Engineering Thermodynamics

ENGINEERING THERMODYNAMICS

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PREFACE

This text was developed as an alternative version of the senior author's book, *Thermodynamics*. The primary spirit of these two books is the same; microscopic arguments are used to provide insight into the basic macroscopic postulates. Indeed, the fundamental developments of the first seven chapters are fully identical in the two books. Beyond this the texts begin to differ. The parent text treats a broad range of applications in engineering, physical chemistry, and includes introductory chapters in statistical thermodynamics, kinetic theory, and irreversible thermodynamics. In contrast, this book concentrates along the lines of more traditional engineering courses. The applications possess a stronger engineering flavor, and introductory chapters on applied one-dimensional gas dynamics and heat transfer are included. Thus, the parent text best serves a basic course for engineers anticipating graduate study, where these subjects will be covered in depth. On the other hand, this version is better suited for mechanical engineers going into practice upon graduation, or for engineers in other fields desiring an introductory background in some important areas of mechanical engineering.

Throughout the text, the value of a systematic methodology in analyses is emphasized. Such an approach is absolutely essential and should be required in the student's problem assignments. A lack of understanding of the fundamentals of engineering frequently is caused by students consistently starting problems "in the middle." Overly easy homework problems can often be successfully solved in this manner, and we have purposely provided longer and more difficult problems, particularly in the later chapters where several of the thermodynamic principles can be brought to bear in a single analysis. We have found that getting into the analysis of simple thermodynamic systems as soon as possible provides good motivation for further developments in theory. For this reason, energy-balance applications are taken up before the introduction of second-law concepts. This arrangement also provides a period for digestion of state and first-law concepts and helps spread the introduction of new ideas more evenly over the course.

Our objective has been to develop the subject matter in a way that retains the generality and simplicity of purely macroscopic thermodynamics and yet draws upon the student's insight into microscopic matters. To this end the microscopic arguments are used to provide an intuitive basis for macroscopic postulates; the laws of thermodynamics are *not* derived from microscopic postulates. This approach preserves the generality of macroscopic thermodynamics and at the same time places the roots for energy, entropy, and temperature firmly in the microscopic world. Our intention is to clearly establish the tie between the macroscopic and microscopic viewpoints at an early stage and provide the student with a full appreciation of the importance of both views.

This book could not have been written without the continued encouragement and suggestions of faculty colleagues and students at our two institutions. In particular, we both obtained a real appreciation for the methodology of thermodynamic analysis from Professor A. L. London. Professors S. J. Kline, A. Anderson, and Philip Schmidt made many helpful criticisms and suggestions during the development of the parent text. The patience of our wives and families in enduring our discussions of Rankine cycles, choked flow, etc., should also be acknowledged.

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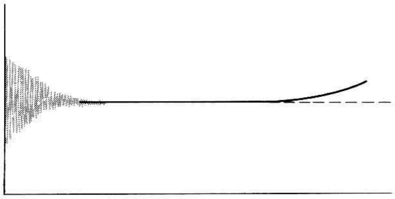
CHAPTER ONE



SOME INTRODUCTORY CONSIDERATIONS

1·1 THE NATURE OF THERMODYNAMICS

Thermodynamics deals with matter and interactions between matter; since every technological system involves matter, thermodynamic analysis is very important in engineering. Examples of thermodynamic analysis are given throughout this text. In particular, the examples of Chaps. Five and Nine show applications to engineering systems, and those of Chaps. Eight and Ten indicate the role of thermodynamics in the study of substances. The student may wish to scan these examples now to get some idea about the direction and scope of the subject.

Thermodynamics centers about the notions of *energy;* the idea that energy is always conserved is both the fundamental starting point and the basis for quantitative analysis. A second concept in thermodynamics is *entropy;* entropy provides a means for determining if a process is possible. Processes which produce entropy are possible, those which destroy entropy are impossible. These ideas of energy and entropy provide the framework of thermodynamics, and a clear understanding of them is therefore crucial. For this reason we shall place heavy emphasis on the development of real understanding of these and related concepts. This development requires exposure to the ideas, a chance to use them operationally, and time for satisfactory digestion. Consequently we shall introduce new concepts gradually and with some repetition, and shall make use of the ideas in practical analysis shortly after their first introduction. The successful student will be one who works hardest on understanding concepts. The engineering calculations that we shall do are intended as vehicles for gaining understanding of the concepts and for developing the ability to carry out such a calculation independently.

What do we need to know about matter in order to carry out an engineering analysis of a system of interest? Matter is composed of particles; any visible piece of matter contains a tremendous number of molecules, atoms, electrons, etc., each of which can have energy in a variety of ways. A *microscopic* description of such a piece would require the enumeration of the state of each particle, an obviously impractical task. In thermodynamics we seek to reduce the bits of information required to adequately describe states of matter from something of the order of 10^{23} to "few." This is accomplished by some sort of *statistical averaging;* we are willing to forego knowledge of microscopic detail in favor of simplicity. Thermodynamics is therefore a *macroscopic* science, which allows us to relate the averaged (macroscopic) properties of matter. Fortunately, the microscopic aspects are not essential in many important technical problems, and we can obtain excellent engineering solutions using the simpler macroscopic ideas.

The ultimate nature of matter is microscopic, of course, and our understanding of macroscopic theories can be considerably enhanced by drawing on microscopic concepts. For instance, it may be hard to visualize an object sitting motionless on a table as having any energy; but the thought of electrons whirling about vibrating nuclei provides a vivid physical picture of that energy and makes it much easier to visualize various means for changing the energy of the object. In this text we shall take optimum advantage of microscopic ideas, using them to provide physical interpretations of macroscopic properties and intuitive bases for macroscopic postulates.

Thermodynamic theory allows us to relate various properties of matter, so that by measuring some of them we can calculate others. Although microscopic ideas are indeed helpful to understanding, thermodynamics does not require the postulation of any particular microscopic models of matter. Other physical theories have been developed which do require specific microscopic models, and from these emerge predictions for the *values* of properties of the substance represented by the model. In statistical mechanics some sort of statistical model of the substance is postulated, and in kinetic theory a dynamic model is employed. These theories, although more specific in their output, are less general than those of thermodynamics. In fact, results from thermodynamics are usually used in association with the microscopic theories. Historically thermodynamics, statistical mechanics, and kinetic theory have developed separately, usually from somewhat different foundations. Our use of microscopic concepts allows us to lay a more common foundation for these three subjects, such that their relation and interdependence can more easily be appreciated. We shall go into some simple microscopic analyses following development of the key thermodynamic ideas.

The knowledge of the behavior of matter obtained from thermodynamics is extremely important in engineering analysis. When carried out in a systematic fashion, such analyses are not very difficult; but we cannot emphasize enough the importance of a systematic methodology, without which easy problems become hard. In parallel with more theoretical thermodynamic developments we shall use the methodology in illustrative engineering examples. Understanding of the basic thermodynamic concepts and principles and the ability to apply them in engineering are the primary objectives of our study.

In this chapter we shall attempt to establish a point of view through discussion of ideas already familiar to the student. The fundamental approach and philosophy adopted in this review of the basic concepts, models, and laws of related branches of physics will be carried over to the new thermodynamic ideas in subsequent chapters.

1·2 CONCEPTS, MODELS, AND LAWS

Concepts form the basis for any science. These are ideas, usually somewhat vague (especially when first encountered), which often defy really adequate definition. The meaning of a new concept can seldom be grasped from reading a one-paragraph discussion. There must be time to become accustomed to the concept, to integrate it with prior knowledge, and to associate it with personal experience. Inability to work with the details of a new subject can often be traced to inadequate understanding of its basic concepts.

The physical world is very complicated, and to include every minute detail in a theoretical analysis would be impracticable. Science has made big steps forward by the use of *models*, which, although always representing some simplifications over reality, reduce the mathematics to a tractable level. The range of validity and utility of the resulting theory is consequently restricted by the idealizations made in formulating the model. Newtonian mechanics is quite adequate for analysis of the great majority of everyday mechanical processes, and inclusion of relativistic effects in such mechanical analysis is an unnecessary complication. However, in many instances such effects are important, and it is the responsibility of the user of any theory to know both its bases and its limitations.

Concepts and models are not enough in themselves for a physical theory. These notions must be expressed in appropriate mathematical terms through basic equations, or *laws*. We choose to look upon a physical law as a contrivance of man that allows him to explain and predict phenomena of nature. Such predictions will be only as accurate and encompassing as the models on which the laws are based, and as new information is gathered and new understanding is developed, man may find it convenient, or perhaps necessary, to alter the basic laws. For example, mechanics is a direct outgrowth of Kepler's astronomical studies and his laws relating to the motion of planets about the sun. Newton generalized these observations and formed new, more basic laws, from which Kepler's rules could be deduced as special consequences. Later Newton's mechanics became merely a special case of Einstein's relativistic mechanics. In general, laws are replaced not because they are incorrect, but because their range of validity is restricted. Such was the case in the early development of thermodynamics, where at one time heat was thought of as something contained within matter. A useful but extremely limited caloric theory of heat, built upon this concept, was discarded more than a century ago; unfortunately, carryover of this misconception inhibits understanding of contemporary thermodynamics.

In many fields of science the concepts are very close to everyday experience, and the difficulties are primarily mathematical in nature. In most of thermodynamics the converse is true; the mathematics is not complicated but the concepts are sometimes difficult to grasp at the beginning, and most of the errors in thermodynamic analysis arise because of lack of clarity in either concepts or methodology. For this reason we shall spend a good deal of time on these matters; they should not be taken lightly, even though it may not be evident why so much attention is paid to apparently small details. To begin the discussion, let us review some concepts that are already familiar, examining them in the manner we shall subsequently employ in thermodynamics.

1·3 A FRESH LOOK AT SOME FAMILIAR CONCEPTS

One of the most important and central concepts in physics is *force*. It took man millenniums to evolve the force concept as a tool for explaining the varied interactions between objects in his environment. He observed that any one of a number of things can cause a given object to assume a certain position or undergo a certain gyration. The perception that in discussing the behavior of the object a particular cause can be replaced by a hypothetical "force" heralded the beginning of mechanics. Today we use this concept almost unconsciously whenever we replace the action of one body upon another by an appropriate force (see Fig. 1·1).

Forces are conceived as those pushes and pulls that tend to make objects move, and an essential part of the concept is that forces are somehow in balance when the object under study is motionless (or when its motion is uniform). It is essential to appreciate that the notion of a balance of forces in the absence of acceleration is an integral part of the force concept; whether or not forces "really exist" is a philosophical question which we need not debate. The fact is that the force concept allows us accurately to predict events in the real world, and this alone justifies its invention.

Forces are conceived as having both magnitude and direction and are treated mathematically as vectors. The vector sum of all forces acting on a body that is not accelerating must be zero.

We imagine that any two bodies in contact will exert forces upon one another. When we analyze the motion of one body, we mentally remove the

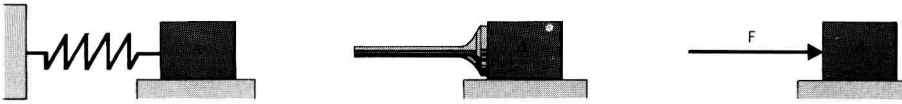


FIG. 1·1 *The effect of either the spring or the shaft on body A can be replaced by* F

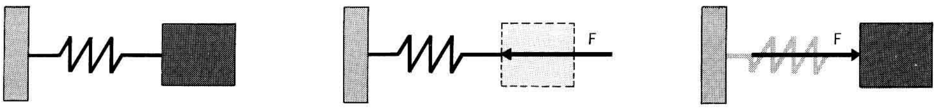


FIG. 1·2 *The notion that "action equals reaction" is an integral part of the force concept*

other and replace its influence on the first by a force (Fig. 1·2). If we wish instead to study the motion of the second body, the first body would be replaced by a force of exactly the same magnitude but acting in the opposite direction. This "action-reaction" principle was formulated by Newton as his third law, but it is really an integral part of the concept of force.

No conceptual quantity becomes operationally useful until some way for its measurement has been established. One possible way of setting up a scale for force is to select some standard spring and say that the force it exerts is some selected constant times its deflection. This scheme has the distinct disadvantage of making the force scale dependent on the choice of material in the spring, among other factors. Suppose someone else set up a similar scale, based on a different kind of spring; the two scales could be adjusted to agree at one point but could not be expected to agree elsewhere. To each one the other would be nonlinear. It is always more desirable to devise scales of measure that are completely independent of the nature of any substance. In principle it is possible to do this for force, taking advantage of the notion that the resultant force on a stationary body is zero. Imagine selecting any reproducible force, such as that produced by a selected spring compressed some selected amount, and designating this as a unit force. Let this force act on a body in sole opposition to two identical forces selected so as to keep the spring at its standard deflection when the body is motionless (the two identical forces could be obtained from any two identical springs, for example). The two identical forces must each be half the unit force, and either can be used to measure such a force (see Fig. 1·3). This process can be continued, and we can collect a set of springs, each measuring some rational fraction or multiple of the unit force. We can therefore, in principle, measure any unknown force to any desired degree of accuracy. The force scale is unique in that it is independent of the nature of any substance. It will be the same regardless of the material of which the springs are made.

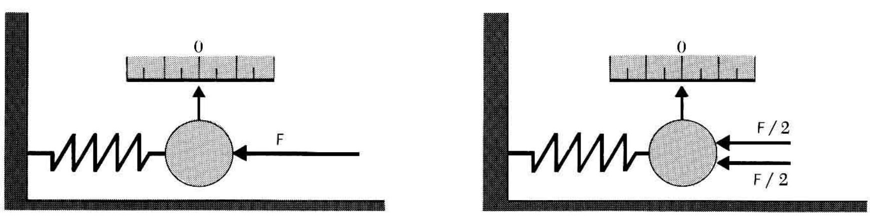


FIG. 1·3 *A unique force scale can be established using symmetry and the concepts of force*