Irving Granet

Thermodynamics and Heat Power

THERMODYNAMICS AND HEAT POWER
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Irving Granet, P.E.
New York Institute
of Technology

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THERMODYNAMICS AND HEAT POWER

PREFACE

In the preface to an earlier introductory text on Thermodynamics I noted that, "The subject of Thermodynamics enjoys the unenviable reputation of being one of the most difficult for students to master". Approximately ten years have elapsed since the publication of this earlier text and in this interval I have been fortunate to have obtained constructive feedback from students, colleagues and professors who used the book. All of these comments have been carefully considered and incorporated into the present book to obtain a *textbook* suitable for a one semester course in Thermodynamics and Heat Power. It is hoped that the present text will help the student to master the subject with less difficulty than in the past. For non-majors, it will provide a completely self contained coverage, while for those majoring in the field it can serve as the text for a first course.

While this book is completely new, it retains some of the basic proven concepts from the earlier text referred to above as well as from texts that I have written on Fluid Mechanics and Strength of Materials. These are:

1. All physical principles are developed as required. For most students who have had an elementary physics course this will serve as a valuable review; for others it will be a logical adjunct development to the main topics.

2. The use of Calculus is completely avoided. Instead, the material is developed from first principles. The use of this approach has been tried and proven itself to be a sound learning situation for both student and instructor.
3. The book contains 471 problems of which 132 are illustrative problems that are completely solved as an integral part of the text material. The problems at the end of the chapters are arranged by topic and answers to even numbered problems are given in the Appendix. The large number of illustrative problems and answers to even numbered problems should make the book useful for independent home study courses and as a reference text.
4. It is important for the technically oriented student to see concrete applications of conceptual material. I have accordingly included a large number of illustrations to give the student a better grasp of the physical hardware being studied.

In order to reflect current advances in the science and technology of thermodynamics, material has been included on nuclear power generation, the Wankel rotary combustion engine, and methods of direct energy conversion. For the data on the thermodynamic properties of water, I have used the latest data from the Steam Tables by Keenan, Keyes, Hill and Moore. Since this material is new and is not generally to be found in other texts, I have extracted portions of these tables with permission of the publisher, John Wiley and Sons, Inc. and included it in the Appendix. Also found in the Appendix is a convenient listing of thermodynamic terms for ready reference. The chapter on heat transfer has been included for completeness for those students who will not take a separate course in heat transfer, as an introduction for a heat transfer course and for general reference.

I am deeply indebted to my many friends and colleagues at the New York Institute of Technology and Queensborough Community College for the generous time that they have contributed to this effort. The students and instructors who used my earlier text helped to create this book by their constructive suggestions. Professor Stanley M. Brodsky of New York Community College reviewed the completed manuscript and I am indebted to him for his invaluable critical review. Miss Ruby Ladislav typed the entire manuscript and her efforts on this book and my earlier books are most gratefully acknowledged.

I find that words cannot express my gratitude to my devoted family for their unselfish support. My wife Arlene and our children, Ellen, Kenny and David expressed their love and devotion by their unlimited patience, kindness and wisdom that enabled me to undertake and complete this book.

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CONTENTS

The following organizations kindly contributed illustrative material. In alphabetical order they are:

American Chain and Cable Corp.

Babcock and Wilcox Co.

Carrier Corporation

Colt Industries, Fairbanks Morse Power Systems Div.

Combustion Engineering, Inc.

Consolidated Edison Corp.

Curtiss-Wright Corp.

Detroit Stoker Corp.

Fairchild Republic Corp.

Ford Motor Co.

Foster Wheeler Corp.

General Electric Co.

National Pipe Bending Co.

Power

Renwal Co.

Rex Chainbelt Inc., Nordberg Div.

Riley Stoker Corp.

Tubular Exhanger Manufacturers Association

United Aircraft Corp., Pratt & Whitney Div.

Westinghouse Electric Co.

Worthington Corporation

Their contribution and the contribution of many others is gratefully acknowledged.

1

FUNDAMENTAL CONCEPTS

1.1 *INTRODUCTION*

Thermodynamics is the study of energy, heat and work, properties of the media employed, and the processes involved. Since energy can be derived from electrical, chemical, nuclear, or other means, thermodynamics plays an important role in all branches of engineering, physics, chemistry, and the biological sciences.

In defining the word thermodynamics we have used the terms energy and heat and work. It is necessary to examine these terms in detail and this will be done in subsequent chapters. In this chapter certain fundamental concepts are defined and basic ideas are developed for future use.

1.2 *PROPERTIES OF A SYSTEM*

In physics, when studying the motion of a rigid body (that is, a body that is not deformed or only slightly deformed by the forces acting on it), extensive use is made of "free-body" diagrams. Briefly, a free-body diagram is an outline of a body (or a portion of a body) showing *all* of the external forces acting on it. A free-body diagram is one example of the concept of a system. As a general concept applicable to all situations we can define a system as a grouping of matter taken in any convenient or arbitrary manner. In addition, a thermodynamic system will invariably have energy transferred from it or to it and can also have energy stored in it. From this definition it will be noted that we are at liberty to choose the grouping, but once having made a choice we must take into account *all* energies involved.

Let us consider a given system and then ask ourselves how we can distinguish changes that occur in the system. It is necessary to have external characteristics which permit us to measure and evaluate system changes. If these external characteristics do not change, we should be able to state that the system has not changed. Some of the external measurements that can be made on a system are temperature, pressure, volume, and position. These observable external characteristics are called properties. When all properties of a system are the same at two different times, we can say that we cannot distinguish any difference in the system at these two times. The properties of a system enable us to uncover differences in the system after it has undergone a change. Therefore, the complete description of a system is given by its properties. The condition of the system, that is, its position, energy content, etc., is called *the state of the system.* Thus its properties determine its state. Those properties that depend upon the size and total mass of a system are termed extensive properties, i.e., they depend upon the extent of the system. An intensive property is independent of the size of the system. Pressure and temperature are examples of intensive properties. In addition, there are properties that are known as specific properties because they are given per unit mass or per defined mass in the system. Specific properties are intensive properties.

It has already been noted that a given state of a system is reproduced when all its properties are the same. Since a given set of properties determines the state of a system, the state is reproduced regardless of the history or path the system may undergo to achieve the state. For example, consider a weight that is lifted vertically from one position to another. This weight can be brought to the same position by first lifting it vertically part of the way, then moving it horizontally to the right, then lifting it another part of the way, then moving it horizontally to the left, and finally lifting it vertically to the desired point. In this example the state of the system at the end of the two processes is the same, and the path the system took did not affect its state after the change occurred.

As we shall see in Chap. 2, a consequence of the foregoing is that the change in energy of a system between two given states is the same, regardless of the method of attaining the state. In mathematical terminology, energy is a state function, not a path function.

The properties temperature and pressure are used throughout this text, and it is necessary to have a good understanding of them. The following sections of this chapter deal in detail with these properties.

1.3 *TEMPERATURE*

The temperature of a system is a measure of the random motion of the molecules of the system. If there are different temperatures within the body (or bodies composing the system) the question arises as to how the temperature at a given location is measured and how this measurement is interpreted. Let us examine this question in detail since similar questions will also have to be considered when other properties of a system are studied. In air at room pressure and temperature there are approximately 2.7×10^{19} molecules per cubic centimeter. If we divide the cube whose dimensions are one centimeter (1 cm) on a side into smaller cubes each of whose sides is one thousandth of a centimeter, there will be about 2.7×10^{10} molecules in each of the smaller cubes, still an extraordinarily large number. Although we speak of temperature at a point, we really mean the average temperature of the molecules in the neighborhood of the point.

Let us now consider two volumes of inert gases separated from each other by a third volume of inert gas. By inert we mean that the gases will not react chemically with each other. If the first volume is brought into contact with the second volume and left there until no observable change occurs in any physical property, the two volumes are said to be in thermal equilibrium. Should the third volume then be brought in contact with the second and no noticeable change in physical properties is observed, the second and third volumes can also be said to be in thermal equilibrium. For the assumed conditions of this experiment it can be concluded that the three volumes are in thermal equilibrium. Based on this discussion, the three volumes can also be stated to be at the same temperature. This simple experiment can be repeated under the same conditions for solids, liquids, and gases, with the same result every time. The results of all these experiments are summarized and embodied in the *Zeroth Law of Thermodynamics*, which states that two systems having equal temperatures with a third system also have equal temperature with each other. As an alternate definition of the Zeroth Law we can say that if two bodies are each in thermal equilibrium with a third body, they are in thermal equilibrium with each other. The importance of this apparently obvious statement was recognized after the First Law was given its name, and consequently, it was called the Zeroth Law to denote that it precedes the First Law just as zero precedes unity. It should be noted that a thermometer measures only its own temperature, and in order that it may be an accurate indication of the temperature of some second system, the thermometer and the second system must be in thermal equilibrium.

The common scales of temperature are called, respectively, the Fahrenheit and Celsius (Centrigrade) temperatures and are defined by using the ice point and boiling point of water at atmospheric pressure. In the Celsius temperature scale, the interval between the ice point and the boiling point is divided into 100 equal parts. In addition, as shown in Fig. 1.1 the Celsius ice point is zero and the Fahrenheit ice point is 32. The conversion from one scale to the other is directly derived from Fig. 1.1 and results in the following relations:

$$^{\circ}C = 5/9\,(^{\circ}F - 32) \tag{1.1}$$

$$^{\circ}F = 9/5\,(^{\circ}C) + 32 \tag{1.2}$$

°F	°C	°K	°R	
212	100	373	672	Atmospheric boiling point
32	0	273	492	Ice point
-460	-273	0	0	Absolute zero

Fig. 1.1

The ability to extrapolate to temperatures below the ice point and above the boiling point of water and to interpolate in these regions is provided by the International Scale of Temperature. This agreed upon standard utilizes the boiling and melting points of different elements and establishes suitable interpolation formulas in the various temperature ranges between these elements. The data for these elements are given in Table 1.1.

Table 1.1

Element	*Melting or Boiling Point at 1 Atmosphere*	*Temperature* °C	°F
Oxygen	Boiling	-182.97	-297.35
Sulfur	Boiling	444.60	832.28
Antimony	Melting	630.50	1166.90
Silver	Melting	960.8	1761.4
Gold	Melting	1063.0	1945.4
Water	Melting	0	32
	Boiling	100	212

Illustrative Problem 1.1

Determine the temperature at which the same value is indicated on both Fahrenheit and Celsius thermometers.

Solution

Using Eq. (1.1) and letting °C = °F

$$^{\circ}F = 5/9\,(^{\circ}F - 32)$$

$$4/9\ ^{\circ}F = \frac{-160}{9}$$

$$^{\circ}F = -40$$

Therefore, both Fahrenheit and Celsius temperature scales indicate the same temperature at -40°.

By using the results of Illustrative Problem 1.1 it is possible to derive an alternate set of equations to convert from the Fahrenheit to the Celsius temperature scale. When this is done, we obtain,

$$^\circ F = 9/5\,(40 + {}^\circ C) - 40 \tag{1.3}$$

$$^\circ C = 5/9\,(40 + {}^\circ F) - 40 \tag{1.4}$$

The symmetry of Eq. (1.3) and (1.4) makes them relatively easy to remember and use.

Let us consider the case of a gas that is confined in a cylinder (with a constant cross-sectional area) by a piston that is free to move. If heat is now removed from the system, the piston will move down, but due to its weight it will maintain a constant pressure on the gas. This procedure can be carried out for several gases, and if volume is plotted as a function of temperature, we obtain a family of straight lines that intersect at zero volume (Fig. 1.2a).

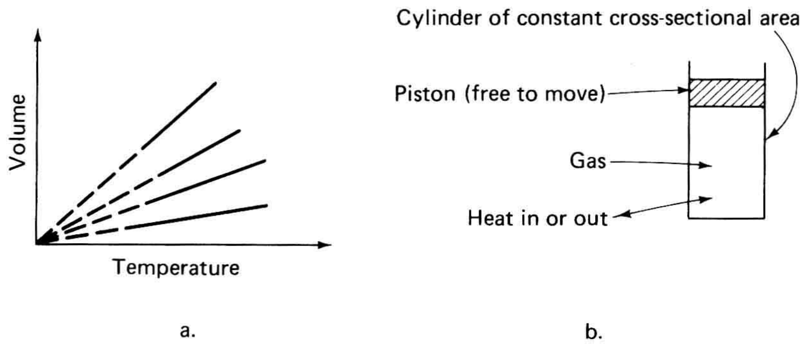

Fig. 1.2 Gas Thermometer

This unique temperature is known as the absolute zero temperature, and the accepted values on the Fahrenheit and Celsius temperature scales are -459.69° and -273.16°, respectively, with the values -460° and -273° used for most engineering calculations. It is also possible to define an absolute temperature scale that is independent of the properties of any substance, and we shall consider this point later in this book.

Thus, we define

$$\text{Degrees Rankine} = {}^\circ R = {}^\circ F + 460 \tag{1.5}$$

$$\text{Degrees Kelvin} = {}^\circ K = {}^\circ C + 273 \tag{1.6}$$

The relation between degrees Rankine, degrees Fahrenheit, degrees Kelvin, and degrees Celsius is also shown in the table of Fig. 1.1.

As has been noted earlier, the state of a system is uniquely determined by its properties. Thus, the accurate measurement of these properties is of great importance from both a theoretical and practical standpoint. Temperatures are measured in many ways but, in general, all of the methods of measuring temperature can be categorized into four classes depending upon the basic physical phenomena used to make the measurement. These classes are:

1/ Methods utilizing the expansion of gases, liquids, or solids.
2/ Methods utilizing the change in electrical resistance of an element.
3/ Methods utilizing the change in electric potential of an element.
4/ Methods utilizing the optical changes of a sensor.

The most common device used to measure temperature is the familiar liquid-in-glass thermometer which consists of a reservoir of liquid and a long glass stem with a fine-line capillary. The operation of this type of thermometer is based upon the coefficient of expansion of the liquid (usually mercury) being greater than the coefficient of expansion of the glass. For accurate measurements, these thermometers are calibrated by either partial, total, or complete immersion in a suitable bath as shown in Fig. 1.3. If the

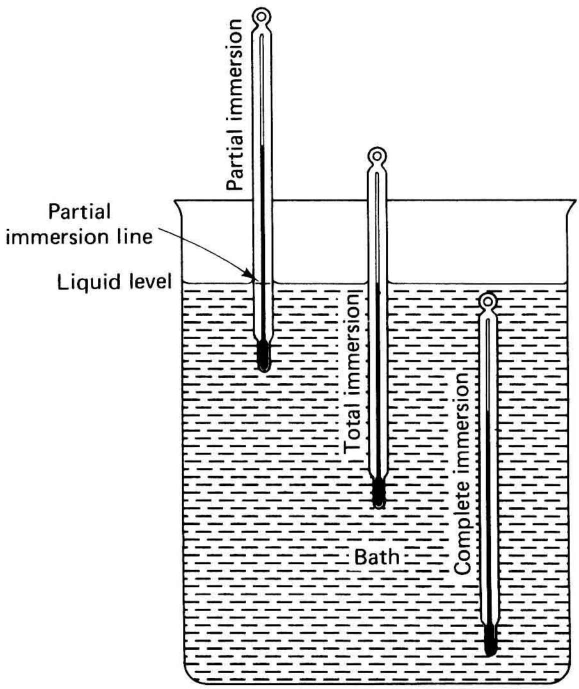

Fig. 1.3 Methods of Calibrating Thermometers

thermometer is calibrated by one method but is used in a different way, it is necessary to make corrections to the readings for the difference in usage. Advantages of the liquid-in-glass thermometers are low cost, simplicity, good reliability, and long life.

Another device that is used to measure temperature or temperature differences depends upon the expansion of materials and is called the bimetallic element. This element usually consists of two thin flat strips placed side-by-side and welded together. The composite strip can be used flat or coiled into a helix or spiral. Changes in temperature cause the strip to change its curvature and the motion produced can be used to move a pointer. The flat bimetallic strip is commonly used in room thermostats where the motion of one end is used to close or open an electrical contact. The action of a bimetallic strip is shown in Fig. 1.4.

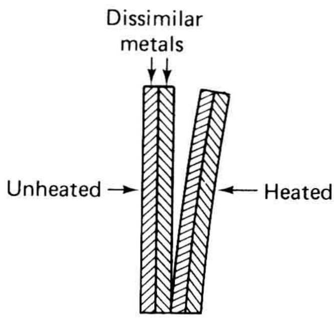

Fig. 1.4 A Bimetallic Strip

Resistance thermometers (Fig. 1.5) are commonly used in industry to measure process temperatures. The basic principle of this type of instrument is that the change in electrical resistance of a sensor due to a change in its temperature is easily measurable. The electrical resistivity of some metals increases very nearly in direct proportion to an increase of temperature. Thus the measured change in resistance of a sensor can be converted to a temperature change. Metals used for the sensors include nickel, copper, and platinum. Because of their calibration stability, high temperature coefficient,

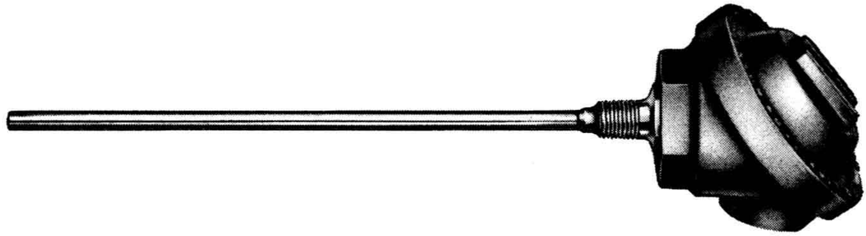

Fig. 1.5. An Industrial Resistance Thermometer (Courtesy of American Chain and Cable Corp.)