Contents

| L | Mod | Modern Steelmaking in Electric Arc Furnaces: | | | |
|------------|------|--|---|----|--|
| | Hist | ory and | d Development | 1 | |
| | 1.1 | Gener | al Requirements to Steelmaking Units | 1 | |
| | | 1.1.1 | Process Requirements | 2 | |
| | | 1.1.2 | Economic Requirements | 2 | |
| | | 1.1.3 | Environmental and Health and Safety Requirements | 5 | |
| | 1.2 | High- | Power Furnaces: Issues of Power Engineering | 7 | |
| | | 1.2.1 | Increasing Power of EAF Transformers | 7 | |
| | | 1.2.2 | Specifics of Furnace Electrical Circuit | 8 | |
| | | 1.2.3 | Optimum Electrical Mode of the Heat | 11 | |
| | | 1.2.4 | Direct Current Furnaces | 12 | |
| | | 1.2.5 | Problems of Energy Supply | 13 | |
| | 1.3 | The M | Most Important Energy and Technology Innovations | 14 | |
| | | 1.3.1 | Intensive Use of Oxygen, Carbon and Chemical Heat | 14 | |
| | | 1.3.2 | Foamed Slag Method | 15 | |
| | | 1.3.3 | Furnace Operation with Hot Heel | 18 | |
| | | 1.3.4 | Single Scrap Charging | 18 | |
| | | 1.3.5 | Use of Hot Metal and Reduced Iron | 19 | |
| | | 1.3.6 | Post-Combustion of CO Above the Bath | 20 | |
| | | 1.3.7 | Increase in Capacity of Furnaces | 21 | |
| | | 1.3.8 | Continuous Charging and Melting of Scrap | | |
| | | | in the Liquid Bath | 22 | |
| | Refe | rences | · · · · · · · · · · · · · · · · · · · | 24 | |
| | | | | | |
| 2 | Elec | tric Ar | rc Furnace as Thermoenergetical Unit | 25 | |
| | 2.1 | Thern | nal Performance of Furnace: Terminology | | |
| | | and D | Designations | 25 | |
| | 2.2 | Extern | nal and Internal Sources of Thermal Energy: | | |
| | | Usefu | ll Heat | 27 | |
| | 2.3 | Factor | rs Limiting the Power of External Sources | 28 | |
| | 2.4 | Key F | Role of Heat Transfer Processes | 29 | |
| Reference. | | | | 31 | |



| 3 | | | mental Laws and Calculating Formulae ansfer Processes | 33 |
|---|-----------------------------------|--------|---|----|
| | 3.1 | | Ways of Heat Transfer: General Concepts | 33 |
| | 3.2 | | action Heat Transfer | 34 |
| | 3.2 | 3.2.1 | Fourier's Law. Flat Uniform Wall. | |
| | | 3.2.1 | Electrical—Thermal Analogy | 34 |
| | | 3.2.2 | Coefficient of Thermal Conductivity | 37 |
| | | 3.2.3 | Multi-Layer Flat Wall | 39 |
| | | 3.2.4 | Contact Thermal Resistance | 41 |
| | | 3.2.5 | Uniform Cylindrical Wall | 42 |
| | | 3.2.6 | Multi-Layer Cylindrical Wall | 43 |
| | | 3.2.7 | Simplifying of Formulae for Calculation | |
| | | 0.2 | of Cylindrical Walls | 44 |
| | | 3.2.8 | Bodies of Complex Shape: Concept of Numerical | |
| | | | Methods of Calculating Stationary | |
| | | | and Non-Stationary Conduction Heat Transfer | 45 |
| | 3.3 | Conve | ective Heat Exchange | 49 |
| | | 3.3.1 | Newton's Law: Coefficient of Heat Transfer α | 49 |
| | | 3.3.2 | Two Modes of Fluid Motion | 50 |
| | | 3.3.3 | Boundary Layer | 50 |
| | | 3.3.4 | Free (Natural) Convection | 52 |
| | | 3.3.5 | Convective Heat Transfer at Forced Motion | 53 |
| | | 3.3.6 | Heat Transfer Between Two Fluid Flows Through | |
| | | | Dividing Wall; Heat Transfer Coefficient k | 55 |
| | 3.4 | Heat 1 | Radiation and Radiant Heat Exchange | 58 |
| | | 3.4.1 | General Concepts | 58 |
| | | 3.4.2 | Stefan-Boltzmann Law; Radiation Density; | |
| | | | Body Emissivity | 59 |
| | | 3.4.3 | Heat Radiation of Gases | 62 |
| | | 3.4.4 | Heat Exchange Between Parallel Surfaces | |
| | | | in Transparent Medium: Effect of Screens | 63 |
| | | 3.4.5 | Heat Exchange Between the Body and Its Envelope: | |
| | | | Transparent Medium | 65 |
| | | 3.4.6 | Heat Exchange Between the Emitting Gas | |
| | | | and the Envelope | 66 |
| 4 | Energy (Heat) Balances of Furnace | | | |
| | 4.1 | | ral Concepts | 67 |
| | 4.2 | | Balances of Different Zones of the Furnace | 69 |
| | 4.3 | | ple of Heat Balance in Modern Furnace | 71 |
| | 4.4 | - | sis of Separate Items of Balance Equations | 72 |
| | | 4.4.1 | Output Items of Balance | 72 |
| | | 4.4.2 | Input Items of Balance | 75 |

75

Contents xi

| | 4.5 | Chem | ical Energy Determination Methods | 70 |
|---|-------|---|---|-----|
| | | 4.5.1 | Utilization of Material Balance Data | 76 |
| | | 4.5.2 | About the So-Called "Energy Equivalent" of Oxygen | 76 |
| | | 4.5.3 | Calculation of Thermal Effects of Chemical Reactions | |
| | | | by Method of Total Enthalpies | 7 |
| | Refe | erences | | 82 |
| 5 | Ene | rov Eff | iciency Criteria of EAFs | 8: |
| | 5.1 | | ninary Considerations | 8: |
| | 5.2 | | non Energy Efficiency Coefficient of EAF | 0. |
| • | 5.2 | | s Deficiencies | 8′ |
| | 5.3 | | fic Coefficients η for Estimation of Energy Efficiency | |
| | | | parate Energy Sources and EAF as a Whole | 89 |
| | 5.4 | | mining Specific Coefficients η | 9: |
| | 2 | 5.4.1 | Electrical Energy Efficiency Coefficient η_{EL} | 9: |
| | | 5.4.2 | Fuel Energy Efficiency Coefficient of Oxy-Gas | - |
| | | 52 | Burners η_{NG} | 93 |
| | | 5.4.3 | Energy Efficiency Coefficient of Coke Charged Along | |
| | | 5.1.5 | with Scrap | 94 |
| | | 5.4.4 | Determining the Specific Coefficients η by the Method | |
| | | 5 | of Inverse Heat Balances | 9: |
| | 5.5 | Tasks | of Practical Uses of Specific Coefficients η | 9: |
| | | | | 9' |
| | rtort | or crices | | |
| 6 | Prel | Preheating of Scrap by Offgases in Combination with Burners | | |
| | 6.1 | Potent | tials and Limiting Factors | 99 |
| | | 6.1.1 | Expediency of Heating | 99 |
| | | 6.1.2 | Comparison of Consumptions of Useful Heat | |
| | | | for Scrap Heating, Scrap Meltdown, and for Heating | |
| | | | of Metal up to Tapping Temperature | 100 |
| | | 6.1.3 | Reduction in Electrical Energy Consumption | |
| | | | with High-Temperature Heating of Scrap: | |
| | | | Calculation of Potentials | 10 |
| | | 6.1.4 | Sample of Realization of High-Temperature Heating: | |
| | | | Process BBC-Brusa | 102 |
| | | 6.1.5 | Specifics of Furnace Scrap Hampering Its Heating | 10. |
| | 6.2 | Heatir | ng on Conveyor | 10: |
| | | 6.2.1 | Consteel Furnaces with Continuous Scrap Charging | |
| | | | into the Bath | 10: |
| | | 6.2.2 | Comparison of Melting Rates, Productivities, | |
| | | | and Electrical Energy Consumptions Between | |
| | | | the Consteel Furnaces and EAFs | 100 |
| | | 6.2.3 | Scrap Preheating Temperature | 109 |

xii Contents

| | 6.3 | Heatin | ng Scrap in a Large-Thickness Layer | 111 | | | |
|---|------|--|--|-----|--|--|--|
| | | 6.3.1 | Heat Transfer Processes | 111 | | | |
| | | 6.3.2 | Heating Scrap in Baskets and Special Buckets | 114 | | | |
| | | 6.3.3 | Twin-Shell Furnaces with Removal of Off-Gas | | | | |
| | | | Through the Second Bath | 118 | | | |
| | 6.4 | Heatin | ng Scrap in Shaft Furnaces | 120 | | | |
| | | 6.4.1 | Shaft Furnaces with Fingers Retaining Scrap | 120 | | | |
| | | 6.4.2 | Shaft Furnaces with Continuous Scrap Charging | | | | |
| | | | into the Liquid Bath by Pushers | 122 | | | |
| | 6.5 | From | Utilizing Off-Gases to Scrap Preheating | | | | |
| | | | rners Only | 126 | | | |
| | Refe | | | 127 | | | |
| | | | | | | | |
| 7 | Rep | laceme | nt of Electric Arcs with High Power | | | | |
| | | | urners | 129 | | | |
| | 7.1 | Attem | pts for Complete Replacement | 129 | | | |
| | 7.2 | | tialities of Existing Burners: Heat Transfer, | | | | |
| | | | ing Factors | 131 | | | |
| | 7.3 | | Power Rotary Burners (HPR-Burners) | 134 | | | |
| | | 7.3.1 | Fundamental Features | 134 | | | |
| | | 7.3.2 | Slag Door Burners: Effectiveness | | | | |
| | | | of Flame-Direction Changes | 134 | | | |
| | | 7.3.3 | Roof Burners | 136 | | | |
| | | 7.3.4 | Oriel Burners | 138 | | | |
| | | 7.3.5 | Sidewall Burners | 140 | | | |
| | 7.4 | Two-S | Stage Process of the Heat with Use of HPR Burners: | | | | |
| | | Indust | trial Trials | 143 | | | |
| | | 7.4.1 | General Energy Ratios | 143 | | | |
| | | 7.4.2 | Process with a Door Burner in 6-ton Furnaces | 145 | | | |
| | | 7.4.3 | Process with Roof Burners in 100-ton | | | | |
| | | | and 200-ton Furnaces | 148 | | | |
| | 7.5 | Fuel A | Arc Furnaces (FAFs) | 151 | | | |
| | | 7.5.1 | FAF with Scrap Heating in a Furnace Freeboard | 151 | | | |
| | | 7.5.2 | Conveyor FAFs with Continuous Scrap Charging | | | | |
| | | | into the Liquid Bath | 153 | | | |
| | | 7.5.3 | Shaft FAFs with Continuous Scrap Charging | | | | |
| | | | by a Pusher | 155 | | | |
| | 7.6 | Econo | omy of Replacement of Electrical Energy with Fuel | 157 | | | |
| | Refe | rences | | 160 | | | |
| c | ъ. | · Di | | | | | |
| 8 | | Basic Physical—Chemical Processes in Liquid Bath Blown with Oxygen: Process Mechanisms | | | | | |
| | 8.1 | | rocess Mechanisms | 161 | | | |
| | 8.2 | | ttion of Carbon | 163 | | | |
| | 0.4 | ONIUG | mon or caroon | 100 | | | |

Contents

xiii

| | 8.3 | Melting of Scrap | 164 |
|----|-------|--|-----|
| | 8.4 | Heating of the Bath | 166 |
| 9 | Bath | Stirring and Splashing During Oxygen Blowing | 169 |
| | 9.1 | Stirring Intensity: Methods and Results of Measurement | 169 |
| | 9.2 | Mechanisms of Bath Stirring | 170 |
| | | 9.2.1 Stirring Through Circulation and Pulsation | 170 |
| | | 9.2.2 Stirring by Oxygen Jets and CO Bubbles | 171 |
| | 9.3 | Factors Limiting Intensity of Bath Oxygen Blowing | |
| | | in Electric Arc Furnaces | 172 |
| | | 9.3.1 Iron Oxidation: Effect of Stirring | 172 |
| | | 9.3.2 Bath Splashing | 174 |
| | 9.4 | Oxygen Jets as a Key to Controlling Processes in the Bath | 177 |
| | Refe | rences | 178 |
| 10 | Jet S | Streams: Fundamental Laws and Calculation Formulae | 179 |
| | | Jet Momentum | 179 |
| | | Flooded Free Turbulent Jet: Formation Mechanism | |
| | | and Basic Principles | 180 |
| | 10.3 | Subsonic Jets: Cylindrical and Tapered Nozzles | 182 |
| | | Supersonic Jets and Nozzles: Operation Modes | 186 |
| | | Simplified Formulae for Calculations of High-Velocity | |
| | | Oxygen Jets and Supersonic Nozzles | 188 |
| | | 10.5.1 A Limiting Value of Jets' Velocity | 190 |
| | 10.6 | Long Range of Jets | 191 |
| | | rence | 191 |
| | | | |
| 11 | Devi | ces for Blowing of Oxygen and Carbon into the Bath | 193 |
| | 11.1 | Blowing by Consumable Pipes Submerged into Melt | |
| | | and by Mobile Water-Cooled Tuyeres | 193 |
| | | 11.1.1 Manually Operated Blowing Through | |
| | | Consumable Pipes | 194 |
| | | 11.1.2 BSE Manipulator | 194 |
| | | 11.1.3 Mobile Water-Cooled Tuyeres | 196 |
| | 11.2 | Jet Modules: Design, Operating Modes, Reliability | 199 |
| | | 11.2.1 Increase in Oxygen Jets Long Range: Coherent Jets | 201 |
| | | 11.2.2 Effectiveness of Use of Oxygen, Carbon, and Natural | |
| | | Gas in the Modules | 203 |
| | 11.3 | Blowing by Tuyeres Installed in the Bottom Lining | 205 |
| | | 11.3.1 Converter-Type Non-Water-Cooled Tuyeres | 205 |
| | | 11.3.2 Tuyeres Cooled by Evaporation of Atomized Water | 207 |
| | | 11.3.3 Explosion-Proof Highly Durable Water-Cooled | |
| | | Tuyeres for Deep Blowing | 209 |
| | Refe | rences | 214 |

xiv Contents

| 12 | Wate | er-Cooled Furnace Elements | 215 | | | |
|----|-------|---|-----|--|--|--|
| | 12.1 | Preliminary Considerations | 215 | | | |
| | 12.2 | Thermal Performance of Elements: Basic Laws | 215 | | | |
| | 12.3 | 3 Principles of Calculation and Design of Water-Cooled | | | | |
| | | Elements | 219 | | | |
| | | 12.3.1 Determining of Heat Flux Rates | 219 | | | |
| | | 12.3.2 Minimum Necessary Water Flow Rate | 221 | | | |
| | | 12.3.3 Critical Zone of the Element | 222 | | | |
| | | 12.3.4 Temperature of Water-Cooled Surfaces | 222 | | | |
| | | 12.3.5 Temperature of External Surfaces | 225 | | | |
| | | 12.3.6 General Diagram of Element Calculation | 226 | | | |
| | | 12.3.7 Hydraulic Resistance of Elements | 226 | | | |
| | 12.4 | Examples of Calculation Analysis of Thermal Performance | | | | |
| | | of Elements | 229 | | | |
| | | 12.4.1 Mobile Oxygen Tuyere | 229 | | | |
| | | 12.4.2 Elements with Pipes Cast into Copper Body | | | | |
| | | and with Channels | 231 | | | |
| | | 12.4.3 Jet Cooling of the Elements | 234 | | | |
| | | 12.4.4 Oxygen Tuyere for Deep Blowing of the Bath | 235 | | | |
| | Refe | rences | 237 | | | |
| 13 | Prin | ciples of Automation of Heat Control | 239 | | | |
| 10 | | Preliminary Considerations | 239 | | | |
| | | Automated Management Systems | 239 | | | |
| | 13.2 | 13.2.1 Use of Accumulated Information: Static Control | 239 | | | |
| | | 13.2.2 Mathematical Simulation as Method of Control | 240 | | | |
| | | 13.2.3 Dynamic Control: Use of On-line Data | 243 | | | |
| | 13 3 | Rational Degree of Automation | 249 | | | |
| | | rences | 250 | | | |
| | recio | | 200 | | | |
| 14 | Off- | Gas Evacuation and Environmental Protection | 251 | | | |
| | 14.1 | Preliminary Considerations | 251 | | | |
| | 14.2 | Formation and Characteristics of Dust-Gas Emissions | 251 | | | |
| | | 14.2.1 Sources of Emissions | 251 | | | |
| | | 14.2.2 Primary and Secondary Emissions | 252 | | | |
| | | 14.2.3 Composition, Temperature, and Heat Content | | | | |
| | | of Off-Gases | 253 | | | |
| | 14.3 | Capturing Emissions: Preparing Emissions for Cleaning | | | | |
| | | in Bag Filters | 255 | | | |
| | | 14.3.1 General Description of the System | 255 | | | |
| | | 14.3.2 Problems of Toxic Emissions | 256 | | | |
| | | 14.3.3 A Simplified Method of Gas Parameters' Calculation | | | | |
| | | in the Direct Evacuation System | 259 | | | |
| | | 14.3.4 Energy Problems | 268 | | | |

| xv |
|----|
| |

| 14.4 Use of Air Curtains | |
|--------------------------|-----|
| Index | 277 |