

Contents

- 1 Introduction.....1**
- 2 Properties of Compressed Air5**
 - 2.1 Mathematical Model of Air6
 - 2.2 Atmospheric Air8
 - 2.3 Definitions Related to Compressed Air9
- 3 Thermodynamic Processes.....11**
 - 3.1 Constant Volume Processes.....11
 - 3.2 Constant Pressure Processes13
 - 3.3 Constant Temperature Processes18
 - 3.4 Reversible Processes without Heat Transfer18
 - 3.5 Polytropic Processes20
 - 3.6 General Processes22
 - 3.7 Sonic Velocity23
- 4 Some Results from Fluid Mechanics.....25**
 - 4.1 Viscosity26
 - 4.2 Continuity Equation.....27
 - 4.3 Free Discharge from Nozzles28
 - 4.4 Orifice Flow.....32
 - 4.4.1 Incompressible Flow32
 - 4.4.2 Compressible Flow34
 - 4.5 Frictional Flow36
- 5 Engineering Flow Rate Calculations.....41**
 - 5.1 Mathematical Flow Rate Model41
 - 5.2 Flow Rate Characteristics of Restrictions.....48
 - 5.3 Simplified Flow Calculations49
 - 5.4 Flow Capacity Specifications in Data Sheets50

6 Modelling of Long Lines	55
6.1 Steady-State Losses of Long Lines.....	55
6.1.1 Fluid Mechanics Model	57
6.1.2 Empirical Models	58
6.1.3 Test Results	59
6.2 Steady-State Losses of Fittings.....	62
6.3 Time Domain Models	65
6.3.1 Derivation of Time Domain Model	65
6.3.2 Test Results in the Time Domain	69
6.4 Frequency Domain Models	76
7 Electro-Mechanical Converters.....	81
7.1 Solenoids	81
7.1.1 Switching Solenoids	83
7.1.2 Proportional Solenoids	85
7.1.3 Pulse-Width Modulation	86
7.2 Voice Coil and Plunger Type Systems	93
7.3 Piezoelectric Actuators	94
7.3.1. Stack Translators	94
7.3.2. Benders.....	94
7.3.3 Piezoelectric Elements in Pneumatic Valves.....	95
8 Cylinders.....	99
8.1 Stroke Cushioning	102
8.2 Mathematical Model.....	112
8.3 Cylinder Parameters	116
8.3.1 Seal Friction.....	116
8.3.2 Cylinder Leakage.....	122
8.3.3 Coefficient of Heat Transfer	123
9 Non-Standard Linear Actuators.....	127
9.1 Multi-Position and Tandem Cylinders.....	127
9.2 Rodless Cylinders	130
9.2.1 Split-Seal or Slot Type	130
9.2.2 Cable Type.....	132
9.2.3 Magnetic Type.....	132
9.3 Bellows	133
9.4 Rolling-Diaphragm Cylinders	137
9.6 Brake Chambers	139
9.5 Muscle Actuators	140
9.6 Impact and Knocking Cylinders	142

10 Semi-Rotary Actuators.....	145
10.1 Cylinder Based Actuators	145
10.2 Vane Type Actuators	148
11 Air Motors and Air Turbines	151
11.1 Vane Motors	153
11.1.1 Principle of Operation of Vane Motors	154
11.1.2 Mathematical Model.....	156
11.1.3 Speed Control	164
11.2 Air Turbines.....	168
12 Directional Control Valves.....	171
12.1 Design of Directional Control Valves	173
12.2 Operation of Directional Control Valves.....	175
12.3 Simulation Model of Directional Control Valves.....	181
13 Shut-Off Valves.....	185
13.1 Non-Return Valves	185
13.2 Non-Return Valves with Override.....	188
13.3 Shuttle Valves.....	189
13.4 Twin Pressure Valves	190
13.5 Quick Exhaust Valves	191
14 Pressure Control Valves.....	193
14.1 Spring Controlled Pressure Regulators.....	193
14.1.1 Design of Direct Acting Valves.....	196
14.1.2 Simulation Model of a Pressure Reducing Valves	199
14.1.3 Linear model.....	202
14.1.4 Non-Linear Effects	203
14.1.5 Design of Pilot Operated Valves	205
14.2 Electrically Operated Pressure Regulators	207
14.3 Pressure Regulators with Closed-Loop Control	209
14.3.1 Reports about Commercial Valves	212
14.4 Pressure Relief Valves.....	212
14.5 Soft-Start Valves.....	213
15 Flow Control Valves	215
15.1 Throttling Valve	215
15.2 One-Way Flow Control Valve.....	216
15.3 Delay Valve	217
15.4 Automatic Shut-Off Valves	218

16 Proportional Directional Control Valves.....	221
16.1 Design of Proportional Directional Control Valves	222
16.2 Operation of Proportional Directional Control Valves.....	224
16.3 Simulation Model of Proportional Control Valves.....	230
16.4 Reports about Experimental and Commercial Valves	232
17 Stroke-Time Control	235
17.1 Circuits using Quick Exhaust Valves	237
17.2 Meter-Out Control	239
17.3 Meter-In Control.....	241
17.4 Circuits using Two Pressures.....	242
17.5 Oil Cushioning.....	244
18 Position Control of Pneumatic Systems	247
18.1 Mathematical Model for Control System Design	249
18.2 Model of Control Valves	250
18.3 Pressure Dynamics	253
18.4 Equation of Motion.....	256
18.5 Control Laws	258
18.5.1 Single Loop Controllers.....	259
18.5.2 Additional Loops	260
18.5.3 State Feedback Control.....	260
18.5.4 Reconstruction of the Velocity and Acceleration Signal.....	263
18.5.5 Non-Linear Control Laws.....	263
18.6 Performance of a Commercial System	265
19 Control of Actuators for Process Valves.....	269
19.1 Characteristics of Process Control Systems	271
19.2 Positioners	273
19.2.1 Pneumatic Positioners	275
19.2.2 Analogue Electro-Pneumatic Positioners	276
19.2.3 Digital Positioners	277

20 Digital Simulation281

 20.1 Modelling Approaches282

 20.2 Principles of Object-Oriented Modelling286

 20.3 The Object-Oriented Modelling Language Modelica.....288

 20.4 Fluid Power Libraries in Modelica289

 20.4.1 Examples of Library Models290

 20.4.2 Complex Component Model of the Pneumatic Library292

 20.5 Library Solution for Example.....293

 20.6 Multi-Domain Models294

References.....297

Index319