

Contents

Preface — VII

Acknowledgements — IX

Chapter 1

Thermodynamics refresher — 1

| | |
|---------|---|
| 1.1 | Applicable laws — 1 |
| 1.1.1 | Boyle's law — 2 |
| 1.1.2 | Charles' law — 2 |
| 1.1.3 | Equation of state for ideal gases — 3 |
| 1.1.4 | Mole — 4 |
| 1.1.5 | Avogadro's law — 4 |
| 1.1.6 | Universal gas constant — 5 |
| 1.1.7 | Dalton's law of partial pressure — 6 |
| 1.1.8 | Amagat–Leduc law of additive volumes — 6 |
| 1.2 | Gas mixtures — 7 |
| 1.2.1 | Relationship between molar fraction and mass fraction — 8 |
| 1.3 | Ideal gas equation of state — 9 |
| 1.4 | Compressibility factors — 11 |
| 1.5 | Real gas equations of state — 13 |
| 1.5.1 | Van der Waals' EOS — 14 |
| 1.5.2 | Redlich–Kwong's EOS — 14 |
| 1.5.3 | Soave–Redlich–Kwong's EOS — 15 |
| 1.5.4 | Benedict–Webb–Rubin — 15 |
| 1.5.5 | Peng–Robinson's EOS — 15 |
| 1.6 | Applied laws of thermodynamics — 16 |
| 1.6.1 | First law of thermodynamics — 16 |
| 1.6.2 | Internal energy as a property — 17 |
| 1.6.3 | Thermodynamic processes and systems — 19 |
| 1.6.3.1 | Open systems — 19 |
| 1.6.3.2 | Closed systems — 19 |
| 1.6.3.3 | Isolated systems — 20 |
| 1.6.4 | Special thermodynamic processes — 20 |
| 1.6.4.1 | Adiabatic process — 20 |
| 1.6.4.2 | Isentropic process — 20 |
| 1.6.4.3 | Isothermal process — 20 |
| 1.6.5 | Second law of thermodynamics — 21 |
| 1.6.6 | Entropy relationships — 23 |
| 1.7 | Specific heats — 24 |
| 1.7.1 | Specific heat at constant volume — 24 |

| | |
|-------|---|
| 1.7.2 | Specific heat at constant pressure — 24 |
| 1.7.3 | Specific heat ratio — 25 |
| 1.8 | Simplification of the compression process — 26 |
| 1.8.1 | For an isentropic (reversible adiabatic) compression process — 30 |
| 1.8.2 | For a polytropic compression process — 30 |
| 1.8.3 | For an isothermal compression process — 30 |
| 1.8.4 | Polytropic efficiency — 32 |

Chapter 2

Brief overview of compression machinery — 33

| | |
|----------|--|
| 2.1 | General overview — 33 |
| 2.2 | Dynamic compressors — 35 |
| 2.2.1 | Centrifugal compressors — 35 |
| 2.2.1.1 | Inlet channel — 36 |
| 2.2.1.2 | Centrifugal impeller — 36 |
| 2.2.1.3 | Diffuser — 38 |
| 2.2.1.4 | Collector (volute/scroll) — 39 |
| 2.2.1.5 | Horizontal and vertical split — 41 |
| 2.2.2 | Axial compressors — 44 |
| 2.3 | Positive displacement compressors — 48 |
| 2.3.1 | Reciprocating compressors — 48 |
| 2.3.1.1 | Cylinder — 51 |
| 2.3.1.2 | Piston, piston rings, and wear bands — 51 |
| 2.3.1.3 | Piston rod — 53 |
| 2.3.1.4 | Packing rings — 53 |
| 2.3.1.5 | Crosshead — 54 |
| 2.3.1.6 | Crankshafts — 55 |
| 2.3.1.7 | Connecting rod and bearings — 55 |
| 2.3.1.8 | Valves — 56 |
| 2.3.2 | Rotary compressors — 56 |
| 2.3.2.1 | Screw compressors — 57 |
| 2.3.2.2 | Operating principles of oil-free (dry) and liquid-flooded (wet) compressors — 58 |
| 2.3.2.3 | Application ranges for rotary screw compressors — 59 |
| 2.3.2.4 | Oil-free versus liquid-flooded twin-screw compressors — 61 |
| 2.3.2.5 | Screw compressor volume control — 63 |
| 2.3.2.6 | Bearings — 66 |
| 2.3.2.7 | Seals — 67 |
| 2.3.2.8 | Rotary sliding vane compressors — 69 |
| 2.3.2.9 | Rotary lobed compressors — 70 |
| 2.3.2.10 | Liquid ring/piston compressors — 71 |
| | References — 73 |

Chapter 3**Technical briefs on dynamic compressor technology — 74**

- 3.1 Axial compressors — 74
 - 3.1.1 Optimization of flow path; optimized blade profiles; comments on application requirements — 74
 - 3.1.1.1 Design procedure — 80
 - 3.1.2 Simplified approaches to evaluating mechanical integrity of axial blading — 90
 - 3.1.2.1 Methods to validate blade resonant frequencies — 90
 - 3.1.2.2 Optimizing blade design to prevent excitation — 92
 - 3.1.2.3 Different modes to be examined to validate excitation avoidance — 96
 - 3.1.2.4 Stress margin verification by test — 98
 - 3.2 Centrifugal compressors — 99
 - 3.2.1 Novel approaches to mitigate fouling spearheaded by Elliott-turbo — 99
 - 3.2.1.1 Surface treatment technologies — 99
 - 3.2.1.2 Discussion on effective wash nozzle arrangements — 110
 - 3.2.2 Modern design and manufacturing considerations — 116
 - 3.2.3 A new approach to uprateability of compressor trains — 119
 - 3.2.3.1 Rotor flexural stiffness limitation — 120
 - 3.2.3.2 Nozzle limitation — 123
 - 3.2.3.3 Shaft end limitation — 124
 - 3.2.4 Using available database to assist design audits and selection — 126
 - 3.2.5 Rethinking driver selections for ethylene refrigeration trains — 128
 - 3.2.5.1 Driver criteria — 128
 - 3.2.5.2 References — 131

Chapter 4**Technical briefs on positive displacement compressors — 133**

- 4.1 Screw compressors — 133
 - 4.1.1 Using innovative new rotor profile to maximize performance of screw compressor rotor in general — 133
 - 4.1.1.1 Identifying the factors influencing screw compressor efficiency — 133
 - 4.1.1.2 Considerations for minimizing leakage paths — 135
 - 4.1.1.3 *L/D* considerations — 136
 - 4.1.1.4 Lobe combination — 137
 - 4.1.1.5 Rotor profile generation and manufacturing complexities — 139
 - 4.1.2 Optimizing slide valve design to improve capacity control — 140
 - 4.1.2.1 Screw compressor slide valves in general — 140

| | |
|---------|---|
| 4.1.2.2 | Different slide valve controlling methods — 141 |
| 4.2 | Reciprocating compressors — 143 |
| 4.2.1 | Understanding various industrial interpretations of rod loading — 143 |
| 4.2.1.1 | Frame loads — 143 |
| 4.2.2 | Recent developments, valve selection, and technical advances — 158 |
| 4.2.2.1 | Overview — 158 |
| 4.2.2.2 | Types of valves — 160 |
| 4.2.2.3 | Examining modular straight-through flow valves — 164 |
| | References — 169 |

Chapter 5

Factory testing of centrifugal compressors — 170

| | |
|---------|--|
| 5.1 | Brief overview of ASME PTC-10 thermodynamic test procedure — 170 |
| 5.1.1 | Introduction — 170 |
| 5.1.2 | Class of performance test — 171 |
| 5.1.3 | Selecting the test gas — 173 |
| 5.1.4 | Instrument and calibration — 175 |
| 5.1.5 | Loop testing — 175 |
| 5.1.6 | Calculation procedures — 177 |
| 5.1.6.1 | Determination of the test speed — 177 |
| 5.1.6.2 | Determination of the test gas volume flow — 179 |
| 5.1.6.3 | Compression power required for test gas — 179 |
| 5.1.6.4 | Determining the machine Mach number — 179 |
| 5.1.7 | Test points — 180 |
| 5.1.7.1 | Side stream compressors — 181 |
| 5.1.8 | Performance evaluation — 182 |
| 5.1.9 | Test report — 183 |
| 5.2 | Discussion of executing a mechanical run test as per API 617 — 183 |
| 5.2.1 | Guidelines and test setup for no-load and full-load mechanical tests — 183 |
| 5.2.1.1 | Test sequence — 186 |
| 5.2.1.2 | The 4 h running test — 186 |
| 5.2.1.3 | Unbalanced rotor verification test — 189 |
| 5.2.1.4 | Acceptance criteria — 190 |
| 5.2.2 | Post test inspection — 193 |
| 5.2.2.1 | Bearings and seals — 193 |
| 5.2.2.2 | Compressor internals — 194 |
| 5.2.2.3 | Hydraulic coupling fit — 194 |
| 5.2.3 | Rotor stability test — 194 |

| | |
|---------|-------------------------|
| 5.2.3.1 | Casing excitation — 194 |
| 5.2.3.2 | Rotor excitation — 194 |
| | References — 196 |

Chapter 6

Measuring of train performance using torque meters — 197

| | |
|---------|--|
| 6.1 | Understanding the basic principles of different measuring techniques — 197 |
| 6.2 | Measurement using phase change between fixed points on a rotor — 198 |
| 6.3 | Measurement using strain gages — 200 |
| 6.4 | New optional features of torque meters — 202 |
| 6.4.1 | Hot alignment — 202 |
| 6.4.2 | Transient/dynamic torque measurement — 203 |
| 6.4.2.1 | Potential uses for dynamic torque monitoring — 203 |
| 6.4.2.2 | Torquetronics dynamic torque-metering system — 203 |
| 6.4.2.3 | Indikon/Riverhawk dynamic torque-meter system — 204 |

Chapter 7

Basic rotordynamics — 205

| | |
|-------|---|
| 7.1 | Introduction to rotordynamics — 205 |
| 7.2 | Lateral dynamics — 206 |
| 7.2.1 | Overview of performance requirements — 206 |
| 7.2.2 | Component modeling considerations — 209 |
| 7.2.3 | Typical lateral analyses — 214 |
| 7.3 | Lateral stability of rotors — 221 |
| 7.4 | Other lateral analysis considerations — 224 |
| 7.5 | Rotordynamics design verification testing — 224 |
| 7.6 | Torsional dynamics — 226 |
| 7.6.1 | Overview of performance requirements — 226 |
| 7.6.2 | Component modeling aspects — 228 |
| 7.6.3 | Typical torsional analyses — 229 |
| 7.6.4 | Other torsional analysis considerations — 234 |
| | References — 234 |

Chapter 8

Approaches for sizing lube oil systems — 237

| | |
|-------|--|
| 8.1 | General approach to equipment sizing — 237 |
| 8.2 | Main and auxiliary standby pump — 239 |
| 8.2.1 | Determining pump capacity — 239 |
| 8.2.2 | Pump's maximum pressure — 239 |
| 8.3 | Oil coolers — 243 |

| | |
|-------|---|
| 8.4 | Reservoir — 245 |
| 8.5 | Oil filters — 246 |
| 8.6 | Oil accumulator — 248 |
| 8.7 | Optimizing coast-down time for RDTs — 254 |
| 8.7.1 | Key design parameters to be examined — 256 |
| 8.7.2 | Methodology used to validate key parameters — 257 |
| | References — 263 |

Chapter 9

Dry Gas Seals, Auxiliaries, and Support Systems — 264

| | |
|----------|---|
| 9.1 | Dry gas seals (DGS) — 264 |
| 9.1.1 | Principle of operation — 265 |
| 9.1.2 | Merits of using different seal configurations — 267 |
| 9.1.2.1 | Tandem seal arrangement — 267 |
| 9.1.2.2 | Double-seal arrangements — 269 |
| 9.1.3 | Dry gas seal support systems — 270 |
| 9.1.3.1 | Seal gas supply — 271 |
| 9.1.3.2 | Monitoring primary seal — 272 |
| 9.1.3.3 | Secondary seal monitoring — 273 |
| 9.1.3.4 | Separation seal supply system and monitoring — 274 |
| 9.1.4 | Dry gas seal innovations — 275 |
| 9.1.4.1 | Increased sealing pressure capabilities — 275 |
| 9.1.4.2 | Expanding temperature capabilities — 277 |
| 9.1.4.3 | Reducing seal leakage — 278 |
| 9.1.4.4 | Slow roll turning and ratcheting — 280 |
| 9.1.4.5 | Separation seals — 281 |
| 9.1.4.6 | Increasing seal reliability — 283 |
| 9.1.4.7 | Dual-phase gas — 285 |
| 9.1.4.8 | Material selection — 286 |
| 9.1.4.9 | Stationary face — 289 |
| 9.1.4.10 | Rotating face — 289 |

Chapter 10

Equipment purchasing — 290

| | |
|------|---|
| 10.1 | Consider single-point responsibility for major fluid machines — 290 |
| | Agreement on “train responsibility” — 290 |
| | Exceptions to the rule — 290 |
| | Focusing on the bright side — 291 |

Chapter 11**Design basics of tabletop foundations for machinery engineers — 294**

- 11.1 Introduction — 294
- 11.2 Common types of compressor foundations — 295
- 11.3 Predimensioning of foundation tabletop — 297
- 11.4 Materials — 299
- 11.5 Structural modeling of the tabletop main objectives of modeling — 300
- References — 301

Chapter 12**Special-purpose couplings — 302**

- 12.1 Introduction — 302
- 12.2 Diaphragm couplings — 302
- 12.3 Disk couplings — 305
- 12.4 Technological improvement to shaft–hub interface joint for low moment couplings — 308
- 12.5 Torsional peak shaver safety hub — 315
- 12.5.1 Data requirements and example — 317
- References — 321

Chapter 13**Compressor controls and protection systems — 322**

- 13.1 Turbomachinery control functions in the distributed control system — 322
- 13.2 TMC requirements — 323
- 13.2.1 Overview of TMC systems — 323
- 13.2.2 Speed control — 324
- 13.2.3 Antisurge control — 325
- 13.2.4 Capacity control — 326
- 13.2.5 Other consideration — 327
- 13.3 Various approaches to TMC architecture and interfaces to DCS — 327
- 13.3.1 Communications — 330
- 13.4 Fault-tolerant architectures — 332
- 13.4.1 Software standards — 334
- 13.5 Surge detection and API-670, fifth edition — 334
- 13.6 New development for TMC systems — 337
- 13.6.1 Signal drift detection — 337

XVIII — Contents

- 13.6.2 Detecting a “frozen” signal — **338**
- 13.6.3 Reducing the risk of antisurge valve not opening — **338**
- 13.7 Instrumentation selection — **340**
- 13.7.1 Flow measurement — **340**
- 13.7.2 Antisurge valve — **340**

Appendix A Physical properties of various gases — 343

Appendix B Sizing different types of compressors — 361

Appendix C Novel mitigation techniques for solving rotor stability problems — 411

Appendix D Machinery quality assessment (MQA) — 429

Index — 463