

Contents

PREFACE	v
CONTENTS	vii
COMMONLY USED SYMBOLS	xiii
1. INTRODUCTION	1
1.1. The vacuum	1
1.1.1. <i>Artificial vacuum</i>	1
1.1.2. <i>Natural vacuum</i>	5
1.2. Fields of application and importance	6
1.2.1. <i>Applications of vacuum techniques</i>	6
1.2.2. <i>Importance of vacuum technology</i>	9
1.3. Main stages in the history of vacuum techniques	10
1.4. Literature sources	12
1.4.1. <i>Books</i>	12
1.4.2. <i>Journals</i>	13
1.4.3. <i>Conference transactions</i>	14
2. RAREFIED GAS THEORY FOR VACUUM TECHNOLOGY	16
2.1. Physical states of matter	16
2.2. Perfect and real gas laws	22
2.2.1. <i>Boyle's law</i>	22
2.2.2. <i>Charles' law</i>	24
2.2.3. <i>The general gas law</i>	25
2.2.4. <i>Molecular density</i>	27
2.2.5. <i>Equation of state of real gases</i>	29
2.3. Motion of molecules in rarefied gases	31
2.3.1. <i>Kinetic energy of molecules</i>	31
2.3.2. <i>Molecular velocities</i>	33
2.3.3. <i>Molecular incidence rate</i>	34
2.4. Pressure and mean free path	36
2.4.1. <i>Mean free path</i>	36
2.4.2. <i>Pressure units</i>	39
2.5. Transport phenomena in viscous state	41
2.5.1. <i>Viscosity of a gas</i>	41
2.5.2. <i>Diffusion of gases</i>	46

2.6.	Transport phenomena in molecular state	48
2.6.1.	<i>The viscous and molecular states</i>	48
2.6.2.	<i>Molecular drag</i>	49
2.7.	Thermal diffusion and energy transport	52
2.7.1.	<i>Thermal transpiration</i>	52
2.7.2.	<i>Thermal diffusion</i>	54
2.7.3.	<i>Heat conductivity of rarefied gases</i>	54
3.	GAS FLOW AT LOW PRESSURES	60
3.1.	Flow regimes, conductance and throughput.	60
3.1.1.	<i>Flow regimes</i>	60
3.1.2.	<i>Conductance</i>	62
3.1.3.	<i>Throughput and pumping speed</i>	65
3.2.	Viscous and turbulent flow	67
3.2.1.	<i>Viscous flow – conductance of an aperture</i>	67
3.2.2.	<i>Viscous flow – conductance of a cylindrical pipe</i>	70
3.2.3.	<i>Viscous flow – surface slip</i>	74
3.2.4.	<i>Viscous flow – rectangular cross section</i>	75
3.2.5.	<i>Viscous flow – annular cross section</i>	76
3.2.6.	<i>Turbulent flow</i>	77
3.3.	Molecular flow	78
3.3.1.	<i>Molecular flow – conductance of an aperture</i>	78
3.3.2.	<i>Molecular flow – conductance of a diaphragm</i>	79
3.3.3.	<i>Molecular flow – long tube of constant cross section</i>	80
3.3.4.	<i>Molecular flow – short tube of constant cross section</i>	84
3.4.	Conductance of combined shapes	86
3.4.1.	<i>Molecular flow – tapered tubes</i>	86
3.4.2.	<i>Molecular flow – elbows</i>	88
3.4.3.	<i>Molecular flow – traps</i>	89
3.4.4.	<i>Molecular flow – optical baffles</i>	94
3.4.5.	<i>Molecular flow – seal interface</i>	98
3.5.	Analytical–statistical calculation of conductances	100
3.6.	Intermediate flow	106
3.6.1.	<i>Knudsen’s equation</i>	106
3.6.2.	<i>The minimum conductance</i>	109
3.6.3.	<i>The transition pressure</i>	111
3.6.4.	<i>Limits of the intermediate range</i>	112
3.6.5.	<i>General equation of flow</i>	114
3.6.6.	<i>The molecular–viscous intersection point</i>	114
3.6.7.	<i>Integrated equation of flow</i>	116
3.7.	Calculation of vacuum systems	121
3.7.1.	<i>Sources of gas in vacuum systems</i>	121

CONTENTS

ix

3.7.2.	<i>Pumpdown in the viscous range</i>	122
3.7.3.	<i>Pumpdown in the molecular range</i>	125
3.7.4.	<i>Steady state with distributed gas load</i>	129
3.7.5.	<i>Nomographic calculation of conductances and pumpdown time</i>	131
3.7.6.	<i>Evaluation of the gas load and pumping requirements</i>	134
4.	PHYSICO-CHEMICAL PHENOMENA IN VACUUM TECHNIQUES	147
4.1.	Evaporation–condensation	147
4.1.1.	<i>Vapours in vacuum systems</i>	147
4.1.2.	<i>Vapour pressure and rate of evaporation</i>	148
4.1.3.	<i>Vapour pressure data</i>	150
4.1.4.	<i>Cryopumping and vacuum coating</i>	154
4.2.	Solubility and permeation	161
4.2.1.	<i>The permeation process</i>	161
4.2.2.	<i>Permeation through vacuum envelopes</i>	164
4.2.3.	<i>Consequences of permeation</i>	167
4.3.	Sorption	170
4.3.1.	<i>Sorption phenomena</i>	170
4.3.2.	<i>Adsorption energies</i>	170
4.3.3.	<i>Monolayer and sticking coefficient</i>	173
4.3.4.	<i>Adsorption isotherms</i>	175
4.3.5.	<i>True surface</i>	178
4.3.6.	<i>Sorption of gases by absorbents</i>	179
4.4.	Desorption–outgassing	183
4.4.1.	<i>Desorption phenomena</i>	183
4.4.2.	<i>Outgassing</i>	184
4.4.3.	<i>Outgassing rates</i>	187
4.5.	Interaction of electrons and ions with surfaces	189
4.5.1.	<i>Electron scattering</i>	189
4.5.2.	<i>Ion scattering</i>	191
4.5.3.	<i>Low energy electron diffraction (LEED)</i>	192
4.5.4.	<i>Auger electron spectroscopy (AES)</i>	193
5.	PRODUCTION OF LOW PRESSURES	197
5.1.	Vacuum pumps	197
5.1.1.	<i>Principles of pumping</i>	197
5.1.2.	<i>Parameters and classifications</i>	197
5.2.	Mechanical pumps	200
5.2.1.	<i>Liquid pumps</i>	200
5.2.2.	<i>Piston pumps</i>	201
5.2.3.	<i>Water ring pumps</i>	203
5.2.4.	<i>Rotating-vane pumps</i>	205

5.2.5.	<i>Sliding-vane pumps</i>	209
5.2.6.	<i>Rotating-plunger pumps</i>	211
5.2.7.	<i>Root's pumps</i>	212
5.2.8.	<i>Molecular pumps</i>	213
5.3.	Vapour pumps	215
5.3.1.	<i>Classification</i>	215
5.3.2.	<i>Vapour ejector pumps</i>	216
5.3.3.	<i>Diffusion pumps</i>	218
5.4.	Ion pumps	226
5.4.1.	<i>Classification</i>	226
5.4.2.	<i>Ion pumping</i>	228
5.4.3.	<i>Evapor-ion pumps</i>	229
5.4.4.	<i>Sputter-ion pumps</i>	234
5.5.	Sorption pumps	238
5.5.1.	<i>Nature of sorption pumping</i>	238
5.5.2.	<i>The sorption pump</i>	240
5.5.3.	<i>Multistage sorption pumping</i>	242
5.6.	Cryopumping	244
5.6.1.	<i>Cryopumping mechanism</i>	244
5.6.2.	<i>Cryopumping arrays</i>	250
5.6.3.	<i>Cryotrapping</i>	253
5.6.4.	<i>Cryopumps</i>	254
5.6.5.	<i>Liquid nitrogen traps</i>	256
5.7.	Gettering	259
5.7.1.	<i>Gettering principles</i>	259
5.7.2.	<i>Flash getters</i>	260
5.7.3.	<i>Bulk and coating getters</i>	262
5.7.4.	<i>Gettering capacity</i>	264
5.7.5.	<i>Sublimation pumps</i>	265
5.8.	Pumping by dilution	266
5.9.	Measurement of pumping speed	267
5.9.1.	<i>Methods of measurement</i>	267
5.9.2.	<i>Constant pressure methods</i>	267
5.9.3.	<i>Constant volume method</i>	270
5.9.4.	<i>Measurement of the pumping speed of mechanical and diffusion pumps</i>	271
5.9.5.	<i>Measurement of the pumping speed of sputter-ion pumps</i>	271
6.	MEASUREMENT OF LOW PRESSURES	274
6.1.	Classification and selection of vacuum gauges	274
6.2.	Mechanical gauges	276
6.2.1.	<i>Bourdon gauge</i>	276

CONTENTS

xi

6.2.2.	<i>Diaphragm gauges</i>	277
6.3.	Gauges using liquids	279
6.3.1.	<i>U-tube manometers</i>	279
6.3.2.	<i>Inclined manometers</i>	280
6.3.3.	<i>Differential manometers</i>	281
6.3.4.	<i>The Dubrovin gauge</i>	281
6.3.5.	<i>The McLeod gauge</i>	283
6.4.	Viscosity (molecular) gauges	291
6.4.1.	<i>Principles</i>	291
6.4.2.	<i>The decrement gauge</i>	291
6.4.3.	<i>The rotating molecular gauge</i>	292
6.4.4.	<i>The resonance type viscosity gauge</i>	293
6.5.	Radiometer (Knudsen) gauge	294
6.6.	Thermal conductivity gauges	296
6.6.1.	<i>Thermal conductivity and heat losses</i>	296
6.6.2.	<i>Pirani gauge</i>	298
6.6.3.	<i>The thermocouple gauge</i>	300
6.6.4.	<i>The thermistor gauge</i>	301
6.6.5.	<i>Combined McLeod–Pirani gauge</i>	302
6.7.	Ionization gauges	303
6.7.1.	<i>The discharge tube</i>	303
6.7.2.	<i>Hot-cathode ionization gauges</i>	304
6.7.3.	<i>Cold-cathode ionization gauges</i>	313
6.7.4.	<i>Gauges with radioactive sources</i>	316
6.8.	Calibration of vacuum gauges	317
6.8.1.	<i>General</i>	317
6.8.2.	<i>McLeod gauge method</i>	318
6.8.3.	<i>Expansion method</i>	318
6.8.4.	<i>Flow method</i>	319
6.8.5.	<i>Pumpdown method</i>	320
6.9.	Partial pressure measurement	320
6.9.1.	<i>General</i>	320
6.9.2.	<i>Magnetic deflection mass spectrometers</i>	321
6.9.3.	<i>The trochoidal (or cycloidal) mass spectrometer</i>	324
6.9.4.	<i>The omegatron</i>	324
6.9.5.	<i>The Farvitron</i>	326
6.9.6.	<i>Quadrupole and monopole mass spectrometers</i>	327
6.9.7.	<i>Time-of-flight mass spectrometers</i>	327
7.	HIGH VACUUM TECHNOLOGY	329
7.1.	Criteria for selection of materials	329
7.1.1.	<i>General</i>	329

7.1.2.	<i>Mechanical strength</i>	329
7.1.3.	<i>Permeability to gases</i>	331
7.1.4.	<i>Vapour pressure and gas evolution</i>	331
7.1.5.	<i>Working conditions</i>	331
7.1.6.	<i>Metal vessels and pipes</i>	331
7.1.7.	<i>Glass vessels and pipes</i>	333
7.1.8.	<i>Elastomer and plastic pipes</i>	333
7.2.	<i>Cleaning techniques</i>	336
7.2.1.	<i>Cleaning of metals</i>	336
7.2.2.	<i>Cleaning of glass</i>	341
7.2.3.	<i>Cleaning of ceramics</i>	342
7.2.4.	<i>Cleaning of rubber</i>	342
7.2.5.	<i>Baking</i>	342
7.3.	<i>Sealing techniques</i>	343
7.3.1.	<i>General, classifications</i>	343
7.3.2.	<i>Permanent seals</i>	343
7.3.3.	<i>Semipermanent and demountable seals</i>	367
7.3.4.	<i>Gasket seals</i>	384
7.3.5.	<i>Electrical lead-throughs</i>	409
7.3.6.	<i>Motion transmission</i>	413
7.3.7.	<i>Material transfer into vacuum systems</i>	417
7.4.	<i>Leak detection</i>	427
7.4.1.	<i>Leak rate and detection</i>	427
7.4.2.	<i>Leakage measurement</i>	435
7.4.3.	<i>Leak location</i>	439
7.4.4.	<i>Sealed unit testing</i>	440
7.4.5.	<i>Sensitive leak detection methods</i>	442
7.5.	<i>Rules for operating vacuum systems</i>	451
REFERENCES		453
SUBJECT INDEX		483