

Contents

| | |
|---|------------|
| Preface | V |
| The Authors | VII |
| The Editor | VII |
| The Coauthors | VIII |
| 1 Functional Zones in the Extruder | 1 |
| 1.1 Transport of Solids into and in the Extruder, Feed Limits | 1 |
| 1.1.1 Characteristic Values and Calculation Possibilities | 2 |
| 1.1.2 Feed Limitations | 8 |
| 1.1.2.1 Granulates | 8 |
| 1.1.2.2 Powder | 9 |
| 1.1.2.3 Flakes | 11 |
| 1.1.2.4 Low-Melting Components | 11 |
| 1.2 Melting of Thermoplastics | 12 |
| 1.2.1 Tasks of the Melting Zone | 12 |
| 1.2.2 Screw Elements and Screw Configuration | 13 |
| 1.2.3 Measuring Techniques | 14 |
| 1.2.4 Essential Steps of Melting | 16 |
| 1.2.5 Calculation Models | 18 |
| 1.3 Mixing and Dispersion | 23 |
| 1.3.1 Overview, Principles, and Experiments | 23 |
| 1.3.1.1 Distributive Mixing - Mixing in Laminar Flow | 23 |
| 1.3.1.2 Dispersive Mixing | 29 |
| 1.3.1.3 Determining the Mixing Quality | 36 |
| 1.3.1.4 Symbols Used in Section 1.3.1 | 38 |
| 1.3.2 Three-Dimensional Calculations of Mixing and Residence Time Behavior | 40 |
| 1.3.2.1 Summary | 48 |

| | | |
|-----------|---|-----------|
| 1.4 | Devolatilization of Polymer Melts | 49 |
| 1.4.1 | Phase Interfaces and Surface Renewal | 49 |
| 1.4.1.1 | Liquid Distribution and Degree of Filling | 49 |
| 1.4.1.2 | Devolatilization Times | 62 |
| 1.4.2 | Concentration in the Devolatilization Zone | 70 |
| 1.4.2.1 | Influence of Dimensionless Groups | 70 |
| 1.4.2.2 | Bubble-Free Liquids | 71 |
| 1.4.2.3 | Influence of Surface Expansion by Bubbles | 76 |
| 1.4.3 | Design of the Devolatilization Zone | 76 |
| 1.4.4 | Numerical Simulation of Film Degassing | 79 |
| 2 | Scale-up and Scale-down | 87 |
| 2.1 | Introduction and Basis Rules for Thermally Sensitive Products | 87 |
| 2.1.1 | Dissimilarity | 88 |
| 2.1.2 | Comparison of Production Machines | 88 |
| 2.1.3 | Scale-down and Ways of Design | 89 |
| 2.1.3.1 | Product Temperature | 90 |
| 2.1.3.1.1 | Product Cooling via the Housing Wall | 91 |
| 2.1.3.1.2 | Temperature Change by a Pressure Difference | 92 |
| 2.1.3.1.3 | Temperature Increase by Power Input | 93 |
| 2.1.3.1.4 | Thermal Product Degradation | 94 |
| 2.1.3.1.5 | Temperature Increase and Internal Friction | 96 |
| 2.1.3.1.6 | Relevance of the Shear Rate | 97 |
| 2.1.3.1.7 | Basis Rules for Scale-up/down | 99 |
| 2.1.3.1.8 | Basis Equations for the Examples | 99 |
| 2.1.4 | Summary/Prospects | 104 |
| 2.2 | Scale-up and Scale-down by Model Laws | 106 |
| 2.2.1 | Basic Problem | 106 |
| 2.2.2 | Simple Scaling Approach | 107 |
| 2.2.3 | Model-Based Scaling Approach | 108 |
| 2.2.3.1 | Model Theory | 108 |
| 2.2.3.2 | Model Exponents | 118 |
| 2.2.3.2.1 | Lengths Exponent | 118 |
| 2.2.3.2.2 | Screw Speed Exponent | 119 |
| 2.2.3.2.3 | Channel Depths Exponent | 120 |
| 2.2.3.2.4 | Pitch Exponent | 120 |
| 2.2.3.2.5 | Relationship between Channel Depths Exponent, Selected Boundary Condition, and Resulting Throughput | 120 |
| 2.2.3.3 | Heat Flows via the Barrel | 122 |
| 2.2.4 | Experimental Results | 123 |

| | | |
|-----------|--|------------|
| 2.3 | Scale-up and Scale-down with Characteristic Numbers | 126 |
| 2.3.1 | Characteristic Numbers of the Whole Machine | 127 |
| 2.3.1.1 | Dimensionless Throughput | 127 |
| 2.3.1.2 | Specific Energy Input | 128 |
| 2.3.2 | Geometric Scale Transfer | 128 |
| 2.3.2.1 | Geometrically Similar Machines | 128 |
| 2.3.2.2 | Extruder Speed and Torque | 129 |
| 2.3.2.3 | Scale Transfer with Different Geometries | 130 |
| 2.3.2.3.1 | Partially Filled Zones | 130 |
| 2.3.2.3.2 | Pressure Buildup | 133 |
| 2.3.2.4 | Dimensional Analysis for Real Product Behavior | 134 |
| 2.3.2.4.1 | Influence of Non-Newtonian Behavior of the Liquid | 134 |
| 2.3.2.4.2 | Temperature Distribution in the Fluid | 135 |
| 2.3.2.4.3 | Influence of Varying Temperature on Viscosity | 136 |
| 2.3.2.5 | Simple Example of a Scale-up | 137 |
| 3 | Machine Technology | 139 |
| 3.1 | ZSK Series and Applications | 139 |
| 3.1.1 | Development up to High Torques, Volumes, and Rotations | 139 |
| 3.1.2 | Torque- and Volume-Limited Throughputs | 143 |
| 3.1.3 | Examples of Applications for the Plastics Industry | 145 |
| 3.1.3.1 | High Torque for Glass Fiber Reinforcement of Plastics | 145 |
| 3.1.3.2 | High Torque for Film Extrusion of Non-Dried PET or PLA | 147 |
| 3.1.3.3 | High Torque with Previously Volume-Limited Applications | 147 |
| 3.1.3.4 | Processing of Temperature- and Shear-Sensitive Products | 149 |
| 3.1.3.4.1 | Compounding and Pelletizing of PVC-P and PVC-U | 149 |
| 3.1.3.4.2 | Compounding of Thermoplastic Elastomers | 150 |
| 3.1.4 | Examples of Applications for the Chemical Industry | 152 |
| 3.1.4.1 | Adhesive and Sealing Materials | 152 |
| 3.1.4.1.1 | Continuous Manufacture of Adhesive Materials | 152 |
| 3.1.4.1.2 | Continuous Manufacture of Sealing Materials | 154 |
| 3.1.4.2 | Chemical Reactions in Twin-Screw Extruders | 155 |
| 3.1.4.2.1 | Manufacture of Thermoplastic Polyurethane (TPU) | 155 |
| 3.1.4.2.2 | Peroxidic Degradation of Polypropylenes | 156 |

| | | |
|---------|--|-----|
| 3.2 | Barrel Units | 156 |
| 3.2.1 | Introduction | 156 |
| 3.2.2 | Design Types | 157 |
| 3.2.2.1 | Tie Rod Version for ZSK 18 - 54 | 157 |
| 3.2.2.2 | Flange Version for ZSK 58 - 320 | 158 |
| 3.2.2.3 | Clamp Version for ZSK 350 - 420 | 158 |
| 3.2.3 | Variants | 159 |
| 3.2.3.1 | Closed Screw Barrel | 159 |
| 3.2.3.2 | Closed Screw Barrel with Bore | 159 |
| 3.2.3.3 | Open Screw Barrel | 160 |
| 3.2.3.4 | Combination Screw Barrel | 160 |
| 3.2.3.5 | Special Forms | 160 |
| 3.2.4 | Wear/Corrosion Protection | 161 |
| 3.2.4.1 | Solid Barrels: Nitrided or Through-Hardened | 161 |
| 3.2.4.2 | Barrel with Liner (Oval Bushing) | 161 |
| 3.2.4.3 | Directly Coated Screw Barrels | 162 |
| 3.2.5 | Heating of Screw Barrels | 162 |
| 3.2.5.1 | Heating Cartridges | 162 |
| 3.2.5.2 | Heater Shells, Heater Plates | 163 |
| 3.2.6 | Cooling and Tempering | 163 |
| 3.2.6.1 | One Cycle | 163 |
| 3.2.6.2 | Two Cycles | 164 |
| 3.3 | Increasing the Twin-Screw Extruder's Availability Using Targeted Material Selection for Components that Come into Contact with Product | 164 |
| 3.3.1 | Introduction | 164 |
| 3.3.2 | Wear Phenomena in Twin-Screw Extruders in Practice | 165 |
| 3.3.2.1 | Abrasive Wear | 166 |
| 3.3.2.2 | Adhesive Wear | 169 |
| 3.3.2.3 | Corrosion | 171 |
| 3.3.3 | Measurement and Assessment of Wear Parameters | 173 |
| 3.3.3.1 | Measuring Resistance to Abrasive Wear | 174 |
| 3.3.3.2 | Measurement of Adhesive Wear | 175 |
| 3.3.3.3 | Measuring Corrosion | 176 |
| 3.3.4 | Design Forms and Materials for Extruder Housings and Screw Elements | 177 |
| 3.3.4.1 | Housing Design Forms | 177 |
| 3.3.4.2 | Screw Element Design Forms | 178 |
| 3.3.4.3 | Material Design of Extruder Housings and Liners | 181 |
| 3.3.4.4 | Material Design of Screw Set Elements | 185 |
| 3.3.5 | Outlook | 187 |

| | | |
|----------|--|------------|
| 3.4 | Dynamic Structural Analysis of Twin-Screw Extruders and Single-Screw Discharge Extruders | 188 |
| 3.4.1 | Structural Model Description | 188 |
| 3.4.2 | Vibration Analysis on a ZSK | 189 |
| 3.4.3 | Optimizing Single-Shaft Extruders | 195 |
| 3.4.4 | Structural Vibration Engineering Design | 198 |
| 3.4.5 | Summary | 203 |
| 3.5 | Measurement Technology and Process-Integrated Quality Assurance .. | 204 |
| 3.5.1 | Metrological Basics | 204 |
| 3.5.2 | Measuring Pressure and Temperature | 205 |
| 3.5.2.1 | Temperature | 205 |
| 3.5.2.2 | Pressure | 207 |
| 3.5.3 | Rheological Measurement Technology | 210 |
| 3.5.3.1 | Laboratory Rheometers | 210 |
| 3.5.3.2 | Process Rheometers | 211 |
| 3.5.4 | Color Measurement | 213 |
| 3.5.5 | Customized Systems | 213 |
| 3.5.5.1 | Ultrasonic Measurement Technology | 214 |
| 3.5.5.2 | Model Predictive Control and Virtual Sensors | 214 |
| 4 | Applications of Co-Rotating Twin-Screw Extruders | 217 |
| 4.1 | Compounding in Practice | 217 |
| 4.1.1 | Throughput Limitation | 217 |
| 4.1.1.1 | Torque Limitation | 218 |
| 4.1.1.2 | Volume Limitation | 218 |
| 4.1.1.3 | Further Limitations | 218 |
| 4.1.1.4 | Limitation by Peripherals | 219 |
| 4.1.2 | Premixing | 220 |
| 4.1.3 | Melt Degassing | 221 |
| 4.1.3.1 | Influencing Factors | 221 |
| 4.1.3.2 | Technical Design | 222 |
| 4.1.4 | Strand Die Head | 224 |
| 4.1.5 | Process Control | 225 |
| 4.1.5.1 | Process Monitoring | 225 |
| 4.1.5.2 | Caution, Trap! | 226 |
| 4.1.6 | Extruder Screws | 226 |
| 4.1.6.1 | Screw Design | 226 |
| 4.1.6.2 | Wear | 227 |
| 4.1.7 | Scale-up | 227 |
| 4.1.7.1 | The Ideal Case | 227 |
| 4.1.7.2 | Reality | 228 |

| | | |
|-----------|--|-----|
| 4.1.7.3 | Special Features of New Developments | 229 |
| 4.1.7.4 | Conclusion | 229 |
| 4.1.8 | Simulation | 229 |
| 4.2 | Color Masterbatches | 230 |
| 4.2.1 | Basic Process Idea | 231 |
| 4.2.2 | Materials | 232 |
| 4.2.2.1 | Pigments | 233 |
| 4.2.2.1.1 | Color Index and Particle Sizes: Pigments at First Glance | 235 |
| 4.2.2.1.2 | Qualitative Description of the Dispersion Quality in a Masterbatch | 236 |
| 4.2.2.1.3 | Dispersion Properties of Organic Pigments ... | 237 |
| 4.2.2.1.4 | Correlation between Dispersion Properties and Process Parameters | 238 |
| 4.2.2.2 | Complex Tasks | 239 |
| 4.2.2.2.1 | Effect Pigments | 239 |
| 4.2.2.2.2 | Organic Pigments with Different Dispersion Characteristics | 240 |
| 4.2.2.3 | Selection of the Polymer | 240 |
| 4.2.2.4 | Additives and Dispersing Agents | 241 |
| 4.2.3 | Mixing | 242 |
| 4.2.3.1 | Gravity Mixer | 242 |
| 4.2.3.2 | Low-Speed Stationary or Mobile (Container) Mixer | 242 |
| 4.2.3.3 | High-Speed Stationary or Mobile (Container) Mixer | 243 |
| 4.2.3.4 | Application Example: Production of Blends for Masterbatch in the Hot Process for Staple Fiber and Film Quality | 243 |
| 4.2.4 | Dosing | 244 |
| 4.2.5 | Extruder | 244 |
| 4.2.5.1 | Premix | 245 |
| 4.2.5.2 | Split-Feed | 246 |
| 4.2.5.3 | Downstream Units | 247 |
| 4.2.5.4 | Process Parameters | 248 |
| 4.2.6 | Quality Determination | 248 |
| 4.2.6.1 | Color Measurement | 249 |
| 4.2.6.2 | Filter Pressure Test | 250 |
| 4.2.6.3 | Agglomerates and Gel Particles | 251 |
| 4.3 | Preparation of TPV by Dynamic Vulcanization on Co-Rotating Twin-Screw Extruders | 252 |
| 4.3.1 | Classification of TPE | 252 |
| 4.3.2 | Preparation of TPV Based on EPDM/PP | 252 |

| | | |
|---------|--|-----|
| 4.3.2.1 | Basic Raw Materials for TPV (EPDM/PP) | 253 |
| 4.3.2.2 | Curing Agents | 254 |
| 4.3.2.3 | Manufacturing Process for TPV (EPDM/PP) | 254 |
| 4.3.2.4 | The Challenge of Dwell Time | 256 |
| 4.3.2.5 | Properties of TPV (EPDM/PP) | 258 |
| 4.3.3 | TPV Based on Renewable Raw Materials (“Bio-TPV”) | 258 |
| 4.3.3.1 | Basic Raw Materials for Bio-TPV | 258 |
| 4.3.3.2 | Production Process for Bio-TPV | 259 |
| 4.3.3.3 | Properties of Bio-TPV | 260 |
| 4.4 | Devolatilization of Polymer Melts Using Co-Rotating Twin-Screw Extruders | 263 |
| 4.4.1 | Devolatilization Tasks | 263 |
| 4.4.2 | Design of Devolatilizing Extruders | 265 |
| 4.4.2.1 | Material Feeding and Flash Devolatilization | 267 |
| 4.4.2.2 | Staggered Vacuums | 269 |
| 4.4.2.3 | Fill Level | 270 |
| 4.4.2.4 | Residual Devolatilization and Use of Stripping Agents | 271 |
| 4.4.2.5 | Design of Extruder and Devolatilization Sections | 276 |
| 4.4.3 | Scale-up of Devolatilization Extruders | 279 |
| 4.4.4 | Process Examples | 281 |
| 4.4.4.1 | Devolatilization of Solvents from LLDPE Melt Solutions | 281 |
| 4.4.4.2 | Devolatilizing Solvents from Synthetic Rubber (Styrene-Butadiene Compounds) | 282 |
| 4.4.4.3 | Devolatilizing Vinyl Acetate from LDPE/EVA Copolymer | 282 |
| 4.4.4.4 | Devolatilization of POM | 283 |
| 4.4.4.5 | Devolatilization of PC | 284 |
| 4.4.4.6 | Devolatilization of PMMA | 284 |
| 4.4.4.7 | Devolatilization of PES and PSU | 285 |
| 4.4.4.8 | Devolatilization of ABS | 287 |
| 4.4.4.9 | Devolatilization of Non-Dried PET | 287 |
| 4.4.5 | Summary | 289 |
| 4.5 | Reactive Extrusion | 290 |
| 4.5.1 | Introduction | 290 |
| 4.5.2 | Influence of Parameters Using Selected Application Examples | 291 |
| 4.5.2.1 | Activated Anionic Polymerization of Lactams | 293 |
| 4.5.2.2 | Polymerization of Acrylates | 294 |
| 4.5.2.3 | Ring-Opening Polymerization of ϵ -Caprolactone | 296 |
| 4.5.3 | Economically Relevant Example: Thermoplastic Polyurethane | 297 |
| 4.5.4 | Modeling | 299 |
| 4.5.5 | Scale-up | 301 |
| 4.6 | Food Extrusion | 304 |

| | | |
|--------------|--|------------|
| 4.6.1 | Extrusion of Breakfast Cereals | 307 |
| 4.6.1.1 | Raw Materials and Mixing | 309 |
| 4.6.1.2 | Preconditioning and Extrusion | 313 |
| 4.6.1.3 | Short-Time Tempering and Flaking | 318 |
| 4.6.1.4 | Roasting, Spraying, and Drying | 321 |
| 4.6.2 | Products | 323 |
| 4.6.3 | Food Safety in Food Extrusion | 325 |
| 4.6.4 | Summary | 328 |
| 4.6.5 | List of Abbreviations | 329 |
| 4.7 | Extrusion of Pharmaceutical Masses | 331 |
| 4.7.1 | Introduction | 331 |
| 4.7.2 | Fundamentals of Melt Extrusion | 331 |
| 4.7.3 | Machine Design | 332 |
| 4.7.4 | System Layout | 334 |
| 4.7.5 | Containment Requirements | 339 |
| 4.7.6 | Summary and Outlook | 339 |
| Index | | 341 |