

Contents

Preface	V
Foreword	VII
The Author	IX
Important Rheological Formulas	XI
The <i>Hagen-Poiseuille</i> Equations	XI
Equations for the Representative Shear Rate	XII
Equations for Calculating the Viscosity	XII
Equations for Calculating the Temperature Shift Factor a_T	XIII
Equation for the Temperature Depending Specific Volume	XIII
1 Introduction	1
1.1 Why Is Rheology Needed in Plastics Technology?	3
1.2 Computer-Aided Simulation Programs for the Design of Injection Molds	7
2 Rheological Phenomena	11
2.1 Shear-Thinning Viscosity	13
2.2 Dilatancy	16
2.3 Thixotropy and Rheopexy	17
2.4 Bingham Behavior	19
2.5 Normal Stresses	22
2.5.1 Origin, Definition, and Characterization	22
2.5.2 Viscoelastic and Normal Stress Effects	23

2.5.2.1	Weissenberg Effect	23
2.5.2.2	Die-Swelling Effect	25
3	Rheological Models	29
3.1	The Ideal Elastic Model	30
3.2	The Ideal Viscous Model (Newtonian Fluid)	31
3.3	The Viscoelastic Model	33
3.3.1	The Kelvin–Voigt Model	33
3.3.2	General Viscoelastic Material	35
4	The Shear Test and the Derivation of Newton’s Law of Friction (Material Law)	37
4.1	The Shear Test	37
4.2	Important Rheological Material Laws	42
5	Flow Types	45
5.1	Shear Flow	45
5.2	Extensional Flow	46
5.3	Orientations	46
5.3.1	Example of Orientations: Molded Panel with Lateral Injection Point	47
5.3.2	Example of Orientations: Molded Part with Bar Sprue and Lateral Film Gate	48
5.3.3	Example of Orientations: Molded Part with Central Gating	49
5.3.4	Orientations: Boundary and Middle Layers	50
5.4	Influence of Extensional Flows	53
5.5	Trouton Approach for Determining the Extensional Viscosity	55
6	Rheometry: Viscometry and Material Data Determination ..	57
6.1	Ranges of Application of the Different Viscometer and Rheometer Types	58
6.2	Prerequisite for Determining the Material Data	60
6.3	Falling Viscometers	61
6.3.1	Determining the Viscosity with Falling Viscometers Using Stokes’s Law	61
6.3.2	Falling Ball Viscometer	63
6.3.3	Rolling Ball Viscometer	64
6.4	Viscosity Balance	65

6.5	Rotational and Oscillation Rheometers	65
6.5.1	Plate–Plate Rheometer	66
6.5.2	Cone–Plate Rheometer	67
6.5.3	Normal Stresses and Viscoelastic Behavior	69
6.5.4	Measurement of the Normal Stresses of Fluids Using Rotational Rheometry	71
6.5.5	Measurement of the Viscoelastic Properties of Fluids Using Oscillation Rheometry	74
6.5.6	The Cox-Merz Relationship	82
6.5.7	Relaxation Test Using a Rotational Rheometer	84
6.5.8	The Large Amplitude Oscillatory Shear (LAOS) Theory	85
6.5.8.1	Historical Overview and Findings of the LAOS Experiments	85
6.5.8.2	Evaluation Methods of LAOS Behavior	87
6.5.8.3	Classification of LAOS Behavior of Complex Fluids into Categories	89
6.5.8.4	LAOS Experiments Using Fourier Transform Rheology ..	89
6.5.8.5	Possibilities and Limitations of LAOS Experiments on Polymer Melts Using FT Rheology	91
6.5.9	Coaxial Cylinder Systems	96
6.6	Capillary Rheometers	98
6.6.1	Low-Pressure Capillary Rheometer	98
6.6.1.1	Determination of the Melt Flow Index (MFI) and the Melt Volume Rate (MVR)	98
6.6.1.2	Determination of the Apparent Shear Rate and Apparent Viscosity Using a Low-Pressure Capillary Rheometer	100
6.6.1.3	Relationship between the MVR/MFI Value and the Molecular Weight	101
6.6.2	High-Pressure Capillary Rheometer (HPCR)	103
6.6.2.1	Determining the Mass Flow–Pressure Function	104
6.6.2.2	Calculation of the Volume Flow Rate	105
6.6.2.3	Calculation of the Apparent Wall Shear Stress and the Apparent Wall Shear Rate	106
6.6.2.4	Determining the True Wall Shear Stress	108
6.6.2.5	Determining the True Wall Shear Rate	113

- 6.6.2.6 Determination of Inlet and Outlet Pressure Losses,
Normal Stresses, and Extensional Viscosity
Using an Inline Pressure Rheometer 118
 - 6.6.2.7 Determination of the Pressure-Dependent Viscosity
Using an Inline Rheometer Nozzle 125
 - 6.7 Extensional Rheology 126
 - 6.7.1 Origin and Definition of Extensional Viscosity 126
 - 6.7.2 Measurement of Extensional Viscosities 128
 - 6.7.2.1 Measurements with Uniaxial Extension 128
 - 6.7.2.2 Determining the Extensional Viscosity with the
Rheotens Test 129
 - 6.7.3 Determination of Extensional Viscosity Using the Approach of
F. N. Cogswell 132
 - 6.8 Theory and Practice of Solution Viscometry 135
 - 6.8.1 Example Measurement of Solution Viscosity Using Polyethylene
Terephthalate (PET) 143
 - 6.8.1.1 Information from Schott Instruments on the
Measurement of Solution Viscosity 151
 - 6.8.1.2 Determination of the *K* Value in Solution According to
Fikentscher 151
- 7 Viscometry—Influences on the Rheological Material Data ... 155**
 - 7.1 Influence of Dissipation 156
 - 7.2 Influence of Temperature on the Flow Curve 158
 - 7.2.1 The Temperature Shift Factor 160
 - 7.2.2 Temperature-Invariant Application of the Flow Curves
(Master Curves) 161
 - 7.2.2.1 Example of a Viscosity Determination for a Selected
Shear Rate and Another Temperature 165
 - 7.2.2.2 *Task*: Determination of the Viscosity for a Given
Shear Rate Using a Master Curve 166
 - 7.2.2.3 *Task*: Exercise on Temperature Shift Using
Zero Viscosity 167
 - 7.2.3 Mathematical Description of the Temperature Shift Factor 168
 - 7.2.3.1 Arrhenius Function 168
 - 7.2.3.2 Equations of Williams, Landel, and Ferry
(WLF Approach) 169
 - 7.2.4 *Task*: Calculation of the Temperature Shift Factor 172

7.3	Thermorheological Variables	173
7.3.1	Changes in the Morphological Structure Due to Heat	173
7.3.2	Fillers	175
7.3.3	Influence of Pressure	179
7.3.4	Influence of the Average Molecular Weight	182
7.3.5	Molecular Weight Distribution	188
7.3.6	Influence of Molecular Weight and Molecular Weight Distribution on Storage and Loss Moduli During Oscillation	190
7.3.6.1	Comparison of Polymer Types with Different Molecular Weight Distributions	191
7.3.6.2	Comparison of Polymer Types with Different Molecular Weights and Molecular Weight Distributions	193
7.4	Influence of Residual Moisture on Shear Viscosity	195
7.5	Task: Description of the Flow Behavior with a Master Curve	196
8	Viscometry—Mathematical Description of the Flow Curve ...	199
8.1	Ostwald and de Waele's Power Approach (Power-Law Model)	200
8.2	The Carreau Approach	203
8.2.1	Task: Graphical Determination of the Constants of the Carreau Approach	205
8.2.2	Consideration of Temperature Dependence in the Carreau Approach	206
8.3	The Cross-WLF Approach	207
8.4	Polynomial Approaches	210
8.4.1	Polynomial Approach According to Münstedt	210
8.4.2	Biquadratic Polynomial Approach	211
8.4.3	Polynomial Approaches for Complex Flow Behavior	211
8.5	Task: Determination of the Consistency Factor and the Viscosity Exponent	211
8.6	Task: Comparison of the Material Laws (Power Approach and Carreau Approach)	212
9	Calculation of Flow Processes	215
9.1	Calculation of the Volume Flow Rate and Pressure Function for Newtonian Fluids	216
9.1.1	Assumptions for Simplifying the Equations	216
9.1.2	Flow Channel with Rectangular Cross Section	216

9.1.3	Flow Channel with Circular Cross Section	221
9.1.4	Channel with Circular Ring Cross Section	224
9.2	Calculation of the Volume Flow Rate and Pressure Function for Shear-Thinning Viscous Fluids	225
9.2.1	Consideration of the Shear-Thinning Viscosity Using the Power Approach	225
9.2.2	Consideration of the Shear-Thinning Viscosity Using the Carreau Approach	227
9.3	Normalized Velocity and Shear Rate Curves	228
9.4	<i>Task:</i> Effect of the Flow Channel on the Melt Volume Flow Rate	231
10	The Representative Shear Rate Method	233
11	Calculation of Flow Processes during Injection Molding	237
11.1	Model Presentation	237
11.2	General Procedure for Calculating Pressure Loss	243
11.2.1	<i>Tasks:</i> Calculation Examples	243
11.2.1.1	Pressure Loss: Plate Geometry	243
11.2.1.2	Pressure Loss: Disk Geometry	244
11.2.2	Influence of Material Properties on the Manufacturing Process ..	245
11.2.3	<i>Task:</i> Pressure Losses during Injection Molding and the Resulting Real Locking Force	246
11.2.4	<i>Task:</i> Consideration of Dissipation and Cooling Effects (Non-Isothermal Flow)	247
11.3	Calculation of the Optimum Filling Time (Injection Rate) during Injection Molding Using the Brinkman Number	250
12	Calculation of Flow Processes in Hot Runner Systems and Extrusion Molds	255
12.1	Basics of the Pressure Curve over the Length of Composite Channel Systems	255
12.1.1	Pressure Curve in Parallel Pipes	256
12.1.2	Pressure Curve in Pipes Arranged in Series	257
12.1.3	Conical Flow Channels	258
12.1.4	Pressure Curve for an Arbitrarily Composed Channel	259
12.2	Rheological Design of Hot Runner Systems for Injection Molding	260
12.3	<i>Tasks:</i> Mathematical Rheological Balancing of Hot Runner Systems	268
12.3.1	Double Mold with Different Melt Distribution Systems	268

12.3.2	Eight-Cavity Mold with Different Melt Distribution Systems	269
12.3.3	Six-Cavity Mold with Different Melt Distribution Systems	271
12.3.4	Family Mold with Two Different Cavities	272
12.4	Rheological Design of Extrusion Molds	273
12.4.1	Mathematical Prerequisites for Balancing	276
12.4.2	Analytical Balancing: Fish-Tail Distributor	278
12.4.3	Analytical Balancing: Coat-Hanger Distributor	280
12.4.4	Numerical Balancing	283
12.4.5	<i>Task:</i> Analytical Balancing of a Fish-Tail Distributor	285
12.4.6	<i>Task:</i> Analytical Balancing of a Coat-Hanger Distributor	286
12.4.7	<i>Task:</i> Numerical Balancing of a Wide Slot Nozzle with a Coat-Hanger Distributor with Segments	286
12.4.8	<i>Task:</i> Calculation of the Output Rate of an Extruder	288
12.4.9	<i>Task:</i> Design of a Slot Die	289
13	Shear and Extensional Pressure Losses at Cross-Sectional Transitions	291
13.1	<i>Task:</i> Extensional and Shear Pressure Losses	295
14	Rheological Mold Design for Injection Molding with the Filling Pattern Method	297
14.1	Reasons for a Graphical Process	297
14.2	Model of the Graphical Mold Filling Process	297
14.3	Rheological Principles	298
14.4	Example of the Filling Pattern Method	301
14.5	<i>Task:</i> Proof of the Independence of the Filling Pattern Method from the Shear-Thinning Viscosity	304
15	Screw Flows	305
15.1	Introduction and Models	305
15.1.1	Melting Model According to Maddock	306
15.1.2	The Two-Plate Model of the Drag Flow	307
15.2	<i>Task:</i> Calculation of the Velocity Profile of a Screw Flow	309
16	Problems with the Flow of Plastic Melts and Solutions	311
16.1	Flow Problems in Multilayer Flows	311
16.1.1	Rearrangement of the Melts	311

16.1.2	Phenomenology of Rearrangement	311
16.1.3	Models for the Development of Rearrangement	312
16.2	Formation of Layer Thicknesses during Sandwich Injection Molding	321
16.3	Normal Stress Effects, Pressure Losses, and Flow Instabilities	330
16.3.1	<i>Task</i> : Total Pressure Drop in an Extrusion Die	334
16.3.2	Effects during Extrusion due to Exceeding the Critical Shear Stress Limit	336
16.3.3	Effects during Injection Molding due to Exceeding the Critical Shear Stress Limit	337
16.3.4	Wall Slip (Stick-Slip Effect)	339
17	Material Parameters	343
17.1	Power-Law (Ostwald and de Waele) Approach	343
17.2	Carreau–WLF Approach	349
17.3	Cross–WLF Approach	356
18	Solutions	359
18.1	Section 7.2.2.2, <i>Task</i> : Determination of the Viscosity for a Given Shear Rate Using a Master Curve	359
18.2	Section 7.2.2.3, <i>Task</i> : Exercise on Temperature Shift Using Zero Viscosity	359
18.3	Section 7.2.4, <i>Task</i> : Calculation of the Temperature Shift Factor	361
18.4	Section 8.1, <i>Task</i> : Graphical Determination of the Constants of the Power Approach	361
18.5	Section 8.2.1, <i>Task</i> : Graphical Determination of the Constants of the Carreau Approach	362
18.6	Section 8.5, <i>Task</i> : Determination of the Consistency Factor and the Viscosity Exponent	362
18.7	Section 8.6, <i>Task</i> : Comparison of the Material Laws (Power Approach and Carreau Approach)	362
18.8	Section 9.4, <i>Task</i> : Effect of the Flow Channel on the Melt Volume Flow Rate	363
18.9	Section 11.2.1.1, <i>Task</i> : Pressure Loss: Plate Geometry	364
18.10	Section 11.2.1.2, <i>Task</i> : Pressure Loss: Disk Geometry	364
18.11	Section 11.2.2, Influence of Material Properties on the Manufacturing Process	364
18.12	Section 11.2.3, <i>Task</i> : Pressure Losses during Injection Molding and the Resulting Real Locking Force	365

18.13 Section 11.2.4, *Task*: Consideration of Dissipation and Cooling Effects
(Non-Isothermal Flow) 365

18.14 Section 11.3, *Task*: Optimum Filling Time 366

18.15 Section 12.3.1, *Task*: Double Mold with Different Melt Distribution
Systems 366

18.16 Section 12.3.2, *Task*: Eight-Cavity Mold with Different Melt Distribution
Systems 367

18.17 Section 12.3.3, *Task*: Six-Cavity Mold with Different Melt Distribution
Systems 367

18.18 Section 12.3.4, *Task*: Family Mold with Two Different Cavities 367

18.19 Section 12.4.5, *Task*: Analytical Balancing of a Fish-Tail Distributor 368

18.20 Section 12.4.6, *Task*: Analytical Balancing of a Coat-Hanger Distributor .. 368

18.21 Section 12.4.7, *Task*: Numerical Balancing of a Wide Slot Nozzle
with a Coat-Hanger Distributor with Segments 369

18.22 Section 12.4.8, *Task*: Calculation of the Output Rate of an Extruder 370

18.23 Section 12.4.9, *Task*: Design of a Slot Die 370

18.24 Section 13.1, *Task*: Extensional and Shear Pressure Losses 370

18.25 Section 14.5, *Task*: Proof of the Independence of the Filling
Pattern Method from the Shear-Thinning Viscosity 370

18.26 Section 16.3.1, *Task*: Total Pressure Drop in an Extrusion Die 371

Index 373