

A User's Guide to Vacuum Technology

Third Edition

John F. O'Hanlon

Professor Emeritus of Electrical and Computer Engineering
The University of Arizona



A JOHN WILEY & SONS, INC., PUBLICATION

Contents

ITS BASIS

1. Vacuum Technology	3
1.1 Units of Measurement	6
References	8
2. Gas Properties	9
2.1 Kinetic Picture of a Gas	9
2.1.1 Velocity Distribution	10
2.1.2 Energy Distribution	11
2.1.3 Mean Free Path	12
2.1.4 Particle Flux	13
2.1.5 Monolayer Formation Time	14
2.1.6 Pressure	14
2.2 Gas Laws	15
2.2.1 Boyle's Law	15
2.2.2 Amonton's Law	16
2.2.3 Charles' Law	16
2.2.4 Dalton's Law	16
2.2.5 Avogadro's Law	16
2.2.6 Graham's Law	17
2.3 Elementary Gas Transport Phenomena	18
2.3.1 Viscosity	18
2.3.2 Thermal Conductivity	20
2.3.3 Diffusion	21
2.3.4 Thermal Transpiration	22
References	23
Problems	24
3. Gas Flow	25
3.1 Flow Regimes	25
3.2 Throughput, Mass Flow, and Conductance	27
3.3 Continuum Flow	28
3.3.1 Orifices	29
3.3.2 Long Round Tubes	30

- 3.3.3 Short Round Tubes 32
- 3.4 Molecular Flow 32
 - 3.4.1 Orifices 33
 - 3.4.2 Long Round Tubes 34
 - 3.4.3 Short Round Tubes 34
 - 3.4.4 Other Short Structure Solutions 36
 - Analytical Solutions 37
 - Monte Carlo Technique 38
 - 3.4.5 Combining Molecular Conductances 39
 - Parallel Conductances 39
 - Series Conductances 39
 - Exit and Entrance Effects 44
 - Series Calculations 45
- 3.5 The Transition Region 49
- 3.6 Models Spanning Several Pressure Regions 50
- 3.7 Summary of Flow Regimes 51
- References 52
- Problems 53

4. Gas Release from Solids

57

- 4.1 Vaporization 57
- 4.2 Diffusion 58
 - 4.2.1 Reduction of Outdiffusion by Vacuum Baking 60
- 4.3 Thermal Desorption 61
 - 4.3.1 Desorption Without Readsorption 62
 - Zero-Order Desorption 62
 - First-Order Desorption 62
 - Second-Order Desorption 63
 - 4.3.2 Desorption from Real Surfaces 65
 - Outgassing Measurements 65
 - Outgassing Models 67
 - Reduction of Outgassing by Baking 68
- 4.4 Stimulated Desorption 70
 - 4.4.1 Electron-Stimulated Desorption 70
 - 4.4.2 Ion-Stimulated Desorption 70
 - 4.4.3 Stimulated Chemical Reactions 70
 - 4.4.4 Photodesorption 71
- 4.5 Permeation 71
 - 4.5.1 Molecular Permeation 71
 - 4.5.2 Dissociative Permeation 73
 - 4.5.3 Permeation and Outgassing Units 73
- 4.6 Pressure Limits 74
- References 77
- Problems 77

MEASUREMENT

- | | |
|---|------------|
| 5. Pressure Gauges | 81 |
| 5.1 Direct-Reading Gauges 81 | |
| 5.1.1 Diaphragm and Bourdon Gauges 82 | |
| 5.1.2 Capacitance Manometers 83 | |
| 5.2 Indirect-Reading Gauges 87 | |
| 5.2.1 Thermal Conductivity Gauges 87 | |
| Pirani Gauge 88 | |
| Thermocouple Gauge 91 | |
| Stability and Calibration 92 | |
| 5.2.2 Spinning Rotor Gauge 92 | |
| 5.2.3 Ionization Gauges 94 | |
| Hot Cathode Gauges 94 | |
| Hot Cathode Gauge Errors 100 | |
| Cold Cathode Gauge 103 | |
| Gauge Calibration 104 | |
| References 105 | |
| Problems 106 | |
|
 | |
| 6. Flow Meters | 109 |
| 6.1 Molar Flow, Mass Flow, and Throughput 109 | |
| 6.2 Rotameters and Chokes 112 | |
| 6.3 Differential Pressure Techniques 114 | |
| 6.4 Thermal Mass Flow Meter Technique 115 | |
| 6.4.1 Mass Flow Meter 115 | |
| 6.4.2 Mass Flow Controller 120 | |
| 6.4.3 Mass Flow Meter Calibration 120 | |
| References 121 | |
| Problems 121 | |
|
 | |
| 7. Pumping Speed | 123 |
| 7.1 Pumping Speed 123 | |
| 7.2 Mechanical Pumps 124 | |
| 7.3 High Vacuum Pumps 125 | |
| 7.3.1 Measurement Techniques 125 | |
| Pump Dependence 126 | |
| Measurement of Water Vapor Pumping Speed 126 | |
| Pumping Speed at the Chamber 127 | |
| 7.3.2 Measurement Error 128 | |
| References 130 | |
| Problems 130 | |

- 8. Residual Gas Analyzers** **133**
- 8.1 Instrument Description 133
- 8.1.1 Ion Sources 134
- Open Ion Sources 135
- Closed Ion Sources 136
- 8.1.2 Mass Filters 139
- Magnetic Sector 139
- RF Quadrupole 141
- Resolving Power 145
- 8.1.3 Detectors 145
- Discrete Dynode Electron Multiplier 147
- Continuous Dynode Electron Multiplier 148
- 8.2 Installation and Operation 150
- 8.2.1 High Vacuum Operation 150
- Mounting 150
- Stability 151
- 8.2.2 Medium and Low Vacuum Sampling 153
- Differentially Pumped Sampling 153
- Miniature Quadrupoles 156
- 8.3 RGA Calibration 156
- 8.4 RGA Selection 158
- References 159
- Problems 160
- 9. Interpretation of RGA Data** **161**
- 9.1 Cracking Patterns 161
- 9.1.1 Dissociative Ionization 161
- 9.1.2 Isotopes 162
- 9.1.3 Multiple Ionization 163
- 9.1.4 Combined Effects 163
- 9.1.5 Ion Molecule Reactions 165
- 9.2 Qualitative Analysis 166
- 9.3 Quantitative Analysis 172
- 9.3.1 Isolated Spectra 172
- 9.3.2 Overlapping Spectra 173
- References 177
- Problems 178
- PRODUCTION**
- 10. Mechanical Pumps** **183**
- 10.1 Rotary Vane Pump 183
- 10.2 Rotary Piston Pump 187

10.3	Lobe Pump	189
10.4	Claw Pump	193
10.5	Scroll Pump	194
10.6	Screw Pump	195
10.7	Diaphragm Pump	196
10.8	Mechanical Pump Operation	198
	References	199
	Problems	199
11.	Turbomolecular Pumps	201
11.1	Pumping Mechanism	201
11.2	Speed-compression Relations	203
	11.2.1 Maximum Compression Ratio	203
	11.2.2 Maximum Speed	206
	11.2.3 General Relation	207
11.3	Ultimate Pressure	209
11.4	Turbomolecular Pump Designs	210
11.5	Turbomolecular Drag Pumps	213
	References	214
	Problems	215
12.	Diffusion Pumps	217
12.1	Pumping Mechanism	217
12.2	Speed-Throughput Characteristics	219
12.3	Boiler Heating Effects	223
12.4	Backstreaming, Baffles, and Traps	224
	References	227
	Problems	228
13.	Pump Fluids	229
13.1	Fluid Properties	229
	13.1.1 Vapor Pressure	229
	13.1.2 Other Properties	233
13.2	Pump Fluid Types	234
	13.2.1 Mineral Oils	234
	13.2.2 Synthetic Fluids	235
	Esters	236
	Silicones	236
	Ethers	237
	Fluorochemicals	237
13.3	Fluid Selection	238
	13.3.1 Rotary Vane, Piston, and Lobe Pumps	238
	13.3.2 Turbomolecular Pumps	240

- 13.3.3 Diffusion Pumps 241
- 13.4 Reclamation 244
- References 244
- Problems 245

- 14. Getter and Ion Pumps** **247**
 - 14.1 Getter Pumps 247
 - 14.1.1 Titanium Sublimation Pumps 248
 - 14.1.2 Nonevaporable Getter 258
 - 14.2 Ion Pumps 256
 - References 260
 - Problems 261

- 15. Cryogenic Pumps** **263**
 - 15.1 Pumping Mechanisms 264
 - 15.2 Speed, Pressure, and Saturation 267
 - 15.3 Refrigeration Techniques 271
 - 15.4 Cryogenic Pump Characteristics 276
 - 15.4.1 Medium Vacuum Sorption Pumps 276
 - 15.4.2 High Vacuum Gas Refrigerator Pumps 279
 - 15.4.3 High Vacuum Liquid Pumps 283
 - References 284
 - Problems 286

MATERIALS

- 16. Materials in Vacuum** **289**
 - 16.1 Metals 290
 - 16.1.1 Vaporization 290
 - 16.1.2 Permeability 290
 - 16.1.3 Outgassing 291
 - Dissolved Gas 292
 - Surface and Near-Surface Gas 295
 - 16.1.4 Structural Metals 299
 - 16.2 Glasses and Ceramics 300
 - 16.3 Polymers 306
 - References 309
 - Problems 311

- 17. Joints, Seals, and Valves** **313**
 - 17.1 Permanent Joints 313
 - 17.1.1 Welding 314
 - 17.1.2 Soldering and Brazing 318

- 17.1.3 Joining Glasses and Ceramics 319
- 17.2 Demountable Joints 321
 - 17.2.1 Elastomer Seals 322
 - 17.2.2 Metal Gaskets 328
- 17.3 Valves and Motion Feedthroughs 329
 - 17.3.1 Small Valves 330
 - 17.3.2 Large Valves 332
 - 17.3.3 Special Purpose Valves 335
 - 17.3.4 Motion Feedthroughs 337
- References 341
- Problems 342

- 18. Lubrication** **345**
 - 18.1 Lubrication Processes 345
 - 18.2 Rheology 347
 - 18.2.1 Absolute Viscosity 347
 - 18.2.2 Kinematic Viscosity 348
 - 18.2.3 Viscosity Index 348
 - 18.3 Lubrication Techniques 349
 - 18.3.1 Liquid Lubrication 349
 - 18.3.2 Grease Lubrication 352
 - 18.3.3 Dry Lubrication 353
 - References 355
 - Problems 356

SYSTEMS

- 19. Rough Vacuum Pumping** **359**
 - 19.1 Pumping Rate 360
 - 19.1.1 Pump Size 360
 - 19.1.2 Aerosol Formation 362
 - 19.2 Crossover 365
 - 19.2.1 Oil Backstreaming 366
 - 19.2.2 Overload Criteria 369
 - Diffusion Pumps 369
 - Turbomolecular Pumps 371
 - Cryogenic Pumps 373
 - Ion Pumps 374
 - References 375
 - Problems 376
- 20. High Vacuum Systems** **379**
 - 20.1 Diffusion-Pumped Systems 379

20.1.1	System Operation	382	
20.1.2	Operating Concerns	383	
20.2	Turbomolecular-Pumped Systems	385	
20.2.1	System Operation	388	
20.2.2	Operating Concerns	389	
20.3	Ion-Pumped Systems	391	
20.3.1	System Operation	391	
20.3.2	Operating Concerns	393	
20.4	Cryogenic-Pumped Systems	394	
20.4.1	System Operation	394	
20.4.2	Regeneration	394	
20.4.3	Operating Concerns	396	
20.5	High Vacuum Chambers	397	
20.5.1	Managing Water Vapor		
	References	400	
	Problems	400	
21.	Ultraclean Vacuum Systems		403
21.1	Ultraclean Pumps	405	
21.1.1	Turbomolecular Pumps	405	
21.1.2	Cryogenic Pumps	406	
21.1.3	Sputter-Ion, TSP, and NEG Pumps	406	
21.2	Ultraclean Chambers	407	
21.2.1	Chamber Materials and Components	407	
21.2.2	Chamber Pumping	409	
21.2.3	Pressure Measurement	412	
	References	412	
	Problems	413	
22.	High Flow Systems		415
22.1	Mechanically Pumped Systems	417	
22.2	Throttled High Vacuum Systems	419	
22.2.1	Process Chambers	419	
22.2.2	Turbo Pumped	421	
22.2.3	Cryo Pumped	424	
	References	429	
	Problems	429	
23.	Multichamber Systems		431
23.1	Flexible Substrates	432	
23.2	Rigid Substrates	434	
23.2.1	Inline Systems	435	
23.2.2	Cluster Systems	440	

23.3 Instrumentation Systems	443
References	444
Problems	444
24. Leak Detection	447
24.1 Instruments	448
24.1.1 Forward-Flow Leak Detector	448
24.1.2 Counter-Flow Leak Detector	449
24.2 Performance	450
24.2.1 Sensitivity	450
24.2.2 Response Time	452
24.2.3 Sampling Pressurized Chambers	453
24.3 Leak-Hunting Techniques	453
References	457
Problems	457
Symbols	459

APPENDIXES

A. Units and Constants	463
A.1 Physical Constants	463
A.2 SI Base Units	463
A.3 Conversion Factors	464
B. Gas Properties	466
B.1 Mean Free Paths of Gases as a Function of Pressure	466
B.2 Physical Properties of Gases and Vapors at $T = 0^{\circ}\text{C}$	467
B.3 Cryogenic Properties of Gases	468
B.4 Gas Conductance and Flow Formulas	469
B.5 Vapor Pressure Curves of Common Gases	475
B.6 Appearances of Discharges in Gases and Vapors at Low Pressures	477
C. Material Properties	478
C.1 Outgassing Rates of Vacuum Baked Metals	478
C.2 Outgassing Rates of Unbaked Metals	479
C.3 Outgassing Rates of Unbaked Ceramics and Glasses	480
C.4 Outgassing Rates of Elastomers	480
C.5 Permeability of Polymeric Materials	481
C.6 Vapor Pressure Curves of Solid and Liquid Elements	482
C.7 Outgassing Rates of Polymers	485
C.8 Austenitic Stainless Steels	486

D. Isotopic Abundances	488
E. Cracking Patterns	492
E.1 Cracking Patterns of Pump Fluids	492
E.2 Cracking Patterns of Gases	494
E.3 Cracking Patterns of Common Vapors	495
E.4 Cracking Patterns of Common Solvents	496
E.5 Cracking Patterns of Semiconductor Dopants	497
F. Pump Fluid Properties	498
F.1 Compatibility of Elastomers and Pump Fluids	498
F.2 Vapor Pressures of Mechanical Pump Fluids	499
F.3 Vapor Pressure of Diffusion Pump Fluids	500
F.4 Kinematic Viscosity of Pump Fluids	501
F.5 Kinematic Viscosity Conversion Factors	502
References	503
Index	505