

# Contents

<b>Preface</b> .....	<b>V</b>
<b>The Authors</b> .....	<b>VII</b>
<b>1 Introduction</b> .....	<b>1</b>
1.1 Technical and Economic Importance of Extruders .....	1
1.1.1 Extruder Types and Terms .....	1
1.1.2 Screw Machines and Plastics .....	2
1.1.3 Economic Core Function of an Extruder in the Plastics Industry .....	3
1.1.4 Extruder Types and Advantages of Closely Intermeshing Co-Rotating Screws .....	5
1.1.5 First Closely Intermeshing Co-Rotating Screws .....	6
1.1.6 Details of Twin-Screws .....	8
1.1.7 Objective of the Book .....	9
1.1.8 Summary .....	10
1.1.9 Prospects .....	10
1.2 Historical Development of Co-Rotating Twin-Screw Extruders .....	11
1.2.1 Preface and Recognition of Bayer Scientists .....	11
1.2.2 Historical Development of Co-Rotating Twin-Screw Extruders ..	17
1.2.2.1 Early Developments .....	17
1.2.2.2 Pioneering Period .....	29
1.2.2.3 New High-Viscosity Technology with Co-Rotating Extruders .....	32
1.2.2.4 Special Developments from Bayer-Hochviskostechnik (High Viscosity Technology Group) .....	37
1.2.2.5 Developments after Licensing .....	39
1.2.2.6 Developments after Expiration of the Primary Patents ..	42
1.3 General Overview of the Compounding Process: Tasks, Selected Applications, and Process Zones .....	45
1.3.1 Compounding Tasks and Requirements .....	45

1.3.2	Tasks and Design of the Processing Zones of a Compounding Extruder .....	47
1.3.2.1	Intake Zone .....	49
1.3.2.2	Plastification Zone .....	50
1.3.2.3	Melt Conveying Zone .....	55
1.3.2.4	Distributive Mixing Zone .....	56
1.3.2.5	Dispersive Mixing Zone .....	58
1.3.2.6	Devolatilization Zone .....	60
1.3.2.7	Pressure Build-Up Zone .....	61
1.3.3	Characteristic Process Parameters .....	64
1.3.3.1	Specific Energy Input .....	64
1.3.3.2	Residence Time Characteristics .....	66
1.3.4	Process Examples .....	68
1.3.4.1	Incorporation of Glass Fibers .....	68
1.3.4.2	Incorporation of Fillers .....	72
1.3.4.3	Production of Masterbatches .....	73
1.3.4.4	Coloring .....	76
1.4	Process Understanding – Overview and Evaluation of Experiments and Models .....	79
1.4.1	Introduction .....	79
1.4.2	Classification of Models and Experiments .....	82
1.4.3	Solid Materials .....	84
1.4.4	Highly Viscous Liquids .....	85
1.4.4.1	One-Dimensional Models .....	85
1.4.4.2	Three-Dimensional Models .....	90
1.4.5	Summary .....	92
1.4.6	Prospects and Proposals .....	94
1.4.6.1	Program for Extruder Configuration .....	94
1.4.6.2	Further Development of Models .....	94
1.4.6.3	New Model Applications – Online .....	94
1.4.6.4	Process Characterization of Screw Elements by Key Figures .....	96
1.5	Conveying and Power Parameters of Standard Conveying Elements ....	97
1.6	Frequently Used Symbols .....	98
<b>2</b>	<b>Basics – Screw Elements .....</b>	<b>101</b>
2.1	Geometry of Co-Rotating Extruders: Conveying and Kneading Elements, Including Clearance Strategies .....	101
2.1.1	Introduction .....	101
2.1.2	The Fully Wiped Profile from Arcs .....	102

2.1.3	Geometric Design of Fully Wiped Profiles	104
2.1.4	Dimensions of Screw Elements with Clearances	105
2.1.5	Transition between Different Numbers of Threads	109
2.1.6	Calculation of a Screw Profile for Production According to Planar Offset	110
2.1.7	Free Cross-Sectional Area	113
2.1.8	Surface of Barrel and Conveying Elements	113
2.1.9	Kneading Elements	115
2.1.10	New Developments with Screw Geometries	117
2.2	Screw Elements and Their Use	118
2.2.1	Construction of Screw Elements	119
2.2.2	Combining Screw Elements	124
2.2.3	Screw Elements and Their Operating Principles	127
2.2.3.1	Conveying Elements	127
2.2.3.2	Kneading Elements	132
2.2.3.3	Sealing Elements	136
2.2.3.4	Mixing Elements	138
2.2.3.5	Special Elements	142
2.3	Overview of Patented Screw Elements	147
2.3.1	WO 2009152910, EP 2291277, US 20110110183	149
2.3.2	WO 2011039016, EP 2483051, US 20120320702	150
2.3.3	WO 2011069896, EP 2509765, US 20120281001	151
2.3.4	DE 00813154, US 2670188	152
2.3.5	DE 19947967, EP 1121238, WO 2000020188	153
2.3.6	US 1868671	154
2.3.7	DE 10207145, EP 1476290, US 20050152214	154
2.3.8	DE 00940109, US 2814472	155
2.3.9	US 5713209	155
2.3.10	US 3717330, DE 2128468	156
2.3.11	DE 4118530, EP 516936, US 5338112	157
2.3.12	US 4131371	158
2.3.13	DE 03412258, US 4824256	158
2.3.14	DE 1180718, US 3254367	159
2.3.15	US 3900187	160
2.3.16	WO 2009153003, EP 2303544, US 20110112255	161
2.3.17	WO 2009152974, EP 2291279, US 20110180949	162
2.3.18	US 3216706	163
2.3.19	WO 2009152968, EP 2303531, US 20110158039	164
2.3.20	WO 2013045623, EP 2760658	165
2.3.21	WO 2009152973, EP 2291270, US 20110141843	166
2.3.22	WO 2009153002, EP 2307182, US 20110096617	167

2.3.23	EP 0002131, JP 54072265, US 4300839	168
2.3.24	DE 19718292, EP 0875356, US 6048088	169
2.3.25	DE 04239220	169
2.3.26	DE 01529919, US 3288077	170
2.3.27	EP 0330308, US 5048971	171
2.3.28	DE 10114727, US 6974243, WO 2002076707	172
2.3.29	US 6783270, WO 2002009919	173
2.3.30	WO 2013128463, EP 2747980, US 20140036614	174
2.3.31	JP 2008183721, DE 102007055764, US 2008181051	175
2.3.32	DE 4329612, EP 641640, US 5573332	176
2.3.33	DE 19860256, EP 1013402, US 6179460	177
2.3.34	DE 04134026, EP 0537450, US 5318358	177
2.3.35	DE 19706134	178
2.3.36	JP 2013028055	179
2.3.37	WO 1998013189, US 6022133, EP 934151	179
2.3.38	WO 1999025537, EP 1032492	180
2.3.39	US 6116770, EP 1035960, WO 2000020189	180
2.3.40	DE 29901899 U1	181
2.3.41	US 6170975, WO 2000047393	181
2.3.42	DE 10150006, EP 1434679, US 7080935	182
2.3.43	DE 4202821, US 5267788, WO 1993014921	182
2.3.44	DE 03014643, EP 0037984, US 4352568	183
2.3.45	DE 02611908, US 4162854	184
2.3.46	WO 1995033608, US 5487602, EP 764074	185
2.3.47	DE 102004010553	186
2.3.48	DE 04115591, EP 0513431	187
2.3.49	WO 2011073181, EP 2512776, US 20120245909	188

### **3 Material Properties of Polymers** ..... **189**

3.1	Rheological Properties of Polymer Melts	189
3.1.1	Introduction and Motivation	189
3.1.2	Classification of Rheological Behavior of Solids and Fluids	190
3.1.3	Comparison of Viscous Fluid and Viscoelastic Fluid	195
3.1.3.1	Viscous Fluids	195
3.1.3.2	Viscoelastic Fluids	196
3.1.4	Temperature Dependence of Shear Viscosity	199
3.1.4.1	Temperature Dependence for Semi-Crystalline Polymers	200
3.1.4.2	Temperature Dependence for Amorphous Polymers	201
3.1.5	Influence of Molecular Parameters on Rheological Properties of Polymer Melts	202

3.1.6	Shear Flows	204
3.1.6.1	Flow Profiles of Pressure-Driven Pipe Flow	205
3.1.6.2	Flow Profiles of Simple Drag Flow	206
3.1.7	Extensional Flows	208
3.2	Material Behavior of Blends – Consideration of Polymer-Filler and Polymer-Polymer Systems	210
3.2.1	Material Properties of Two-Substance Systems	212
3.2.1.1	Introduction to Mixed Systems	212
3.2.1.2	Thermodynamic Material Data of Two-Substance Mixtures	212
3.2.1.3	Viscosities of Two-Substance Mixtures	214
3.2.1.4	Compatible Polymer Blends	216
3.2.1.5	Immiscible (Incompatible) Polymer Blends	216
3.2.2	Process Behavior during Plasticizing of Two-Substance Polymer Systems	219
3.2.2.1	Calculation of the Melting Behavior of Two-Substance Systems	224
3.2.3	Final Remarks for Use in Practice	224
3.2.4	Conclusion	225
3.3	Diffusive Mass Transport in Polymers	227
3.3.1	Mechanisms of Mass Transport	227
3.3.1.1	Concentration Distribution Near the Phase Interface	228
3.3.2	Influencing Quantities of the Material Properties	247
3.4	Influence Factors and Reduction of Degradation during Polymer Processing	252
3.4.1	Introduction	252
3.4.2	Chemical Reactions	253
3.4.2.1	Damage through Thermal Degradation	254
3.4.2.2	Oxidative Degradation	256
3.4.2.3	Chemical Degradation Reactions via Residual Water	258
3.4.2.4	Degradation via Mechanical Stress	259
3.4.2.5	Influence of Metals on Degradation	259
3.4.3	Relationship between Polymer Degradation and Properties	260
3.4.4	Reduction of Polymer Degradation during Processing	262
3.4.4.1	Extruder Screw Design or Processing Parameters	262
3.4.4.2	Changes of Melt Flow Behavior via Molecular Weight and Flow Modifiers	263
3.4.4.3	Minimization of Reaction Partners	264
3.4.4.4	Additives for Reduction of Polymer Degradation	264
3.4.5	Summary	266

3.5	Calculation Basis for the Flow in Wedge Shaped Shear Gaps and Flow Properties of Filled Polymer Melts	268
3.5.1	Consideration of Pseudoplastic Flow Behavior of Plastic Melts in the Wedge Gap Flow and Key Numbers for the Evaluation of the Dispersion	268
3.5.1.1	Introduction – Deformation of Plastic Melts, Shear, and Elongation in the Wedge Gap Flow	268
3.5.1.2	Calculation of the Wedge Gap Flow for Highly Viscous Fluids	271
3.5.1.3	Plastic Melts with Different Pseudoplastic Flow Behavior	274
3.5.1.4	Results of the Simulation	276
3.5.2	Modeling of the Flow Behavior of Highly Filled Plastics	285
3.5.2.1	Viscosity of Polymers with Different Filler Contents	285
3.5.2.2	CARPOW Approach for the Viscosity Function of Highly Filled Polymers	288
3.5.2.3	Summary	289
<b>4</b>	<b>Conveying Behavior, Pressure and Performance Behavior</b>	<b>291</b>
4.1	Introduction of Conveying and Pressure Behavior of Highly Viscous Liquids in Extruders	291
4.1.1	Throughput and Pressure Behavior, Dimensionless Key Figures	291
4.1.1.1	Shear Rate and Viscosity	291
4.1.1.2	Simple Qualitative Consideration on Simple Plane Flow	293
4.1.1.3	Extruder Key Figures and Pressure Basic Equation for Extruders	300
4.2	Introduction of the Performance Behavior of Highly Viscous Liquids in Extruders	320
4.2.1	Throughput Performance Behavior of the Plane Flow between Two Plates	320
4.2.2	Performance Key Figure for an Annular Gap	321
4.2.3	Basic Equation of the Performance Characteristic of Extruders	323
4.3	Dissipation, Pump Efficiency Degree, Temperature Increase, and Heat Transfer	326
4.3.1	Dissipation	326
4.3.2	Pump Efficiency Degree	326
4.3.3	Temperature Increase	329
4.3.4	Heat Transfer	337

4.4	Prospect to the Sections 4.1, 4.2, and 4.3	339
4.5	Pressure Generation and Energy Input in the Melt	341
4.5.1	Operating Conditions of Conveying Screw Elements	341
4.5.2	Illustration of Dimensionless Groups	343
4.5.3	Calculation of the Back-Pressure Length	349
4.5.4	Efficiency during Pressure Generation	350
4.5.5	Example for the Design of a Pressure Build-up Zone	352
4.5.6	Pressure and Energy Behavior with Shear Thinning	353
4.6	Tasks Regarding the Power Input and the Back-Pressure Length	360
4.6.1	Task: Influence of the Flight Pitch	360
4.6.2	Task: Partial Filling	362
4.6.3	Task: Design of a Pressure Build-up Zone with Uniform Pitch as Well as Fully and Partially Filled Areas	363
4.6.4	Task: Design of the Pressure Build-up Zone with Various Elements with 40 mm and 60 mm Pitch Combined	367
4.6.5	Task: Impact of Shear Thinning Effects	368
4.7	Computational Fluid Dynamics	370
4.7.1	Introduction to Computational Fluid Dynamics	370
4.7.2	Fully Filled Screw Sections	374
4.7.2.1	Example 1	374
4.7.2.2	Example 2	391
4.7.2.3	Conclusion and Outlook	393
4.7.3	Partly Filled Screw Sections	397
<b>Index</b>		<b>405</b>