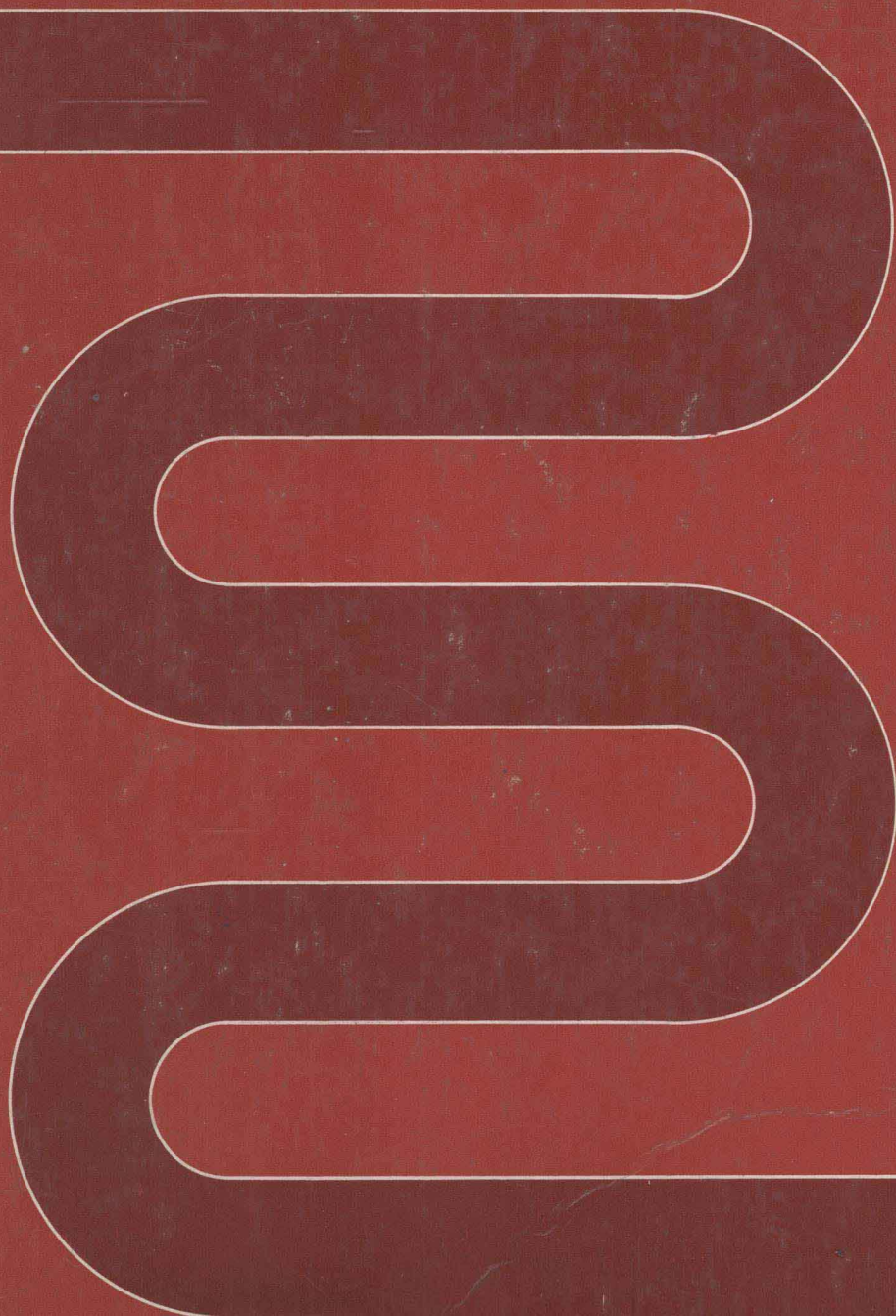


William L. Haberman  
James E. A. John

ENGINEERING  
THERMODYNAMICS



# ENGINEERING THERMODYNAMICS

**William L. Haberman**

*Engineering Consultant*

*Rockville, Maryland*

**James E. A. John**

*Chairman, Department of Mechanical Engineering*

*The Ohio State University*

ALLYN AND BACON, INC.

Boston    London    Sydney    Toronto

To the Memory of My Father

William L. Haberman

To My Wife

James E. A. John



**Copyright © 1980 by Allyn and Bacon, Inc.,  
470 Atlantic Avenue, Boston, Massachusetts 02210.**

All rights reserved. No part of the material protected by this copyright notice may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying, recording, or by any information storage and retrieval system, without written permission from the copyright owner.

**Library of Congress Cataloging in Publication Data**

Haberman, William L. 1922-  
Engineering thermodynamics.

Includes index.

I. Thermodynamics. I. John, James E. A., joint  
author. II. Title.  
TJ265 .H24 621.4'021 79-11143  
ISBN 0-205-06570-8

Printed in the United States of America

# **ENGINEERING THERMODYNAMICS**

# PREFACE

This book is intended to provide the undergraduate engineering student with an understanding of the basic principles of thermodynamics. It is realized that many texts on engineering thermodynamics are currently available; some have met with considerable success over a period of years. However, virtually all such texts are more or less oriented towards an engineering science approach. Current trends in engineering education are directed away from this approach, and more towards an applications oriented approach. One manifestation of this trend is the increased emphasis on design in engineering curricula. This text in engineering thermodynamics is aimed at this applications oriented trend.

A course in thermodynamics is generally one of the first courses that the engineering student is exposed to in his chosen field. This student lacks the sophistication of a senior level student; yet too often his course in thermodynamics tends to be a series of very abstract concepts, with little application to the real world. These days, the student is very well informed on what is occurring in the nation and in the world. For example, at present the steam power plant and the automotive engine are subjects of great discussion and controversy, involving energy utilization, emissions, and other factors. In textbooks, the Rankine and Otto cycles are too often treated in a cursory manner, with no attempt to tie the cycles to real systems. Here, we have attempted, wherever possible, to use realistic values of pressures and temperatures; further, we have used the basic concepts of thermodynamics to explain why we are facing such problems as thermal pollution, air pollution, etc. In this way, the student should come to see thermodynamics as an exciting, relevant course to study.

In most available thermodynamics texts, the first several chapters and many pages of material are devoted to an almost endless series of definitions. Too often, the student becomes lost or loses motivation. From such an exposure, the student gets the impression that everything he is learning in thermodynamics is new; the series of definitions and words he is exposed to amplify this impression. However, the student has already been exposed to the First Law and many thermodynamic principles in his physics courses. We have tried to take full advantage of this exposure by first drawing on material already covered in physics courses dealing with the conservation of energy, then relating this to the thermodynamic system. Therefore, we have placed our discussion of the First Law ahead of the material on thermodynamic properties in Chapters 4 and 5. This way, the student can see very

clearly the need for tables of such properties and the necessity for learning how to use them.

Two methods have been used by other texts in presenting the concepts of entropy and the Second Law. One is the classical approach, starting with the Kelvin-Planck and Clausius statements of the Second Law. The other is a statistical mechanics approach, starting with the definition of entropy in terms of probability. Unfortunately, texts employing the latter approach use statistical mechanics only to derive entropy, and do not use the approach either before or after the chapter on entropy. The student is left with a seemingly contrived derivation, and a resultant poor understanding of entropy. In this text, we have chosen to start with the definition, explanation and examples of reversible processes. Once the significance of the concept of reversibility has been established, we introduce reversible cycles, the Clausius Inequality and then entropy. Entropy is shown to represent a measure of irreversibility. In this way, the student is able to grasp the logic of introducing entropy as a thermodynamic property. This is reinforced with many examples of the application of entropy and the Second Law.

The laws of thermodynamics and the basic thermodynamic properties are introduced in the first six chapters. The last four chapters are devoted to engineering applications. Problems and examples in the last four chapters have been carefully selected to reflect real engineering situations. Differences between theory and practice are discussed and difficulties involved in the possible achievement of theoretical efficiencies are analyzed. Chapter 8 presents a very thorough treatment of power and refrigeration cycles. Whereas most texts present little more than  $p$ - $v$  and  $T$ - $s$  diagrams, here we have discussed much of the hardware, the engineering and environmental considerations, and the basic thermodynamics of refrigerators, heat pumps, stationary power plants, and automotive engines. Chapter 10 on future energy conversion systems should demonstrate to the student the continuing utility of thermodynamics in treating a wide variety of new problems and situations.

Many worked out examples are provided throughout the text, as well as extensive problem sets at the end of each chapter. Since one of the goals of the text is to give the student an understanding of how to solve engineering problems, the examples and problems involve systems and devices that are familiar to the student and have application in the real world. In many cases, photographs and sketches of hardware are provided along with the discussion to bring the point more graphically to the student. It is recognized that many students have not previously had a great deal of exposure to engineering hardware; pains will be taken to ensure that, before a device is introduced in the text or in a problem, a description is given of the device and its function. We have found that, as an example, many students do

not know the difference between a turbine, a pump, and a compressor; as a result, they find it difficult to analyze problems involving these devices.

A dual system of units is used. It is felt that, although we are currently switching over to SI (Système International) units in the United States, the student must still deal with English units. One has only to walk through a power plant to observe that virtually all pressures, temperatures and dimensions are still measured and indicated in psi, °F, and feet; there are many other industries where English units still predominate as well. However, most other countries in the world use SI units. Therefore, we feel that the engineering student should have a feel for both systems. With the use of dual units, the reader should be able to obtain a comparison of the two systems and an understanding of the magnitude of the units. Complete tables of thermodynamic properties for four substances, water, air, R-22 and carbon dioxide, are given in the Appendices in SI as well as English units.

It is hoped that this text will provide a good grounding in basic thermodynamics, while still being interesting, relevant, and motivational.

We acknowledge the many useful suggestions and ideas that we have picked up from students and colleagues in over 20 years of teaching. We also thank Jane Steele for her help in typing and preparing portions of the manuscript.

*William L. Haberman*  
*Rockville, Maryland*

*James E. A. John*  
*The Ohio State University*  
*Columbus, Ohio*

# CONTENTS

|   |           |
|---|-----------|
| PREFACE   | ix        |
| <b>CHAPTER 1 Introduction</b>                                       | <b>1</b>  |
| 1.1 What is Thermodynamics?   | 1         |
| 1.2 Thermodynamic Systems   | 2         |
| 1.3 Thermodynamic Properties  | 4         |
| 1.4 Equilibrium   | 10        |
| 1.5 Units   | 13        |
| 1.6 Summary   | 21        |
| <b>CHAPTER 2 The First Law of Thermodynamics for Closed Systems</b> | <b>24</b> |
| 2.1 Introduction  | 25        |
| 2.2 Work  | 26        |
| 2.3 Heat  | 35        |
| 2.4 Internal Energy   | 37        |
| 2.5 The First Law of Thermodynamics for Closed Systems              | 38        |
| <b>CHAPTER 3 The First Law of Thermodynamics for Open Systems</b>   | <b>50</b> |
| 3.1 What Are Open Systems?  | 50        |
| 3.2 The Conservation of Mass for Open Systems                       | 51        |
| 3.3 The Energy Equation for Open Systems                            | 55        |
| 3.4 Applications of Steady-Flow Open Systems                        | 58        |
| 3.5 Charging and Discharging of Compressed Gas Tanks                | 69        |

|                  |  |            |
|------------------|--|------------|
| <b>CHAPTER 4</b> | <b>Thermodynamic Properties of Substances</b>                          | <b>77</b>  |
| 4.1              | Introduction   | 77         |
| 4.2              | Thermodynamic Properties of Water (Liquid and Vapor Phases)            | 77         |
| 4.3              | Independent Properties   | 89         |
| 4.4              | Thermodynamic Properties of Other Substances (Liquid and Vapor Phases) | 91         |
| 4.5              | Ideal Gases  | 97         |
| 4.6              | Thermodynamic Properties of Substances with a Solid Phase              | 102        |
| <b>CHAPTER 5</b> | <b>Gases and Gas-Vapor Mixtures</b>                                    | <b>108</b> |
| 5.1              | Introduction   | 108        |
| 5.2              | Thermodynamic Properties of Ideal Gas Mixtures                         | 108        |
| 5.3              | Thermodynamic Properties of Gas-Vapor Mixtures                         | 116        |
| 5.4              | Thermodynamic Properties of Moist Air (Psychrometrics)                 | 119        |
| <b>CHAPTER 6</b> | <b>The Second Law of Thermodynamics</b>                                | <b>133</b> |
| 6.1              | Introduction   | 133        |
| 6.2              | Reversible Processes   | 134        |
| 6.3              | Reversible Cycles  | 136        |
| 6.4              | Thermodynamic Temperature Scale  | 143        |
| 6.5              | Clausius' Inequality   | 146        |
| 6.6              | Entropy  | 150        |
| 6.7              | Entropy and Irreversibility  | 153        |
| 6.8              | Numerical Evaluation of Entropy  | 160        |
| 6.9              | Applications of the Second Law   | 166        |

## **CHAPTER 7 Thermodynamic Processes 174**

- 7.1 Introduction 174
- 7.2 Constant Volume Process 175
- 7.3 Constant Pressure (Isobaric) Process 177
- 7.4 Throttling Process (Constant Enthalpy) 180
- 7.5 Isothermal Process 182
- 7.6 Adiabatic and Isentropic Processes 185
- 7.7 Polytropic Processes 192
- 7.8 Humidity Processes 198

## **CHAPTER 8 Power and Refrigeration Cycles 205**

- 8.1 Thermodynamics of Cycles 205
- 8.2 Vapor Power Cycles: The Rankine Cycle 208
- 8.3 Vapor Refrigeration Cycles: The Reversed Rankine Cycle 233
- 8.4 Gas Power and Refrigeration Cycles: The Brayton Cycle 249
- 8.5 Power Cycles: The Otto Cycle 276
- 8.6 Power Cycles: The Diesel Cycle 291
- 8.7 Gas Power Cycles with Regeneration: The Stirling and Ericsson Cycles 300

## **CHAPTER 9 Combustion Processes 320**

- 9.1 Introduction 320
- 9.2 Balancing a Chemical Equation 321
- 9.3 First Law for Combustion Processes 326
- 9.4 Chemical Equilibrium 335
- 9.5 Pollutant Formation in Combustion Processes 344

|                 |   |   |            |
|-----------------|---|---|------------|
| <b>CHAPTER</b>  | <b>10</b>                                   | <b>Thermodynamics of Some New<br/>Energy Conversion Systems</b>       | <b>353</b> |
| 10.1            | Introduction                                | 353   |            |
| 10.2            | Electric Power from Ocean Thermal Gradients | 357   |            |
| 10.3            | Geothermal Energy                           | 362   |            |
| 10.4            | Fuel Cells                                  | 367   |            |
| 10.5            | Solar Air Conditioning Systems              | 371   |            |
| <b>APPENDIX</b> | <b>A</b>                                    | <b>Thermodynamic Properties—<br/>English Units</b>                    | <b>383</b> |
| <b>APPENDIX</b> | <b>B</b>                                    | <b>Thermodynamic Properties—<br/>SI Units</b>                         | <b>441</b> |
| <b>APPENDIX</b> | <b>C</b>                                    | <b>Conversion Factors</b>   | <b>501</b> |
| <b>APPENDIX</b> | <b>D</b>                                    | <b>Using the Tables of Thermodynamic<br/>Properties of Substances</b> | <b>505</b> |
| <b>INDEX</b>    |   |   | <b>509</b> |

# Introduction

## 1.1 WHAT IS THERMODYNAMICS?

Our modern technological society is based largely on the replacement of human and animal labor by inanimate, power-producing machinery. Examples of such machinery are steam power plants that generate electricity, locomotives that pull freight and passenger trains, and internal combustion engines that power automobiles. In each of these examples, working fluids such as steam and gases are generated by combustion of a fuel-air mixture and then are caused to act upon mechanical devices to produce power. Predictions of how much energy can be obtained from the working fluid and how well the extraction of energy from the working fluid can be accomplished are the province of an area of engineering called *thermodynamics*.

Thermodynamics is based on two experimentally observed laws. The first is the *law of conservation of energy*, familiar to the student from the study of classical mechanics. Whereas in mechanics only potential and kinetic energies are involved, in thermodynamics the law of conservation of energy is extended to include thermal and other forms of energy. When an energy transformation occurs, the same total energy must be present after the transformation as before; in other words, according to the first law, all the different types of energy must be accounted for and balanced out when a transformation occurs. For example, in an automobile engine, a specific quantity of thermal energy is released due to the combustion of gasoline in the engine cylinders. Some of this energy goes out the tailpipe as heated exhaust gases and is lost; some is

converted to useful work in moving the car; and some is dissipated to the air via the cooling system. Whereas the distribution of these various types of energy is clearly of importance to the engineer, who wants to obtain as much useful work as possible from a given quantity of fuel, the first law merely states that energy can be neither created nor destroyed; it does not provide information as to the ultimate distribution of the energy in its various forms.

The second law provides further information about energy transformations. For example, it places a *limitation* on the amount of useful mechanical work that can be obtained from combustion of the fuel in an automobile engine. The first law states that energy must be conserved. Thus, according to the first law, all the thermal energy available from combustion of the fuel could be converted to useful mechanical work with no losses. Intuitively, however, we know that thermal and other losses are present in the engine. The second law provides a quantitative prediction of the extent of these losses.

An understanding of thermodynamics and the limitations it imposes on the conversion of energy from one form to another is very relevant to what is going on in the world today. With limited supplies of conventional energy resources of oil and gas, and with increased demands for an improved standard of living and an accompanying increased demand for energy, it is important that we obtain the maximum utilization of our oil, gas, and coal reserves. Conversion of the chemical energy available in these fuels to usable form should be done as efficiently as possible. Further, we must examine the potential of new sources of energy, such as the sun and the oceans. Again, thermodynamics will be used to evaluate new energy sources and methods of converting the available energy to useful form.

## 1.2 THERMODYNAMIC SYSTEM

In treating problems in engineering mechanics, it is important first to define a free body, then analyze the forces acting on it, and finally apply the appropriate equations of motion. In thermodynamics, we are interested in the changes that take place either to a substance or within a device as the result of energy transfer or energy transformation. Analogous to the free body, we define a *thermodynamic system* to be the substance or volume in space that we wish to study. Everything outside the boundaries of the system is called the *surroundings*. In a thermodynamic analysis, we must carefully define the system boundaries and then study the changes that take place either to the

working fluid within the system or to the working fluid as it crosses the system boundaries.

We can define three types of thermodynamic systems: closed, open, and isolated. In a *closed system*, no mass crosses the system boundaries. For example, in a certain situation, we might wish to define a closed system as the liquid water and water vapor contained within a rigid vessel (Figure 1.1). In this case, during a process in which thermal energy is added to the system, the volume of the system remains constant since the vessel is rigid. The addition of energy causes the relative amounts of liquid and vapor within the system to change.

In another case, we might define a closed system to be the gases contained within a piston-cylinder arrangement (Figure 1.2). As the piston is forced upward during a process, the system is reduced in volume; again, no mass crosses the system boundaries, so the system is still closed.

In an *open system*, mass does cross the system boundaries. Generally, we define an open system to be a fixed volume in space. For example, if we wish to

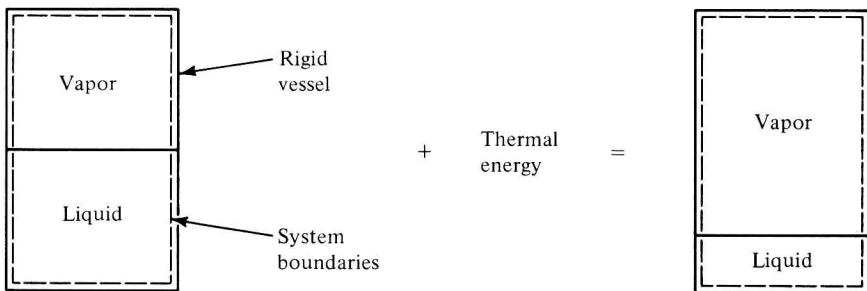


FIGURE 1.1 *Closed System with Constant Volume.*

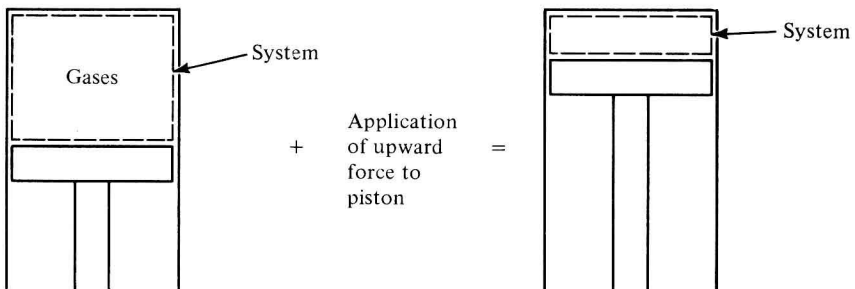
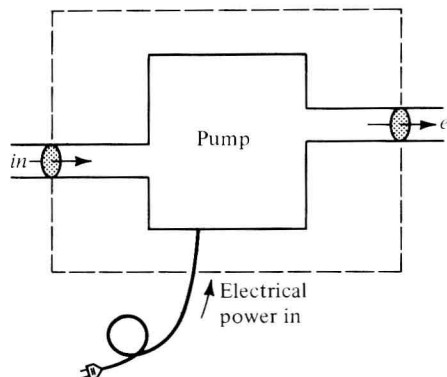


FIGURE 1.2 *Closed System with Non-constant Volume.*

FIGURE 1.3 *Open System.*

analyze thermodynamically the operation of a water pump, we might use the system boundaries shown in Figure 1.3. In this case, the working fluid, water, flows into the system across the surface labeled *in*; then it flows out across surface *e* at higher pressure. Electrical power is supplied across the system boundary to drive the pump.

An *isolated system* is one that is completely isolated from its surroundings. In other words, no energy crosses the boundaries of an isolated system.

In the next chapter, when we start working problems involving the first law of thermodynamics, we will show how to select the boundaries of a system for a given analytical situation.

### 1.3 THERMODYNAMIC PROPERTIES

The thermodynamic state of a substance is described by a specification of the thermodynamic properties of the substance at that state. For a given state of a substance, each of the thermodynamic properties has one and only one value. In thermodynamics we want to be able to evaluate quantitatively the change of state of a system as a result of energy transfer across system boundaries or energy transformation within a system. The state of a thermodynamic system is given by a specification of the properties of the substance comprising the system, such as temperature and pressure. Note that if we refer to the value of a property for a system, we imply that this property is the same at all points of the system. This situation, in which the value of a property has significance for

an entire system, is called *thermodynamic equilibrium*. For example, if we say that the temperature of a system in thermodynamic equilibrium is  $25^{\circ}\text{C}$ , we mean that the temperature at each point throughout the entire system is  $25^{\circ}\text{C}$ . In this text we will deal with *equilibrium thermodynamics*, a study of the change of equilibrium state of a system due to energy transfer across system boundaries or energy transformation within the system.

There are two types of thermodynamic properties: extensive and intensive. *Extensive properties*, such as mass and total volume, depend on the total mass of the substance present. *Intensive properties* are definable at a point in a substance; if a substance is uniform and homogeneous, the value of the intensive property will be the same at each point in the substance. Specific properties are defined as properties per unit mass, and hence they are intensive. For example, we define *specific volume* as the volume of a substance per unit mass.

To illustrate further the difference between intensive and extensive properties, consider a system consisting of a mass of 10 pounds of a substance, with a system volume of 10 cubic feet. We will assume that the substance is homogeneous and is uniformly distributed over the system volume. This means that at each point in the system, the specific volume is  $10/10$  or 1 cubic foot per pound. Now divide the system into two equal parts, as shown in Figure 1.4. The mass of the left side is  $1/2$  the total mass, and the volume of the left side is  $1/2$  the total volume. However, the specific volume of the left side is still  $5/5$ , or 1 cubic foot per pound. In other words, an extensive property of a system is equal to the sum of the values of the extensive properties of its parts. An intensive property of a system is equal to the value of the intensive property of each of its parts.

We will now discuss several important thermodynamic properties—pressure, density, and temperature—which may already be familiar to the student from introductory courses in physics. Later in the text, other thermodynamic properties, such as internal energy, enthalpy, and entropy, will be introduced.

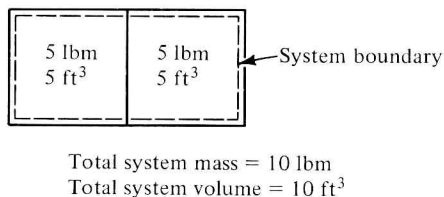


FIGURE 1.4

The mean fluid *pressure*,  $p$ , over a plane area is defined to be the ratio of the normal component of force exerted by the fluid on that area to the area. The pressure at a point on the area is the limit that the mean pressure approaches as the area is reduced to a very small size around the point. Since pressure can be defined at a point on a surface, it is an intensive property.

Several methods are used to measure the pressure of a fluid. Usually a pressure gauge measures the difference between the local atmospheric pressure surrounding the gauge (ambient pressure) and the pressure in the region to which the gauge is attached (Figure 1.5). The gauge reading  $p_g$  is

$$p_g = p_{\text{chamber}} - p_{\text{ambient}}$$

The actual total pressure in the chamber is

$$p_{\text{chamber}} = p_g + p_{\text{ambient}}$$

The total pressure exerted is called *absolute pressure*.

Another method of measuring pressure is to use a U-tube manometer in which the pressure difference is used to support a liquid column. As shown in Figure 1.6(a), with the right leg open to atmospheric pressure, the magnitude of the distance  $d$  gives an indication of the pressure difference between the chamber and the atmosphere (see Example 1.2). Note that the manometer measures a gauge pressure, the difference between chamber pressure and local atmospheric pressure. The simple U-tube manometer shown in Figure 1.6(a) can be modified to measure absolute pressure. The right leg is sealed off and evacuated, so that the pressure at the top of the leg is zero as shown in Figure 1.6(b). Such a pressure-measuring device is called a *barometer*. The difference  $d$  in the levels is proportional to the absolute pressure  $p$ . A barometer can thus be utilized to determine local atmospheric pressure.

Another thermodynamic property is *density*,  $\rho$ , which is defined as the mass of a substance per unit volume of that substance. The reciprocal of density has already been introduced and is called *specific volume*,  $v$ .

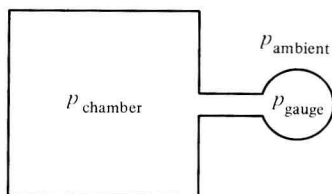


FIGURE 1.5 Pressure Gauge.