# ENGINEERING THERMODYNAMICS

SECOND EDITION

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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. 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 strong engineering flavor, and introductory chapters on applied one-dimensional gas dynamics and heat transfer are included.

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 futher 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.

Some modest changes in the ordering of second-law material have been made for this edition. While the microscopic insights that are characteristic of the first edition are retained, the exemplary microscopic calculations have been placed in a position where they may be omitted by the instructor who prefers to follow a more tranditional macroscopic approach. More emphasis has been placed on the concept of entropy production for we have found in our own teaching that this assists the students in understanding and working with the second law. The format for applied second-law analysis is more strongly stated, and a number of new examples of second-law analysis have been added. In these examples emphasis is placed on analysis of the best possible performance, and availability concepts are introduced. Motivation for engineering applications of the second law is provided by the obvious importance of such analysis to the national program of energy conservation.

This second edition is very strongly "dimensionally bilingual," with equal emphasis given to metric (SI) and English units. We believe that it is important that today's engineers think metric but also be fully comfortable with the English units. There are many reasons for this, including the need to be able to communicate with persons who are not comfortable with metric units and the need to use data in English units (today very little of the information actually used by engineers is available in SI). Examples, problems, and thermodynamic data in both SI and English units are included.

Thermodynamics is often characterized as a difficult subject. Indeed, if one's approach is to memorize every equation developed in the course, the subject will be very difficult. However, we urge the student to adopt a fundamental approach; work to understand the concepts and develop the ability to apply the basic principles in a systematic way. The student who takes this approach will find that the subject is really quite easy, and that it provides a tremendously useful set of tools for engineering analysis.

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 value of systematic methodology in engineering thermodynamic analysis from Professor A. L. London. We are also indebted to colleagues at other institutions who, through use of our earlier edition, have helped us improve the current version. And to our wives and families, who patiently endured our discussions and long hours over manuscripts, we express our special appreciation.

**William C. Reynolds**
**Henry C. Perkins**

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# CONTENTS

CHAPTER ONE

# SOME INTRODUCTORY CONSIDERATIONS

## 1·1 THE NATURE OF THERMODYNAMICS

Thermodynamics is one of the most important areas of engineering science. It is the science used to explain how most things work, why some things do not work the way that they were intended, and why other things just cannot possibly work at all. It is a key part of the science engineers use to design automotive engines, heat pumps, rocket motors, power stations, life support systems, gas turbines, air conditioners, firefighting equipment, artificial kidneys, superconducting transmission lines, chemical refineries, high-power lasers, and solar heating systems. Students who have an interest in any of these need to understand and use thermodynamics.

Thermodynamics centers about the notions of *energy*; the idea that energy is conserved is the *first law of thermodynamics.* It is the starting point for the science of thermodynamics and for engineering 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. This idea is the basis for the *second law of thermodynamics*, about which you may have heard. It also provides the basis for an engineering analysis in which one calculates the maximum amount of useful power that can be obtained from a given energy source, or the minimum amount of power input required to do a certain task. These calculations can be made



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without any specific notions about the nature of the systems involved, and it is this great generality that gives thermodynamics its tremendous power.

A clear understanding of the ideas of energy and entropy are essential for one who needs to use thermodynamics in engineering analysis. Traditionally thermodynamics has been regarded as a difficult subject, and hundreds of textbooks on the subject have been written in an effort to develop better clarity and rigor. Most of these books ignore the fact that matter is inherently molecular, and try to develop the ideas by forgetting that molecules exist. This *classical* or *macroscopic* approach to thermodynamics, which is mathematically rather simple, is of considerable intellectual interest, but because it is so abstract it is hard to grasp for someone who does not already know the subject. Another approach is to start at the molecular level and develop equations from this base. But this *microscopic* approach is mathematically rather involved and difficult for someone who does not already know the basic ideas. We shall follow an intermediate approach, drawing upon microscopic ideas where these provide understanding of the macroscopic mathematics one actually uses in engineering analysis. We think this approach makes thermodynamics easily understood, and this is highly desirable for such an important subject.

There is another important difference between thermodynamics as taught, say, by physicists and chemists, and as taught and used by engineers. The pure scientist is interested primarily in analyzing specific pieces of matter that interact with one another, while engineers are usually interested in analyzing complex systems through which matter is flowing. Scientists are interested in using thermodynamics to predict and relate the properties of matter; engineers are interested in using this data, together with the basic ideas of energy conservation and entropy production, to analyze the behavior of complex technological systems. In this book we deal with both points of view, but our emphasis is clearly on the engineer's needs and approach to thermodynamics.

Figure 1·1 is an example of the sort of system of interest to engineers, a large central power station. In this particular plant the energy *source* is petroleum in one of several forms, or sometimes natural gas, and the function of the plant is to convert as much of this energy as possible to electric energy and to send this energy down the transmission line. Simply expressed, the plant does this by boiling water and using the steam to turn a turbine which turns an electric generator. The simplest such power plants are able to convert only about 25 percent of the fuel energy to electric energy. The plant shown in Fig. 1·1 converts approximately 40 percent; it has been ingeniously designed through careful application of the basic principles of thermodynamics to the hundreds of components in the system. The design engineers who made these calculations used data on the properties of steam developed by physical chemists who in turn used experimental measurements in concert with thermodynamic theory to develop the property data. Plants presently being studied could convert as much as 55 percent of the fuel energy to electric energy, if they indeed perform as predicted by thermodynamic analysis. Improvement in power plant efficiency is one of the main objectives of national energy conservation programs.

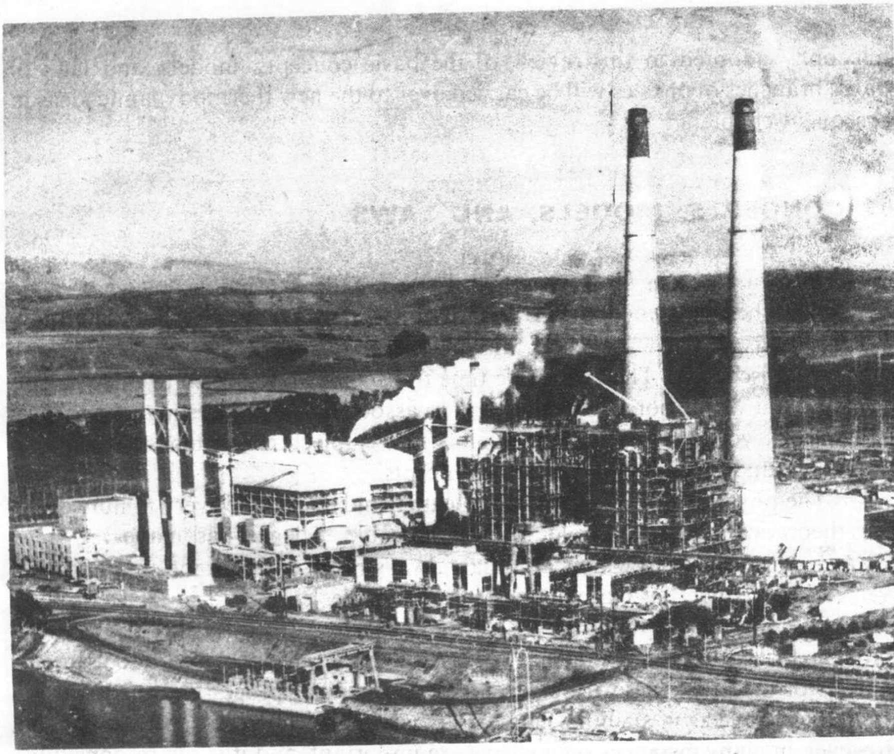

*Figure 1·1. The Moss Landing power station. (Courtesy of Pacific Gas and Electric Co.)*

With the advent of the energy crisis, thermodynamics has enjoyed renewed popularity in engineering schools. As oil prices rise, other energy forms become competitive, and a great deal of new and exciting engineering will have to be done to develop these new energy resources: solar, geothermal, wind, coal gasification, biomass energy plantations, and eventually fusion. In each case thermodynamics will play a crucial role in the engineering analysis. In addition, there is great need to develop ways to do things using less energy. An engineer with a solid background in thermodynamics and the ability to use it accurately in engineering analysis will be able to participate in these important technological developments.

An important attribute of a good engineer is the ability to work accurately in a careful and organized manner. We cannot emphasize enough the importance of a systematic methodology, without which easy problems become hard and much time can be wasted stewing over wrong answers or building devices that will not work. In parallel with the developments of thermodynamic theory, we shall present a methodology we have found to be quite effective in engineering analysis. 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 use of *models* which, although always representing some simplification 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.

## 1·3 CONCEPTS FROM MECHANICS

Let's review some basic ideas from mechanics, the science that describes the motion of objects. Practically all problems in thermodynamics can be handled with newtonian mechanics, i.e., without reference to relativistic effects: exceptions include analyses of the interior of stars and the flow of gases at speeds approaching that of light. The mechanics we shall use is entirely newtonian.

The ideas from mechanics we shall find most important are *force, mass, velocity, acceleration, work, torque, kinetic energy*, and *potential energy*. Some of these are concepts and some are definitions. Newton's laws of motion are also important, though some are really parts of other concepts and not laws at all. Mechanics is important because measurement of energy is ultimately tied to measurement of work, in both newtonian and relativistic thermodynamics. Work is in turn defined in terms of forces and motions. Force is a basic concept that must be very well understood by the student of thermodynamics. We expect that you are familiar with the concept; you should find the following presentation different and, hopefully, refreshing.

**Force.** Force is a concept, and so it defies definition. We can use words like "a push" or "a pull" to help explain what we mean, but these are not definitions of force. However, these words do suggest that a force has a point of application and a direction. And, since something has to do the pushing or pulling, a force must somehow be connected with the interaction between two things. Pushes and pulls tend to produce acceleration, bending, denting, or other behavioral changes in the object pushed or pulled, and so force is an essential idea in describing the reasons for these sorts of changes. These changes can be produced in a given system by interaction with an infinite variety of other systems. For example, people could push a car, a truck could push the car, or a strong wind could blow the car along a road. If the pushes of the people, truck, and wind were all identical, the car would experience the same motion, and blindfolded riders in the car could not tell why they were moving. In analyzing the car we would mentally replace whatever it was that was doing the pushing by a force (Fig. 1·2), and we could calculate the motion of the car in terms of the magnitude of the force without any reference to what was producing it. So, force is a convenient abstraction we use to represent mentally the pushing or pulling interaction between things.

When we use arrows passing through particular points to identify forces, we imply that forces are vectorlike quantities having magnitude, direction, and point of application. So, the mathematics of forces is that of vectors, if due regard

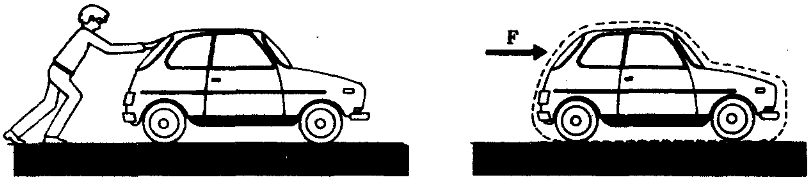


*Figure 1·2. Forces replace external pushes or pulls*

is given to the point of application. Thus the net effect of two forces acting on the same point is exactly as would be produced by the vector sum of the forces. This vector nature of force is a key part of the force concept.

Force cannot be made into a useful quantitative idea without the addition of two other conceptual aspects. The first is usually billed as *Newton's third law*: If one object exerts a force **F** on another, then the second object exerts an equal but opposite force on the first. This is really part of the force concept; without it forces cannot be measured, hence the law cannot be tested. The second additional part of the force concept is the notion that it takes a net unbalance of force to produce acceleration of the object on which the forces act; if the net forces are balanced (i.e., if the vector sum is zero), the object will not accelerate. This is called *Newton's first law*, but it is really part of the concept of force; it is impossible to establish a means for measuring forces without invoking the law, hence the law cannot be tested.

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

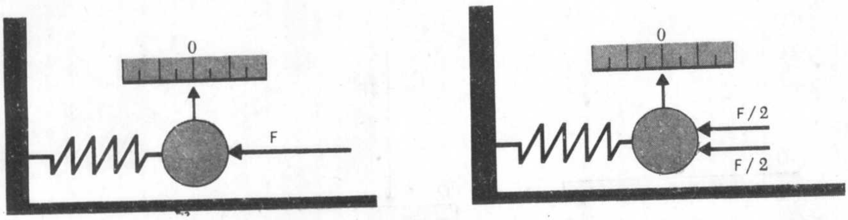


*Figure 1·3. A unique force scale can be established using symmetry and the concepts of force*

nature of any substance. It will be the same regardless of the material of which the springs are made.

**Torque.** Torque is another aspect of force that is important in engineering. Recall that the torque, or moment, of a force about a particular point is defined as the product of the force and the distance from the point to the force vector.

The *law of the lever* is a torque balance on a stationary object. It is not a law at all, but is instead something that one can prove using the ideas of force discussed above and one of the most basic ideas for scientific reasoning: *symmetry*. The thought processes involved are shown in Fig. 1·4. The symmetry of the coplanar force set of Fig. 1·4*a* requires that it be a *zero set*, meaning that the forces would produce neither translational nor rotational accelerations if they acted on the bar. Figure 1·4*b* also shows a zero set, and the sum of these two zero sets (Fig. 1·4*c*) forms a third *nonsymmetric zero set* which is equivalent to the force set in Fig. 1·4*d*. In Fig. 1·4*d* the ratio of the forces at *A* and *C* is the inverse of the ratio of their distance from point *O*. This argument can be continued, and one can construct an infinite number of zero sets with one force at *O*, another at *C*, and the third at some point *A* along the bar. In every case the ratio of the force at *A* to that at *C* is found to be exactly the inverse of the ratio of their distances from the potential pivot point *O*; hence, the law of the lever:

$$\frac{\mathsf{F}_A}{\mathsf{F}_C} = \frac{L_C}{L_A}$$

This may be recast as

$$\mathsf{F}_A L_A = \mathsf{F}_C L_C \tag{1·1a}$$

or

$$\mathsf{T}_A = \mathsf{T}_C \tag{1·1b}$$

Equation (1·1*b*) states that the torque of force $\mathsf{F}_A$, about the pivot point *O*, is exactly balanced by the torque of force $\mathsf{F}_B$.

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