Through Porous Media.....	273
7.4.3	He II Fountain Pumps.....	275
7.4.4	He II Vapor: Liquid Phase Separators.....	277
7.5	Kapitza Conductance	278
7.5.1	Phonon Radiation Limit	280
7.5.2	Acoustic Mismatch Theory	285
7.5.3	Small Heat Flux Kapitza Conductance ($\Delta T \ll T$).....	289
7.5.4	Large Heat Flux Kapitza Conductance ($\Delta T \approx T$)	292
7.6	Film Boiling Heat Transfer	295
7.6.1	Film Boiling Heat Transfer Experiments.....	296
7.6.2	Theoretical Models for Film Boiling Heat Transfer	301
7.6.3	Transient Film Boiling Heat Transfer	307
	References.....	311
	Further Readings	315
8	Liquefaction and Refrigeration Systems.....	317
8.1	Ideal Liquefaction.....	318
8.2	First Law of Steady Flows.....	323
8.3	Isenthalpic Expansion.....	324
8.3.1	Joule–Thomson Effect	324
8.3.2	Joule–Thomson Coefficient of Real Gases	328
8.3.3	Joule–Thomson Liquefier.....	332
8.3.4	Cascade JT Liquefier.....	337
8.3.5	He II JT Liquefier	338
8.4	Isentropic Expansion.....	342
8.4.1	Claude Liquefier	343
8.4.2	Collins Helium Liquefaction System	349

8.5	Closed–Cycle Refrigeration	350
8.5.1	Isothermal Refrigeration	353
8.5.2	Isobaric Refrigeration	354
8.6	Regenerative Refrigeration Cycles.....	358
8.6.1	Stirling Cycle.....	359
8.6.2	Gifford McMahon Cycle	362
8.6.3	Pulse Tube Cryocoolers	364
8.6.4	Hybrid Helium Liquefiers.....	365
8.7	Nonideal Refrigeration Components	367
8.8	Refrigeration Technology	368
8.9	Summary.....	371
	References.....	375
	Further Readings	375
9	^3He and Refrigeration Below 1 K	377
9.1	Properties of Pure ^3He	378
9.2	^3He – ^4He Mixtures and Dilution Refrigeration.....	380
9.3	Statistical Models for Pure ^3He	383
9.4	Submillikelvin Refrigeration	386
9.5	Superfluid ^3He	388
	References.....	392
	Further Readings	392
10	Special Topics in Helium Cryogenics	393
10.1	Thermal Insulation.....	393
10.1.1	Solid Conduction	394
10.1.2	Gas Conduction.....	395
10.1.3	Radiation Heat Transfer	397
10.1.4	Multilayer Insulation (MLI)	402
10.1.5	Powder Insulations.....	404
10.2	Helium Adsorption	405
10.2.1	Adsorption Thermodynamics.....	406
10.2.2	Physical Properties of Helium Films	412
10.3	Magnetic Refrigeration	414
10.3.1	Paramagnetic Materials.....	415
10.3.2	Thermodynamics of Magnetic Refrigeration.....	420
10.3.3	Continuous Magnetic Refrigerators	424
10.3.4	Nuclear Demagnetization.....	426
	References.....	428
	Further Readings	429
	Appendix 1 Compressibility Factor for Helium.....	431
	Appendix 2 Properties of Liquid Helium	435
	Appendix 3 He II Heat Conductivity Function.....	447

Appendix 4 Temperature-Entropy Diagrams for Helium..... 449

Appendix 5 T-S Diagrams in He II Region..... 451

Appendix 6 Helium T-S Diagrams 455

Index..... 461

About the Author..... 469

Helium Cryogenics

Van Sciver, S.W.

2012, XXIV, 470 p. 220 illus., 9 illus. in color., Hardcover

ISBN: 978-1-4419-9978-8