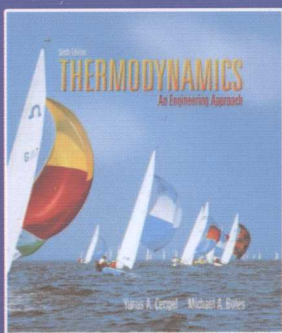


英文版

工程热力学 (第六版)



Thermodynamics
An Engineering Approach
Sixth Edition

[美] Yunus A. Çengel 著
Michael A. Boles
何雅玲 缩编



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北京·BEIJING

内 容 简 介

本书根据 Yunus A. Çengel 和 Michael A. Boles 两位教授编著的热力学经典权威教材 *Thermodynamics, An Engineering Approach, Sixth Edition* 缩减而成。该缩编版保留了原著的特色, 注意引导学生正确分析和理解问题, 注重培养学生解决工程实际问题的能力。本书第 1 章及第 2 章介绍工程热力学中涉及的一些基本概念及能量传递和转化过程遵循的热力学第一定律; 第 3 章介绍纯物质的性质; 第 4 章和第 5 章分别介绍闭口系和开口系能量方程; 第 6 章和第 7 章介绍热力学第二定律及熵; 第 8 章至第 10 章介绍典型的气体动力循环、蒸汽动力循环及制冷循环; 第 11 章介绍热力学一般关系式; 第 12 章介绍理想和真实气体混合物的热力学性质计算; 第 13 章介绍湿空气; 第 14 章介绍气体和蒸汽的可压缩流动。

本书可作为高等学校能源动力、核热工、化工、机械、航天与航空、交通运输、环境、武器、土建等类专业的工程热力学双语教学教材, 也可供有关工程技术人员参考。

Yunus A. Çengel, Michael A. Boles

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缩编者序

由 Yunus A. Çengel 和 Michael A. Boles 编著的 *Thermodynamics, An Engineering Approach, Sixth Edition* 一书是热力学经典权威教材,而本书就是由该经典教材缩减而成的。

Thermodynamics, An Engineering Approach, Sixth Edition 一书写作科学严谨,循序渐进,分析透彻,富有启发,趣味性和可读性强,内容相当丰富。作者在书中,通过不懈的努力,笔者认为至少达到了以下效果:(1)充分地给学生展现了工程热力学从宏观到微观、从日常生活到工业生产等方方面面的、广泛的、丰富多彩的应用背景,从而说明了工程热力学这门学科与我们日常物质生活和工业生产的密切关系,激发学生学习的兴趣和动力;(2)通过对物理概念的深入解释和对基本原理的透彻分析,强调并引导学生学会抓住热力学问题的物理本质,学会正确分析和理解问题,使之受益终身;(3)通过对大量的来自于工程实际例题的练习,帮助学生学会应用所学知识分析和解决实际问题,增强能力,让学生享受工程热力学学习的乐趣,激发学生的创新性和对客观事物的深刻理解。

本书删减时,在内容的取舍上,除考虑工程热力学经典内容外,还尽可能的保留了原版以上叙述的有特色的内容。保留的内容有:(1)能够启发学生思维,使学生对工程热力学基本概念、物理本质有更深入了解的内容;(2)一些新的学科前沿知识,有利于学生可持续发展的内容;(3)有利于学生今后进行学科交叉学习的内容;(4)有利于培养学生对工程热力学兴趣和解决实际问题能力的内容;(5)每章开头的本章内容介绍及章末的知识点总结,这些都有助于学生掌握相关内容;(6)习题中部分综合分析和设计性题目,这些可充分发挥学生的潜力。

本书缩减后共 14 章。第 1 章及第 2 章介绍工程热力学中涉及的一些基本概念及能量传递和转化过程遵循的热力学第一定律;第 3 章介绍纯物质的性质;第 4 章和第 5 章分别介绍闭口系和开口系能量方程;第 6 章和第 7 章介绍热力学第二定律及熵;第 8 章至第 10 章介绍典型的气体动力循环、蒸汽动力循环及制冷循环;第 11 章介绍热力学一般关系式;第 12 章介绍理想和真实气体混合物的热力性质计算;第 13 章介绍湿空气;第 14 章介绍气体和蒸汽的可压缩流动。

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由于缩编者水平所限,存在许多不当和欠缺之处,诚恳祈望广大读者批评指正。

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Chapter 1

INTRODUCTION AND BASIC CONCEPTS

Every science has a unique vocabulary associated with it, and thermodynamics is no exception. Precise definition of basic concepts forms a sound foundation for the development of a science and prevents possible misunderstandings. We start this chapter with an overview of thermodynamics and continue with a discussion of some basic concepts such as *system*, *state*, *state postulate*, *equilibrium*, and *process*. We also discuss *temperature* and *temperature scales* with particular emphasis on the International Temperature Scale of 1990. We then present *pressure*, which is the normal force exerted by a fluid per unit area and discuss *absolute* and *gauge* pressures, the variation of pressure with depth, and pressure measurement devices, such as manometers and barometers. Careful study of these concepts is essential for a good understanding of the topics in the following chapters. Finally, we present an intuitive systematic *problem-solving technique* that can be used as a model in solving engineering problems.

1-1 • THERMODYNAMICS AND ENERGY

Thermodynamics can be defined as the science of *energy*. Although everybody has a feeling of what energy is, it is difficult to give a precise definition for it. Energy can be viewed as the ability to cause changes.

The name *thermodynamics* stems from the Greek words *therme* (heat) and *dynamis* (power), which is most descriptive of the early efforts to convert heat into power. Today the same name is broadly interpreted to include all aspects of energy and energy transformations, including power generation, refrigeration, and relationships among the properties of matter.

One of the most fundamental laws of nature is the **conservation of energy principle**. It simply states that during an interaction, energy can change from one form to another but the total amount of energy remains constant. That is, energy cannot be created or destroyed. A rock falling off a cliff, for example, picks up speed as a result of its potential energy being converted to kinetic energy (Fig. 1-1). The conservation of energy principle also forms the backbone of the diet industry: A person who has a greater energy input (food) than energy output (exercise) will gain weight (store energy in the form of fat), and a person who has a smaller energy input than output will lose weight (Fig. 1-2). The change in the energy content of a body or any other system is equal to the difference between the energy input and the energy output, and the energy balance is expressed as $E_{in} - E_{out} = \Delta E$.

Objectives

The objectives of Chapter 1 are to:

- Identify the unique vocabulary associated with thermodynamics through the precise definition of basic concepts to form a sound foundation for the development of the principles of thermodynamics.
- Explain the basic concepts of thermodynamics such as system, state, state postulate, equilibrium, process, and cycle.
- Review concepts of temperature, temperature scales, pressure, and absolute and gauge pressure.
- Introduce an intuitive systematic problem-solving technique.

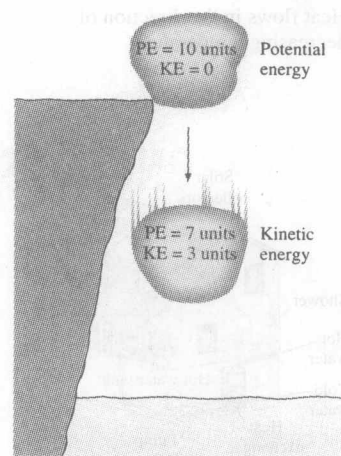


FIGURE 1-1

Energy cannot be created or destroyed; it can only change forms (the first law).

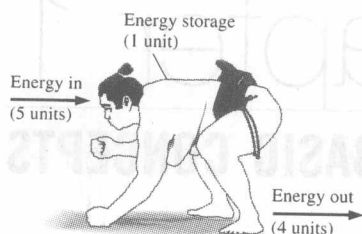


FIGURE 1-2

Conservation of energy principle for the human body.

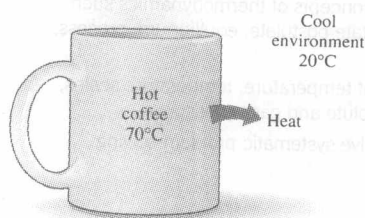


FIGURE 1-3

Heat flows in the direction of decreasing temperature.

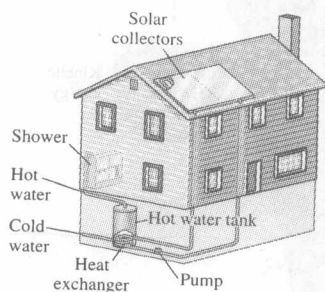


FIGURE 1-4

The design of many engineering systems, such as this solar hot water system, involves thermodynamics.

The **first law of thermodynamics** is simply an expression of the conservation of energy principle, and it asserts that *energy* is a thermodynamic property. The **second law of thermodynamics** asserts that energy has *quality* as well as *quantity*, and actual processes occur in the direction of decreasing quality of energy. For example, a cup of hot coffee left on a table eventually cools, but a cup of cool coffee in the same room never gets hot by itself (Fig. 1-3). The high-temperature energy of the coffee is degraded (transformed into a less useful form at a lower temperature) once it is transferred to the surrounding air.

Although the principles of thermodynamics have been in existence since the creation of the universe, thermodynamics did not emerge as a science until the construction of the first successful atmospheric steam engines in England by Thomas Savery in 1697 and Thomas Newcomen in 1712. These engines were very slow and inefficient, but they opened the way for the development of a new science.

The first and second laws of thermodynamics emerged simultaneously in the 1850s, primarily out of the works of William Rankine, Rudolph Clausius, and Lord Kelvin (formerly William Thomson). The term *thermodynamics* was first used in a publication by Lord Kelvin in 1849. The first thermodynamic textbook was written in 1859 by William Rankine, a professor at the University of Glasgow.

It is well-known that a substance consists of a large number of particles called *molecules*. The properties of the substance naturally depend on the behavior of these particles. For example, the pressure of a gas in a container is the result of momentum transfer between the molecules and the walls of the container. However, one does not need to know the behavior of the gas particles to determine the pressure in the container. It would be sufficient to attach a pressure gage to the container. This macroscopic approach to the study of thermodynamics that does not require a knowledge of the behavior of individual particles is called **classical thermodynamics**. It provides a direct and easy way to the solution of engineering problems. A more elaborate approach, based on the average behavior of large groups of individual particles, is called **statistical thermodynamics**. This microscopic approach is rather involved and is used in this text only in the supporting role.

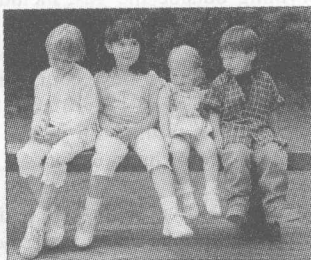
Application Areas of Thermodynamics

All activities in nature involve some interaction between energy and matter; thus, it is hard to imagine an area that does not relate to thermodynamics in some manner. Therefore, developing a good understanding of basic principles of thermodynamics has long been an essential part of engineering education.

Thermodynamics is commonly encountered in many engineering systems and other aspects of life, and one does not need to go very far to see some application areas of it. In fact, one does not need to go anywhere. The heart is constantly pumping blood to all parts of the human body, various energy conversions occur in trillions of body cells, and the body heat generated is constantly rejected to the environment. The human comfort is closely tied to the rate of this metabolic heat rejection. We try to control this heat transfer rate by adjusting our clothing to the environmental conditions.

Other applications of thermodynamics are right where one lives. An ordinary house is, in some respects, an exhibition hall filled with wonders of thermodynamics (Fig. 1-4). Many ordinary household utensils and appliances are designed, in whole or in part, by using the principles of thermodynamics. Some examples include the electric or gas range, the heating and

the TV. On a larger scale, thermodynamics plays a major part in the design and analysis of automotive engines, rockets, jet engines, and conventional or nuclear power plants, solar collectors, and the design of vehicles from ordinary cars to airplanes (Fig. 1–5). The energy-efficient home that you may be living in, for example, is designed on the basis of minimizing heat loss in winter and heat gain in summer. The size, location, and the power input of the fan of your computer is also selected after an analysis that involves thermodynamics.



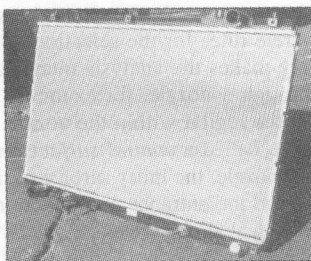
The human body



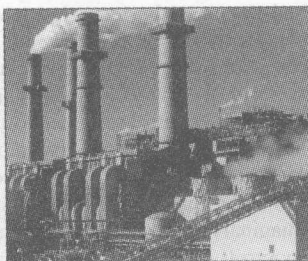
Air conditioning systems



Airplanes



Car radiators



Power plants



Refrigeration systems

FIGURE 1–5

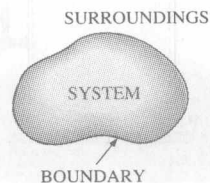
Some application areas of thermodynamics.

A/C unit, fridge, radiator: © The McGraw-Hill Companies, Inc./Jill Braaten, photographer; Plane: © Vol. 14/PhotoDisc; Humans: © Vol. 121/PhotoDisc; Power plant: © Corbis Royalty Free

1–2 • SYSTEMS AND CONTROL VOLUMES

A system is defined as a *quantity of matter or a region in space chosen for study*. The mass or region outside the system is called the **surroundings**. The real or imaginary surface that separates the system from its surroundings is called the **boundary**. These terms are illustrated in Fig. 1–6. The boundary of a system can be *fixed* or *movable*. Note that the boundary is the contact surface shared by both the system and the surroundings. Mathematically speaking, the boundary has zero thickness, and thus it can neither contain any mass nor occupy any volume in space.

Systems may be considered to be *closed* or *open*, depending on whether a fixed mass or a fixed volume in space is chosen for study. A **closed system** (also known as a **control mass**) consists of a fixed amount of mass, and no mass can cross its boundary. That is, no mass can enter or leave a closed system, as shown in Fig. 1–7. But energy, in the form of heat or work, can cross the boundary; and the volume of a closed system does not have to be

**FIGURE 1–6**

System, surroundings, and boundary.

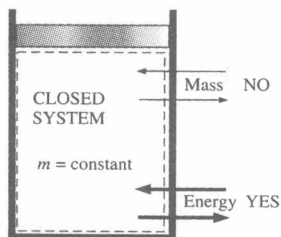


FIGURE 1-7

Mass cannot cross the boundaries of a closed system, but energy can.

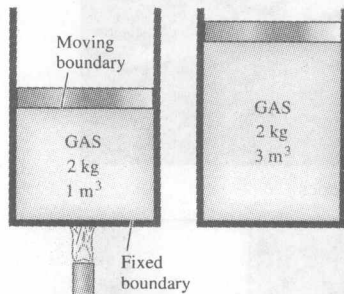


FIGURE 1-8

A closed system with a moving boundary.

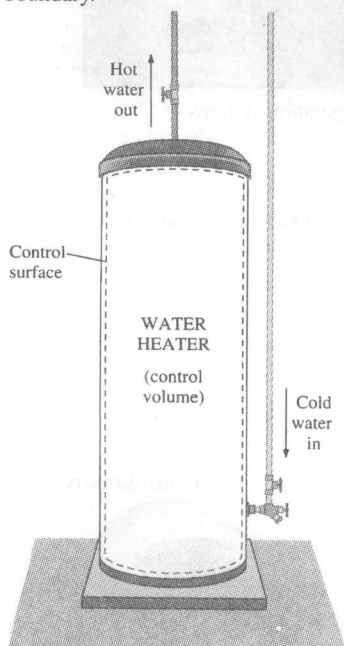


FIGURE 1-10

An open system (a control volume) with one inlet and one exit.

fixed. If, as a special case, even energy is not allowed to cross the boundary, that system is called an **isolated system**.

Consider the piston-cylinder device shown in Fig. 1-8. Let us say that we would like to find out what happens to the enclosed gas when it is heated. Since we are focusing our attention on the gas, it is our system. The inner surfaces of the piston and the cylinder form the boundary, and since no mass is crossing this boundary, it is a closed system. Notice that energy may cross the boundary, and part of the boundary (the inner surface of the piston, in this case) may move. Everything outside the gas, including the piston and the cylinder, is the surroundings.

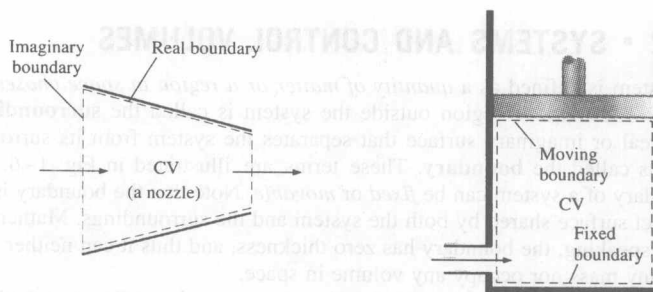
An **open system**, or a **control volume**, as it is often called, is a properly selected region in space. It usually encloses a device that involves mass flow such as a compressor, turbine, or nozzle. Flow through these devices is best studied by selecting the region within the device as the control volume. Both mass and energy can cross the boundary of a control volume.

A large number of engineering problems involve mass flow in and out of a system and, therefore, are modeled as *control volumes*. A water heater, a car radiator, a turbine, and a compressor all involve mass flow and should be analyzed as control volumes (open systems) instead of as control masses (closed systems). In general, *any arbitrary region in space* can be selected as a control volume. There are no concrete rules for the selection of control volumes, but the proper choice certainly makes the analysis much easier. If we were to analyze the flow of air through a nozzle, for example, a good choice for the control volume would be the region within the nozzle.

The boundaries of a control volume are called a *control surface*, and they can be real or imaginary. In the case of a nozzle, the inner surface of the nozzle forms the real part of the boundary, and the entrance and exit areas form the imaginary part, since there are no physical surfaces there (Fig. 1-9a).

A control volume can be fixed in size and shape, as in the case of a nozzle, or it may involve a moving boundary, as shown in Fig. 1-9b. Most control volumes, however, have fixed boundaries and thus do not involve any moving boundaries. A control volume can also involve heat and work interactions just as a closed system, in addition to mass interaction.

As an example of an open system, consider the water heater shown in Fig. 1-10. Let us say that we would like to determine how much heat we



(a) A control volume with real and imaginary boundaries

(b) A control volume with fixed and moving boundaries

FIGURE 1-9

A control volume can involve fixed, moving, real, and imaginary boundaries.

must transfer to the water in the tank in order to supply a steady stream of hot water. Since hot water will leave the tank and be replaced by cold water, it is not convenient to choose a fixed mass as our system for the analysis. Instead, we can concentrate our attention on the volume formed by the interior surfaces of the tank and consider the hot and cold water streams as mass leaving and entering the control volume. The interior surfaces of the tank form the control surface for this case, and mass is crossing the control surface at two locations.

In an engineering analysis, the system under study *must* be defined carefully. In most cases, the system investigated is quite simple and obvious, and defining the system may seem like a tedious and unnecessary task. In other cases, however, the system under study may be rather involved, and a proper choice of the system may greatly simplify the analysis.

1-3 • PROPERTIES OF A SYSTEM

Any characteristic of a system is called a **property**. Some familiar properties are pressure P , temperature T , volume V , and mass m . The list can be extended to include less familiar ones such as viscosity, thermal conductivity, modulus of elasticity, thermal expansion coefficient, electric resistivity, and even velocity and elevation.

Properties are considered to be either *intensive* or *extensive*. **Intensive properties** are those that are independent of the mass of a system, such as temperature, pressure, and density. **Extensive properties** are those whose values depend on the size—or extent—of the system. Total mass, total volume, and total momentum are some examples of extensive properties. An easy way to determine whether a property is intensive or extensive is to divide the system into two equal parts with an imaginary partition, as shown in Fig. 1-11. Each part will have the same value of intensive properties as the original system, but half the value of the extensive properties.

Generally, uppercase letters are used to denote extensive properties (with mass m being a major exception), and lowercase letters are used for intensive properties (with pressure P and temperature T being the obvious exceptions).

Extensive properties per unit mass are called **specific properties**. Some examples of specific properties are specific volume ($v = V/m$) and specific total energy ($e = E/m$).

Continuum

Matter is made up of atoms that are widely spaced in the gas phase. Yet it is very convenient to disregard the atomic nature of a substance and view it as a continuous, homogeneous matter with no holes, that is, a **continuum**. The continuum idealization allows us to treat properties as point functions and to assume the properties vary continually in space with no jump discontinuities. This idealization is valid as long as the size of the system we deal with is large relative to the space between the molecules. This is the case in practically all problems, except some specialized ones. The continuum idealization is implicit in many statements we make, such as “the density of water in a glass is the same at any point.”

To have a sense of the distance involved at the molecular level, consider a container filled with oxygen at atmospheric conditions. The diameter of the oxygen molecule is about 3×10^{-10} m and its mass is 5.3×10^{-26} kg. Also, the *mean free path* of oxygen at 1 atm pressure and 20°C is 6.3×10^{-8} m. That is, an oxygen molecule travels, on average, a distance of 6.3×10^{-8} m (about 200 times of its diameter) before it collides with another molecule.

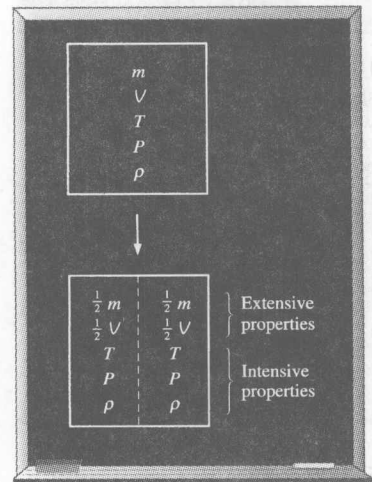


FIGURE 1-11

Criterion to differentiate intensive and extensive properties.

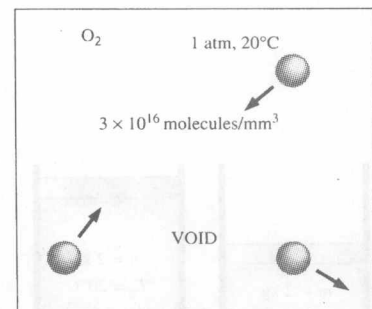
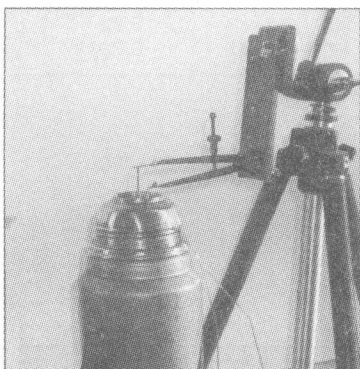


FIGURE 1-12

Despite the large gaps between molecules, a substance can be treated as a continuum because of the very large number of molecules even in an extremely small volume.



Use actual data from the experiment shown here to obtain the **density** of water in the neighborhood of 4°C.

© Ronald Multisen

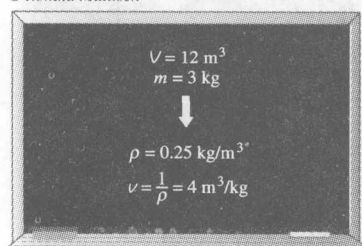
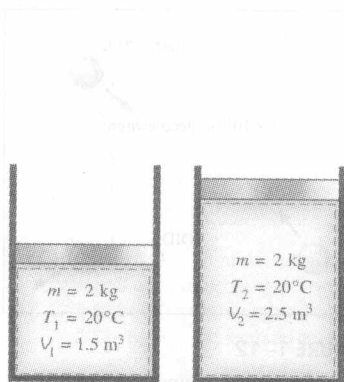


FIGURE 1-13

Density is mass per unit volume; specific volume is volume per unit mass.



(a) State 1

(b) State 2

FIGURE 1-14

A system at two different states.

Also, there are about 3×10^{16} molecules of oxygen in the tiny volume of 1 mm^3 at 1 atm pressure and 20°C (Fig. 1-12). The continuum model is applicable as long as the characteristic length of the system (such as its diameter) is much larger than the mean free path of the molecules. At very high vacuums or very high elevations, the mean free path may become large (for example, it is about 0.1 m for atmospheric air at an elevation of 100 km). For such cases the **rarefied gas flow theory** should be used, and the impact of individual molecules should be considered. In this text we will limit our consideration to substances that can be modeled as a continuum.

1-4 • DENSITY AND SPECIFIC GRAVITY

Density is defined as *mass per unit volume* (Fig. 1-13).

$$\text{Density:} \quad \rho = \frac{m}{V} \quad (\text{kg/m}^3) \quad (1-1)$$

The reciprocal of density is the **specific volume** ν , which is defined as *volume per unit mass*. That is,

$$\nu = \frac{V}{m} = \frac{1}{\rho} \quad (1-2)$$

For a differential volume element of mass δm and volume δV , density can be expressed as $\rho = \delta m / \delta V$.

The density of a substance, in general, depends on temperature and pressure. The density of most gases is proportional to pressure and inversely proportional to temperature. Liquids and solids, on the other hand, are essentially incompressible substances, and the variation of their density with pressure is usually negligible. At 20°C, for example, the density of water changes from 998 kg/m³ at 1 atm to 1003 kg/m³ at 100 atm, a change of just 0.5 percent. The density of liquids and solids depends more strongly on temperature than it does on pressure. At 1 atm, for example, the density of water changes from 998 kg/m³ at 20°C to 975 kg/m³ at 75°C, a change of 2.3 percent, which can still be neglected in many engineering analyses.

The weight of a unit volume of a substance is called **specific weight** and is expressed as

$$\text{Specific weight:} \quad \gamma_s = \rho g \quad (\text{N/m}^3) \quad (1-3)$$

where g is the gravitational acceleration.

The densities of liquids are essentially constant, and thus they can often be approximated as being incompressible substances during most processes without sacrificing much in accuracy.

1-5 • STATE AND EQUILIBRIUM

Consider a system not undergoing any change. At this point, all the properties can be measured or calculated throughout the entire system, which gives us a set of properties that completely describes the condition, or the **state**, of the system. At a given state, all the properties of a system have fixed values. If the value of even one property changes, the state will change to a different one. In Fig. 1-14 a system is shown at two different states.

Thermodynamics deals with *equilibrium* states. The word **equilibrium** implies a state of balance. In an equilibrium state there are no unbalanced

potentials (or driving forces) within the system. A system in equilibrium experiences no changes when it is isolated from its surroundings.

There are many types of equilibrium, and a system is not in thermodynamic equilibrium unless the conditions of all the relevant types of equilibrium are satisfied. For example, a system is in **thermal equilibrium** if the temperature is the same throughout the entire system, as shown in Fig. 1–15. That is, the system involves no temperature differential, which is the driving force for heat flow. **Mechanical equilibrium** is related to pressure, and a system is in mechanical equilibrium if there is no change in pressure at any point of the system with time. However, the pressure may vary within the system with elevation as a result of gravitational effects. For example, the higher pressure at a bottom layer is balanced by the extra weight it must carry, and, therefore, there is no imbalance of forces. The variation of pressure as a result of gravity in most thermodynamic systems is relatively small and usually disregarded. If a system involves two phases, it is in **phase equilibrium** when the mass of each phase reaches an equilibrium level and stays there. Finally, a system is in **chemical equilibrium** if its chemical composition does not change with time, that is, no chemical reactions occur. A system will not be in equilibrium unless all the relevant equilibrium criteria are satisfied.

The State Postulate

As noted earlier, the state of a system is described by its properties. But we know from experience that we do not need to specify all the properties in order to fix a state. Once a sufficient number of properties are specified, the rest of the properties assume certain values automatically. That is, specifying a certain number of properties is sufficient to fix a state. The number of properties required to fix the state of a system is given by the **state postulate**:

The state of a simple compressible system is completely specified by two independent, intensive properties.

A system is called a **simple compressible system** in the absence of electrical, magnetic, gravitational, motion, and surface tension effects. These effects are due to external force fields and are negligible for most engineering problems. Otherwise, an additional property needs to be specified for each effect that is significant. If the gravitational effects are to be considered, for example, the elevation z needs to be specified in addition to the two properties necessary to fix the state.

The state postulate requires that the two properties specified be independent to fix the state. Two properties are **independent** if one property can be varied while the other one is held constant. Temperature and specific volume, for example, are always independent properties, and together they can fix the state of a simple compressible system (Fig. 1–16). Temperature and pressure, however, are independent properties for single-phase systems, but are dependent properties for multiphase systems. At sea level ($P = 1$ atm), water boils at 100°C , but on a mountaintop where the pressure is lower, water boils at a lower temperature. That is, $T = f(P)$ during a phase-change process; thus, temperature and pressure are not sufficient to fix the state of a two-phase system. Phase-change processes are discussed in detail in Chap. 3.

1–6 • PROCESSES AND CYCLES

Any change that a system undergoes from one equilibrium state to

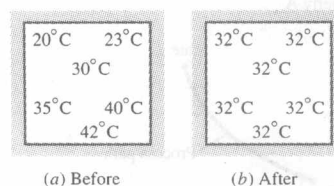


FIGURE 1–15

A closed system reaching thermal equilibrium.

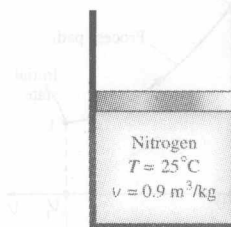


FIGURE 1–16

The state of nitrogen is fixed by two independent, intensive properties.