

Contents

1	Heat Transfer	1
1.1	Introduction	1
1.2	Modes of Heat Transfer	2
1.2.1	Heat Conduction	2
1.2.2	Differential Equation of Heat Conduction and Boundary Conditions	4
1.2.3	Steady State Conduction Heat Transfer in Bodies Without Internal Heat Generation ($w = 0$)	7
1.2.4	Steady State Conduction Heat Transfer in Bodies with Internal Heat Generation ($w \neq 0$)	13
1.2.5	Transient Conduction Heat Transfer in Bodies Without Internal Heat Generation ($w = 0$)	16
1.3	Heat Convection	40
1.3.1	Introduction	40
1.3.2	Average Nusselt Number in Forced Convection Flow Parallel to a Flat Plane of Length ℓ	44
1.3.3	Average Nusselt Number in Forced Convection Flow Normal to the Axis of a Cylinder	45
1.3.4	Average Nusselt Number in Natural Convection from Isothermal Vertical Planes or Horizontal Cylinder	46
1.4	Radiation Heat Transfer	47
1.4.1	Radiation Between Surfaces of Solids Separated by a Non Absorbing Medium	50
	References	54
2	Electromagnetic Fields in Electro-technologies	57
2.1	Basic Equations	57
2.2	Equations for AC Fields	60

2.3	Electromagnetic Wave Diffusion in Conductive Half-Space	62
2.3.1	Electromagnetic Field Distribution	62
2.3.2	Current and Power Distributions	65
2.3.3	Wave Impedance.	67
2.4	Special Electromagnetic Phenomena in Electro-technologies	68
2.4.1	Skin-Effect.	68
2.4.2	Exponential Distributions and Equivalent Surface Active Layer	69
2.4.3	Non-exponential Distributions of Current Density and Heat Sources.	70
2.4.4	Proximity Effect	73
2.4.5	Ring Effect	75
2.4.6	Slot Effect	76
2.4.7	Load and Coil End- and Edge-Effects	77
	References.	81
3	Arc Furnaces	83
3.1	Introduction	83
3.2	EAFs for Steel Production	86
3.2.1	Steel Production Process	86
3.2.2	Installation Description	89
3.2.3	Power Supply System of EAFs	89
3.2.4	High Voltage Installation.	91
3.2.5	Furnace Transformer	94
3.2.6	Secondary High-Current Circuit	98
3.2.7	Electrodes	104
3.2.8	Furnace Vessel	108
3.3	Equivalent Circuits of EAF.	121
3.3.1	Single Phase Equivalent Circuit.	121
3.3.2	Circuit Analysis with Sinusoidal Quantities.	123
3.3.3	Arc Characteristics	137
3.3.4	Single-Phase and Three-Phase Symmetric Circuits with Arc	144
3.3.5	Non-symmetric Three Phase Circuits: Phasor Diagram, “Dead” and “Wild” Phases	152
3.4	Power Control and Energy Balance of EAFs for Steel Production	157
3.4.1	Steel Production Cycle	157
3.4.2	Innovations in Modern Furnaces	161
3.4.3	Selection of Operating Point	166
3.4.4	Power Control Systems	169
3.4.5	Energy Balance of EAFs.	171
3.5	Interference of EAFs on the Supply Network (“Flicker”).	174
3.6	DC Arc Furnaces	181

3.7	Submerged Arc Furnaces	187
3.7.1	Description	187
3.7.2	Technological Processes and Influence on Design of Submerged Arc Furnaces	188
3.7.3	Self Baking Electrodes	197
3.7.4	Energetic Characteristics of Reduction Furnaces	200
	References.	203
4	Resistance Furnaces	207
4.1	Introduction to Resistance Heating	207
4.2	Resistance Furnaces	208
4.3	Types and Classification of Resistance Furnaces	209
4.3.1	Low Temperature Batch Furnaces	210
4.3.2	Medium Temperature Batch Furnaces	212
4.3.3	Continuous Furnaces	213
4.3.4	High Temperature Furnaces.	216
4.3.5	Furnaces with Protective Atmospheres	217
4.3.6	Vacuum Furnaces	219
4.3.7	Special Furnaces	222
4.4	The Heating Chamber.	224
4.4.1	Energy Balance of the Furnace	224
4.4.2	Heating Cycle of an Empty Furnace	225
4.4.3	Refractory, Insulating and Metallic Materials	227
4.4.4	Wall Design	233
4.4.5	Thermal Inertia and Cooling Speed.	238
4.4.6	Furnaces with Low Thermal Inertia.	238
4.5	Test Methods of Batch Resistor Furnaces.	245
4.5.1	Direct (or “Classic”) Method.	246
4.5.2	Method Beuken-I (Indirect Method)	247
4.5.3	Test Method Beuken-II	251
4.6	Heating Elements	252
4.6.1	Material Requirements.	252
4.6.2	Metallic Alloys	254
4.6.3	Non-metallic Resistors.	258
4.6.4	Resistors Life	261
4.6.5	Types of Resistors.	262
4.6.6	Design of Classical Metallic Resistors.	270
4.6.7	Furnaces with High Specific Power Resistors	282
4.7	Energy Balance of Resistance Furnaces	283
	References.	285
5	Direct Resistance Heating.	287
5.1	Introduction	287
5.2	DRH with DC Supply	290
5.2.1	Basic DC Electrical Equations.	290

5.2.2	Influence of Variations with Temperature of Material Characteristics	292
5.2.3	Influence of Radiation Losses on Heating Transient	294
5.3	DRH With AC Supply	299
5.3.1	Distributions of Current and Power Density	299
5.3.2	Transient Temperature Distribution in Cylindrical Body with AC Current Supply	306
5.3.3	Heating Transient in Ferromagnetic Steel Bars	309
5.3.4	Installations for Bar Heating	311
5.3.5	Efficiency and Energy Consumption	317
5.3.6	Calculation of DRH Installations	321
5.3.7	Influence of Electrical Installation Design on the Heating of Steel Bars	336
5.4	Miscellanea	344
5.4.1	DRH Tubes Heating with DC Supply	344
5.4.2	DRH Tube Heating with AC Supply	345
5.4.3	AC-DRH of Bars with Rectangular or Square Cross Section	347
5.4.4	DRH of Continuous Heaters for Metal Wires and Strips	349
	References	351
6	Induction Heating	353
6.1	Introduction	353
6.2	Induced Current and Power Density Distributions Within a Solid, Cylindrical Body in Longitudinal Magnetic Field	358
6.3	Power Induced in a Cylindrical Workpiece and Equivalent Impedance of the Inductor-Load System	367
6.3.1	Specific Surface Power Density	368
6.3.2	Total Flux and Impedance Z_{e0}	370
6.3.3	Equations of the Semi-infinite Plane	372
6.4	Heating of Hollow Cylindrical Workpieces in Axial Magnetic Field	374
6.4.1	General Solution	374
6.4.2	Heating of Tubes with External Inductors	376
6.4.3	Hollow Cylinder with Internal Exciting Magnetic Field	378
6.5	Electrical Parameters of Inductors	380
6.5.1	Resistance and Internal Reactance of the Inductor	380
6.5.2	Electrical Efficiency of the Inductor-Load System	382
6.5.3	Quality and Power Factors	384

6.6	Transient Temperature Distribution in Cylindrical Workpieces Heated by Induction	387
6.6.1	Localized Surface Heating	389
6.6.2	Quasi Uniform Heating	390
6.7	Variation of Material Characteristics During Heating	398
6.7.1	Non-magnetic Materials	399
6.7.2	Magnetic Materials	401
6.8	Calculation of Inductors	410
6.8.1	Approximate Method of the Electric Circuit Equivalent to Magnetic Reluctances	410
6.8.2	Analytical Methods	416
6.8.3	Numerical Methods	420
6.9	Industrial Applications of Induction Heating	425
6.9.1	Induction Furnaces	425
6.9.2	Induction Crucible Furnaces	429
6.9.3	Channel Induction Furnaces	449
6.9.4	Through Heating Prior Hot Working of Metals	456
6.9.5	Induction Heat Treatments	484
	References	522
7	High Frequency and Microwave Heating	525
7.1	Introduction	525
7.2	Theoretical Background	526
7.2.1	Power Transformed into Heat	529
7.2.2	Parallel and Series Equivalent Circuits	530
7.3	Physical Properties of Dielectric Materials	531
7.3.1	Polarization Processes	531
7.3.2	Influence of Frequency on Relaxation Polarization	533
7.3.3	Complex Dielectric Constant with Relaxation Polarization and Conduction	537
7.3.4	Influence of Temperature on Dielectric Characteristics	538
7.3.5	Typical Values of Loss Factors	543
7.4	Frequency Selection	546
7.5	Electric Field Distribution in the Load	547
7.5.1	“Thermal” Penetration Depth	547
7.5.2	Electric Field Intensity and Equivalent Parameters of Heterogeneous Charges	548
7.5.3	Field Uniformity	553
7.6	Calculation of the Working Capacitor	566
7.7	Transient Temperature Distribution in the Load	572
7.8	Other Types of Applicators	580
7.9	Microwave Heating	583
7.9.1	Generators	584

7.9.2	Waveguides	587
7.9.3	The Resonant Cavity	590
7.10	Industrial Applications of High Frequency and Microwave Heating	594
7.10.1	Gluing of Wood	595
7.10.2	Welding Sheets of Thermoplastic Materials	597
7.10.3	Preheating of Thermosetting Resins and Rubber	601
7.10.4	Applications in Textile, Paper and Food Sectors	603
	References	609
	Appendix: Tables and Formulae	611

Fundamentals of Electroheat

Electrical Technologies for Process Heating

Lupi, S.

2017, XVII, 620 p. 446 illus., 18 illus. in color.,

Hardcover

ISBN: 978-3-319-46014-7