

Vacuum Technology

By ANDREW GUTHRIE

Vacuum Technology

Andrew Guthrie, Professor of Physics

ALAMEDA STATE COLLEGE, HAYWARD, CALIFORNIA

John Wiley and Sons, Inc.

NEW YORK AND LONDON

Copyright © 1963 by John Wiley & Sons, Inc.

All Rights Reserved

This book or any part thereof
must not be reproduced in any form
without the written permission of the publisher.

15.000

Library of Congress Catalog Card Number: 63-20631

Printed in the United States of America

Preface

Developments in the vacuum field have been rapid during the last few years. These developments have included much larger systems, new techniques and equipment, and operation at extremely low pressures. More people are continually becoming involved in vacuum work. There are a number of excellent books on the subject of vacuum; however, in general, they assume a fair degree of scientific knowledge on the part of the reader and treat the broader principles and techniques of vacuum. It is the purpose of this book to consolidate the vast amount of material on this subject, both published and unpublished, into sets of working rules primarily for technicians engaged in setting up, operating, and maintaining vacuum systems.

The treatment is nonmathematical, with the arithmetic used extending only to the application of decimals, powers of ten, and logarithms. Where simple arithmetic is involved, numerous examples are given. However, tables, graphs, and simple rules are employed extensively. Using the material in this book, the technician should be able to choose the appropriate commercial vacuum components, fabricate various parts for vacuum use, set up a complete system, test components and complete systems, perform routine maintenance, and recognize and correct malfunctions. Chapter 14 is devoted exclusively to very high and ultra-high vacuum systems, but some information pertaining to such systems is contained in other chapters.

Although this book is intended primarily for the technician, it is hoped that it will be useful to a certain degree to the engineer and the scientist because of its tables and graphs, and the physical data and design formulas included in the appendices.

The terminology used generally follows that recommended by the American Vacuum Society in its *Glossary of Terms Used in Vacuum Technology* (Pergamon Press, London, 1958). Extensive use has been

vi Preface

made of data from various manufacturers, and every effort has been made to acknowledge the source of such information in the text.

I wish to express my appreciation to Carole Abbott for typing the manuscript, and for subsequent help on details which had to be worked out while the book was in various stages of publication.

ANDREW GUTHRIE

Berkeley, California
August 1963

vi Preface

made of data from various manufacturers, and every effort has been made to acknowledge the source of such information in the text.

I wish to express my appreciation to Carole Abbott for typing the manuscript, and for subsequent help on details which had to be worked out while the book was in various stages of publication.

ANDREW GUTHRIE

Berkeley, California
August 1963

Contents

Chapter One The Nature of Vacuum 1

- 1.1 What Is Vacuum? 1
- 1.2 General Nature of a Gas 1
- 1.3 The Atmosphere 4
- 1.4 Units of Pressure 7
- 1.5 Decimals and Powers of Ten 9
- 1.6 Degrees of Vacuum 11
- 1.7 Mean Free Path of a Gas 11
- 1.8 Temperature Scales 13
- 1.9 Effect of Pressure on a Gas 15
- 1.10 Effect of Temperature on a Gas 17
- 1.11 The General Gas Law 19
- 1.12 Some Other Characteristics of Gases 21

Chapter Two Vacuum Systems 23

- 2.1 Elements of a Vacuum System 23
- 2.2 Some Types of Vacuum Systems 25
- 2.3 Quantity of Gas and Throughput 26
- 2.4 Comparison with an Electric Circuit 28
- 2.5 Comparison with Water Flow 30
- 2.6 Resistances Connected in Series 31
- 2.7 Resistances Connected in Parallel 34
- 2.8 The Use of Logarithms 36
- 2.9 Logarithmic Scales 37
- 2.10 Pumping Speed 41
- 2.11 Losses in Pumping Speed 42

Chapter Three Rotary Oil-Sealed Pumps 49

- 3.1 The Nature of Such Pumps 49
- 3.2 Pump Oils and the Oil System 50
- 3.3 Ultimate Pressure 52
- 3.4 Pumping Speed 53
- 3.5 Effect of Connecting Lines 56
- 3.6 Pump Size and Pump-Down Time—Method 1 62
- 3.7 Pump Size and Pump-Down Time—Method 2 65
- 3.8 Pump Size and Pump-Down Time—Method 3 67
- 3.9 Gas Handling Capacity of a Pump 69
- 3.10 Some General Rules 70
- 3.11 Setting Up Rotary Oil-Sealed Pumps 70
- 3.12 Starting Rotary Oil-Sealed Pumps 72
- 3.13 Stopping Rotary Oil-Sealed Pumps 72
- 3.14 Maintenance Problems 73
- 3.15 Use of a Nomograph 76

Chapter Four Vapor Pumps 77

- 4.1 General Nature of Vapor Pumps 77
- 4.2 Some Features of Diffusion Pumps 79
- 4.3 Some Features of Ejector Pumps 84
- 4.4 Mercury versus Oil 87
- 4.5 Pump Performance 89
- 4.6 Performance Characteristics of Diffusion Pumps 92
- 4.7 Performance Characteristics of Ejector Pumps 98
- 4.8 Migration of Pump Fluid 98
- 4.9 Backing Pump Requirements 100
- 4.10 Effect of Connecting Lines 101
- 4.11 Pump-Down Time for Vapor Pumps 103
- 4.12 Operating a Vapor Pump 104
- 4.13 Poor Operation or Failure of Vapor Pumps 105

Chapter Five Some Other Types of Pumps 109

- 5.1 Molecular Drag Pumps 109
- 5.2 Roots Blower Pumps 113
- 5.3 The Use of Getters as Pumps 117

- 5.4 Gettering and Ionizing 122
- 5.5 Pumps Using Evaporation and Ionization 124
- 5.6 Pumps Using Sputtering and Ionization 125
- 5.7 Cryopumping 132
- 5.8 Other Sorption Pumps 138
- 5.9 Water Aspirator, Toepler, and Sprengel Pumps 139

Chapter Six Measurement of Pressure 142

- 6.1 The Nature of Vacuum Gauges 142
- 6.2 Bourdon and Diaphragm Gauges 143
- 6.3 U-Tube Manometers 146
- 6.4 McLeod Gauges 150
- 6.5 Pirani and Thermocouple Gauges 162
- 6.6 Thermionic Ionization Gauges 168
- 6.7 Cold Cathode Ionization Gauge 176
- 6.8 Gauges Using Radioactive Materials 181
- 6.9 Viscosity- and Radiometer-Type Gauges 184
- 6.10 Use of Discharge Tube to Measure Pressure 187
- 6.11 Gauges to Measure Very Low Pressures 190
- 6.12 Calibration and Ranges of Vacuum Gauges 193

Chapter Seven Measurement of Pumping Speed 198

- 7.1 Why Measure Pumping Speed? 198
- 7.2 The Metered-Leak Method 199
- 7.3 Positioning of Vacuum Gauge and Air Leak 201
- 7.4 Admission of Air 202
- 7.5 Vacuum Gauges 205
- 7.6 Test Dome 206
- 7.7 Rate-of-Rise Measurement 207
- 7.8 Use of a Known Conductance 211

Chapter Eight Properties of Some Vacuum Materials 216

- 8.1 The Elements 216
- 8.2 Mercury and Water 218
- 8.3 Liquids Used in Vacuum Practice 219

- 11.4 Operation and Maintenance of Baffles and Traps 338
- 11.5 Liquid Nitrogen Filling Systems 341
- 11.6 Pumping Losses in Baffles and Traps 343
- 11.7 The Functions of Vacuum Valves 349
- 11.8 Gate, Disk, and Flap Valves 351
- 11.9 Globe, Needle, and Diaphragm Valves 356
- 11.10 Stopcock, Plug, and Ball Valves 359
- 11.11 Bakable Valves 363
- 11.12 Some Special Valves 367
- 11.13 Care and Maintenance of Valves 369

Chapter Twelve Some Other Vacuum Components 371

- 12.1 Common Static Seals Using Elastomers 371
- 12.2 Sliding and Rotating Seals 377
- 12.3 High Temperature Seals 383
- 12.4 Low Temperature Seals 388
- 12.5 Some Other Forms of Seals 391
- 12.6 Couplings, Hose Clamps, etc. 395
- 12.7 Electrical Lead-Throughs 398
- 12.8 Leak Devices and Cut-Offs 401
- 12.9 Protective Devices 407

Chapter Thirteen Conventional Vacuum Systems 411

- 13.1 The Nature of Such Systems 411
- 13.2 Basic Design Considerations 412
- 13.3 Conductances of Components 413
- 13.4 Designing a Vacuum System 414
- 13.5 Setting Up a New Vacuum System 422
- 13.6 Starting Up a Vacuum System 423
- 13.7 Starting and Operating Tight Vacuum Systems 426
- 13.8 Shutting Down a Vacuum System 428
- 13.9 Maintenance Problems with Vacuum Systems 429
- 13.10 The Small Vacuum Laboratory 430

Chapter Fourteen Very High and Ultra-High Vacuum Systems 433

- 14.1 The Nature of Such Systems 433
- 14.2 Small Very High Vacuum Systems 434

The Nature of Vacuum

1.1 What Is Vacuum?

The word vacuum is derived from the Greek word meaning empty. In practice some type of vessel (vacuum enclosure, chamber, or container) which is open to the surrounding air is used. As air is removed by some pumping means, a vacuum is obtained. Clearly various degrees of vacuum can be obtained, depending on how much air is removed from the enclosure. Practically, a vacuum vessel which is empty, i.e., free of all matter, is never obtained. If this were possible the vacuum would be called *perfect* or *absolute*. Many vacuum terms are defined in the text as they are used. The subject of vacuum is treated in general in the references listed in Appendix E.

1.2 General Nature of a Gas

The word gas is often used loosely in vacuum practice to denote both *noncondensable gases* and *vapors*. The noncondensable gases, sometimes called *permanent gases*, cannot be compressed to liquid or solid form at ordinary room temperature. Dry air is an example of a noncondensable gas, and water vapor is an example of a vapor.

2 *Vacuum Technology*

In order to produce liquid air it is necessary not only to use a high degree of compression but also to do so at low temperatures.

A gas is made up of many, small, invisible particles called molecules which are moving about rapidly in all directions. It is possible to visualize these molecules by imagining tennis balls moving about rapidly in all directions in a room. They collide with each other and rebound from the walls of the room. Most of them move with about the same speed, although occasionally it will be observed that one moves considerably faster or slower than the others. Figure 1.1 is a schematic representation of a vessel containing a gas. The arrows show the directions in which the molecules are moving, and it is found that, on the average, as many molecules are moving in one direction as in any other direction.

If the enclosure shown in Fig. 1.1 were heated, it would be found that the molecules had a greater mean speed than before the enclosure was heated. Again an occasional molecule would be found to be moving considerably faster or slower than the bulk of the molecules. The speeds of molecules are quite high, even at room temperature (20° centigrade or 68° Fahrenheit). At this temperature a hydrogen molecule has an average speed of about 5700 feet per second whereas an air molecule has an average speed of about 1500 feet per second. Actually air consists of several gases, the most prominent being nitrogen and oxygen (see Table 1.1). The average speed for an air molecule given above is an average for the molecules of the various gaseous constituents. The distance between molecules is, on the average, much greater than the diameter of a molecule. This is true for the air

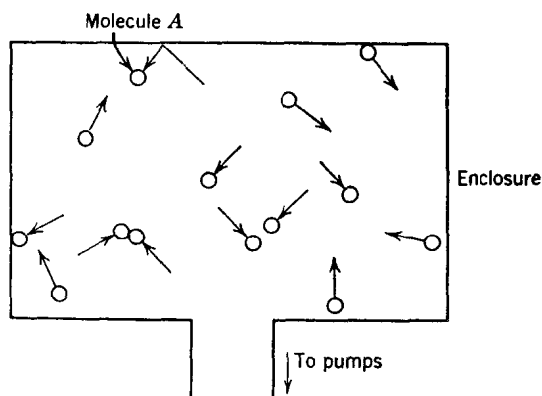


Fig. 1.1 Molecules moving about in an enclosure.

Table 1.1 Composition of Dry Air at Sea Level

Gas	Percent by Volume
Nitrogen	78.08
Oxygen	20.95
Argon	0.93
Carbon dioxide	0.03
Neon	0.0018
Helium	0.0005
Methane	0.0002
Krypton	0.0001
Hydrogen	0.00005
Xenon, etc.	Traces

Handbook of Chemistry and Physics, Chemical Rubber Publishing Co., Cleveland, Ohio, 43rd ed., 1961.

around us, and if some of the air is removed from such an enclosure as shown in Fig. 1.1, the average distance increases since there are fewer molecules distributed through the volume.

Referring again to Fig. 1.1, it is seen that molecule *A* has struck the inside wall of the enclosure and rebounded. Actually many molecules strike the wall in a short time, and they strike from all directions up to grazing incidence. The striking and rebounding of the molecule results in a "push" or force on the wall. The average force on a unit area of the wall, say one square inch, is called the *pressure*. This is a fundamental quantity in vacuum work. The pressure of a gas depends on how many molecules are striking the unit area in any given time (a second, a minute, etc.) and on how fast they are moving. Consequently, the pressure will drop as the gas is pumped out (fewer molecules) and will rise as the gas is heated (molecules move faster).

It has been stated that a gas exerts a pressure on the inside walls of the enclosure. Actually there is a gas pressure anywhere in the gas. Suppose an object, such as a sheet of metal, is placed in the enclosure. Then each side of the sheet will be subjected to a pressure equal to that exerted on the inside walls of the enclosure. This is illustrated in Fig. 1.2. Although many units of pressure are used in

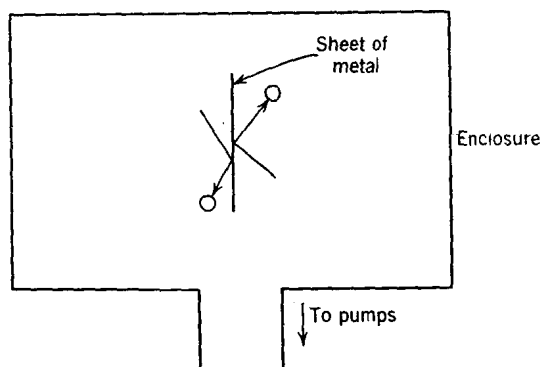


Fig. 1.2 Molecules exert a pressure on an object in the gas.

practice, they are all derived from one basic unit, which depends on the characteristics of the air around us (the atmosphere). Consequently, this unit is discussed next.

1.3 The Atmosphere

Since in most vacuum work some type of vessel which is open to the air (the atmosphere) is used, gases making up the atmosphere are of considerable importance. Table 1.1 shows the proportions of the various gases making up dry air at sea level. The proportions change (very slowly) with altitude, but this change becomes significant only at extremely high altitudes.

The atmosphere exerts a pressure on any object immersed in it. Normally reference is made to the pressure at sea level and at a temperature of 0° centigrade (0°C) or 32° Fahrenheit (32°F), called the *standard* or *normal atmosphere* (atm). The relationships between the various temperature scales are discussed in Section 1.8. To measure the actual pressure of the atmosphere, a glass U-tube partially filled with mercury is used, with one end connected to some type of vacuum pump. This is illustrated in Fig. 1.3*b*. If both ends of the U-tube are exposed to air, the mercury levels in both sides will be the same (Fig. 1.3*a*). This is simply an example of a liquid seeking its own level. If one side of the U-tube is connected to the vacuum pump, the mercury will rise in that side and fall in the other side, as is shown in Fig. 1.3*b*. This difference in level is caused by the atmosphere exerting a pressure on the mercury in side *B*. There is no balancing pressure on side *A*

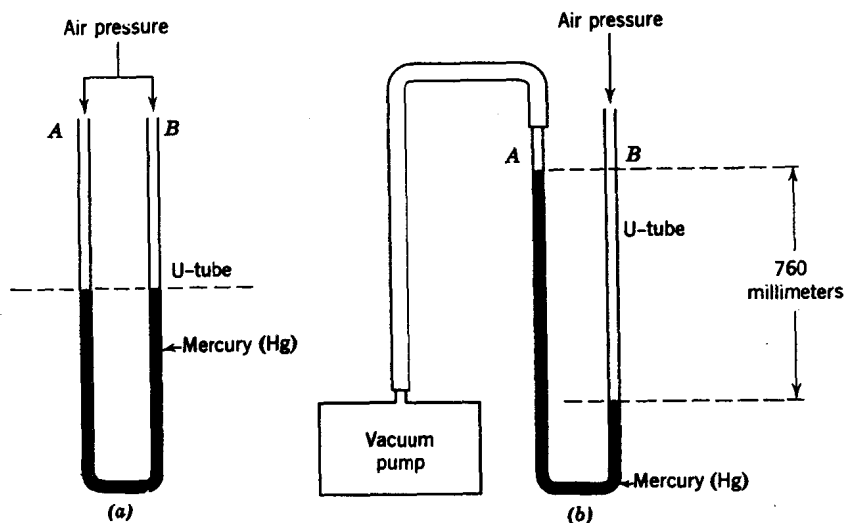


Fig. 1.3 (a) U-tube with both sides exposed to the atmosphere. (b) U-tube with one side pumped.

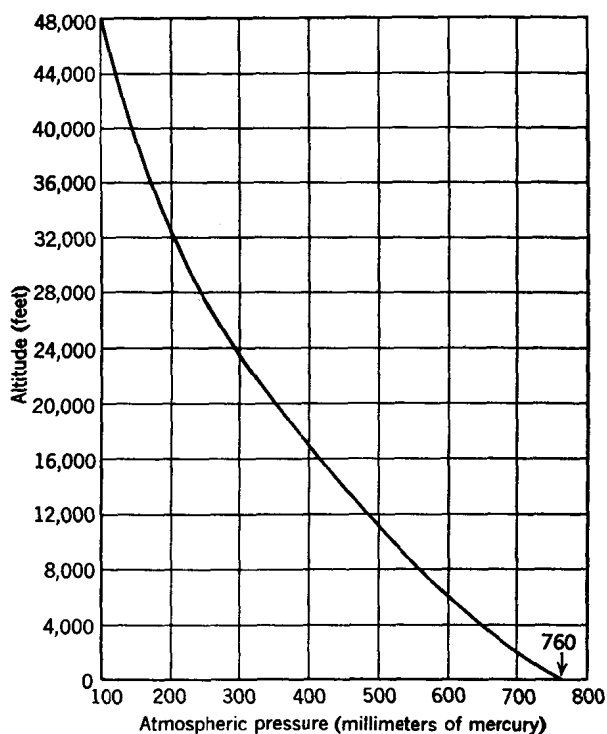


Fig. 1.4 Change in atmospheric pressure with altitude.