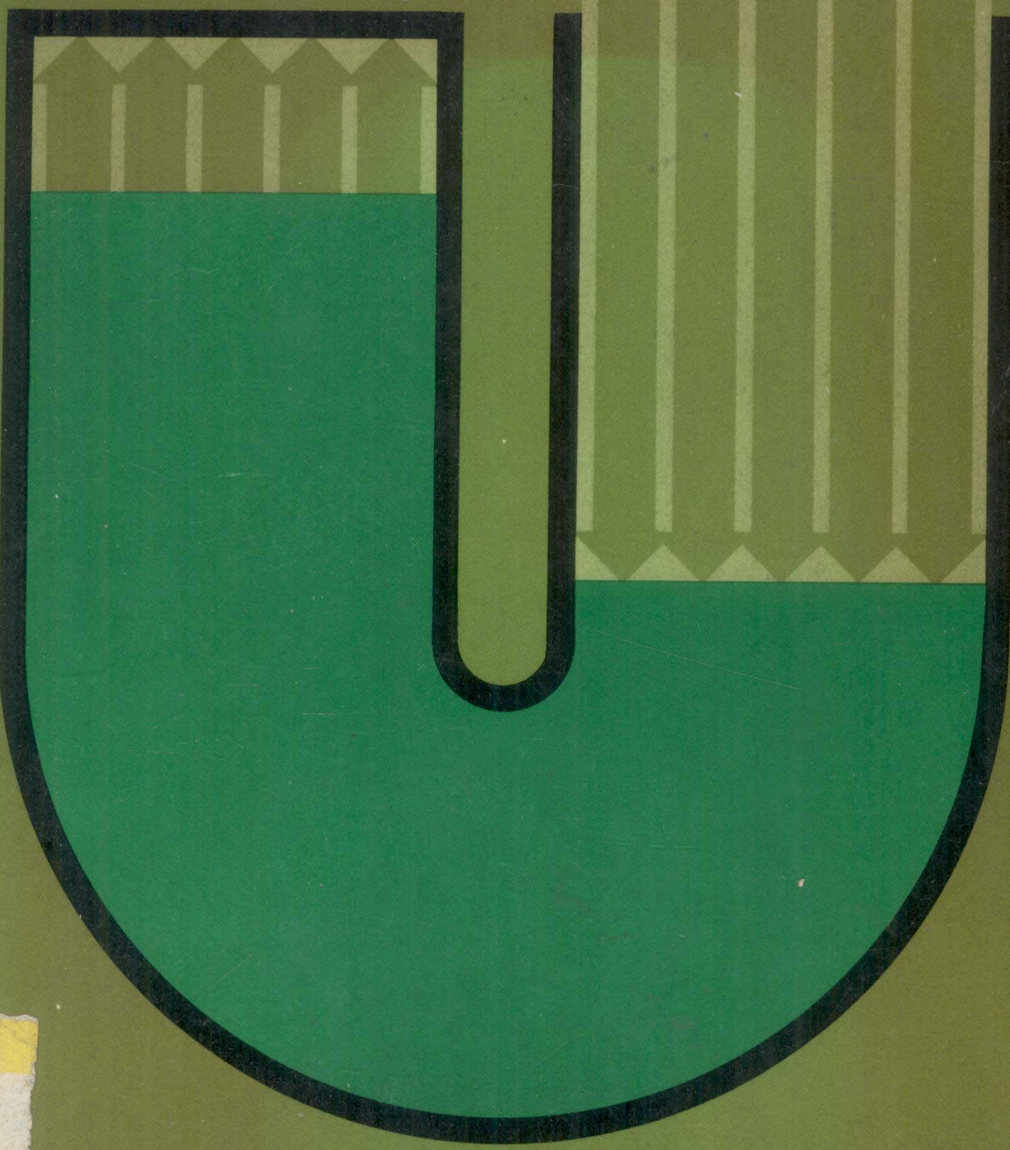
Thermofluid Mechanics

PEFLEY & MURRAY



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Thermofluid Mechanics

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INTERNATIONAL STUDENT EDITION

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Preface

Why thermofluid mechanics? Since 1951 the authors have had responsible charge of teaching thermodynamics and fluid mechanics at the University of Santa Clara. After several years of presenting separate first courses in these subjects, it became apparent that the students were encountering unnecessary confusion. This confusion arose from the fact that the intimate relationship between the two subjects was sensed by the students but was not clearly perceived. Conflicting notation, terminology, and dimensional systems further tended to obscure their view. Moreover, the fundamental principles employed seemed to shift with the course rather than with the type of problem to be solved. Most thermodynamics texts failed to exploit effectively Newton's laws of motion, and fluid-mechanics texts paid little heed to the concepts of state, property, and process or to the laws of thermodynamics. Proper sequencing of the two courses was also a perennial problem, for in each subject area concepts from the other discipline were presupposed.

Thermofluid Mechanics has evolved over a period of several years as an integrated treatment of thermodynamics and fluid mechanics for engineers. It clarifies the relationships between these subjects and delimits the fundamental differences. Intended for use in a two-semester junior-level course for students in all branches of engineering, the coverage is sufficiently broad to meet the needs of the student whose major does not require advanced study in any area of thermofluid mechanics, yet it is deep enough to serve as a foundation for the advanced studies of the aeronautical, chemical, civil, and mechanical engineer. The macroscopic viewpoint is employed throughout. Knowledge of calculus, including partial derivatives and some elementary concepts of ordinary differential equations, is assumed. Familiarity with vector algebra is also assumed, but a high degree of manipulative skill is not required.

The first twelve chapters are considered the basic core of the text. They can be supplemented by material from the remaining chapters, depending upon the wishes of the instructor and the purpose of the course.

In conclusion, the authors are deeply grateful to their students, fellow faculty members, and the administrative officers and staff at the University of Santa Clara. Without their full cooperation and encouragement, this text would not have been completed.

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Thermofluid Mechanics

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Chapter 1 introduction

In the most ancient and primitive societies of which we have record, man utilized fire. He may have used it only to warm himself or to provide protection against wild animals, but he did utilize it. He also developed tools to use in his work, but for countless generations he alone provided the energy required to operate them. It has been only within the last two hundred years that man has learned to use effectively the energy released by combustion to operate his tools and machines, and in almost every instance of this utilization the flow of some fluid is involved.

Canals and other water-distribution appurtenances uncovered by archaeologists indicate that in the prehistoric civilizations of Egypt, Mesopotamia, and India, man developed some ability to control the flow of water.[1]† By 1000 B.C. crude paddle wheels and windmills had appeared, but the availability of animal and slave labor held back the development of these devices until the Middle Ages. From then until the advent of the steam engine, wind and moving water were the only significant inanimate sources of energy which man utilized in performing his work.

Since ancient times, then, man has dealt with the basic ingredients of modern power-producing systems—thermal energy and moving fluids; only recently has he effectively coupled these to perform useful work. Technology developed as an art, as empirical "know-how." But as man acquired knowledge and understanding of mathematics and the laws of nature, his technology became less empirical and his progress more rapid.

Thermofluid mechanics encompasses two disciplines—thermodynamics and fluid mechanics. *Thermodynamics* is the body of scientific knowledge dealing with energy, particular emphasis being placed on heat-work transformations and changes of state. *Fluid mechanics* is the study of fluid motion.

In most thermodynamic systems that are of interest to the engineer, the working substance is a fluid—a fluid to which energy is added, within which it is transformed, and from which it is extracted. In fluid

† Superscript numbers correspond to numbered references at the end of the chapter.

mechanics the laws of thermodynamics are powerful tools for analysis, but they are not the only tools. Newton's laws of motion and the law of mass conservation† are equally important. Consequently, in the analysis of engineering thermodynamic systems it is frequently necessary to apply all these laws simultaneously. To learn to do this effectively, one should therefore study both subject areas simultaneously. The presentation of such a unified approach is the purpose of this text.

1-1 BASIC CONCEPTS AND DEFINITIONS

In any specialized subject area a technical vocabulary is essential. New meanings are given to familiar words, and new words are invented to identify special concepts associated with the subject. Some terminology can be defined precisely, but the meanings of words which represent fundamental concepts must be distilled from experience. Although the technical vocabulary of thermofluid mechanics is extensive, only a minimum, or working, vocabulary needs to be established before we discuss some of the fundamental concepts and principles of the subject.

Systems: *A system is a specified region under examination.* It may contain either a constant or a variable mass; its boundary may be fixed or deformable; it may be at rest or in motion with respect to a chosen coordinate system; *but that which is included within the region must be clearly specified.* The region outside the system's boundary is called the *surroundings.* A system diagram shows the system's boundary and all significant interactions between the system and the surroundings. If the only interactions of interest are forces, the system diagram reduces to the familiar "free-body diagram" of mechanics. Other interactions that are generally of interest are mass, energy, and momentum transfers.

There are two types of system: the *closed system*, across the boundary of which there is no mass transfer (Fig. 1-1*a* and *c*), and the *open system*, which does have mass transfer at its boundary (Fig. 1-1*b* and *d*). A particularly important subclassification is the *control volume*, which is an open system having a boundary that is fixed with respect to an inertial (nonaccelerating, nonrotating) coordinate system.

The fundamental laws of physical science were originally formulated for closed systems, but in the application of these laws to engineering problems, the control volume is generally the most convenient type to employ. In this book the fundamental laws are introduced and discussed in the closed-system context; subsequently, they are transposed to forms which are appropriate for control-volume analyses.

† Relativistic effects are negligible in the analyses of the systems with which we shall deal.

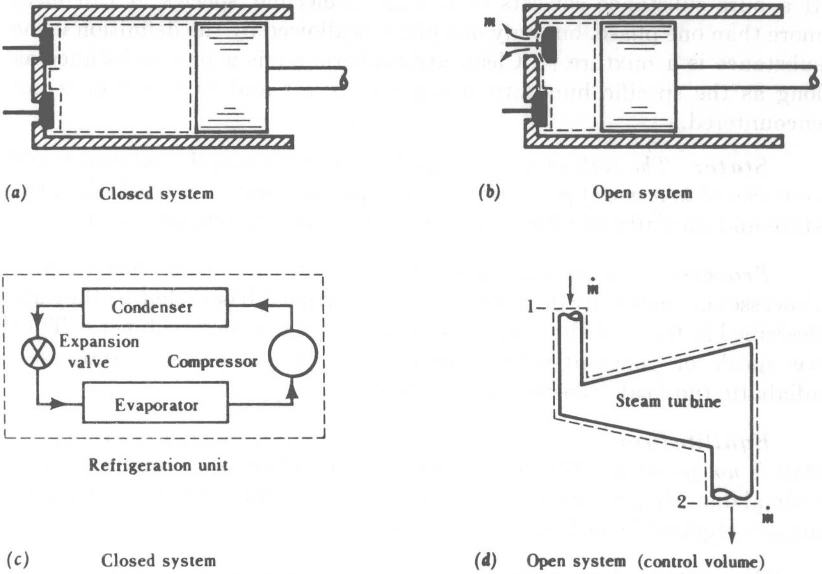

Fig. 1-1 System diagrams. Dashed lines indicate the system's boundaries. Except for mass transfer, interactions with the surroundings have not been shown.

Phase: *A phase is a portion of matter which, on a macroscopic† scale, is homogeneous in chemical composition and in physical structure.* It may exist in any number of unconnected pieces within a system. As an example, consider a saturated solution of table salt (NaCl) and water (H_2O) which is prepared with an excess of salt to ensure saturation. The system contains two phases, solid NaCl and the aqueous solution. The grains of salt exist as unconnected pieces; nevertheless, they constitute a single phase, for they all have the same chemical composition and physical structure. The solution contains several chemical species, but its composition is homogeneous on a macroscopic scale; it is therefore a single phase. A mixture of oil and water, on the other hand, contains two phases, for its composition is not homogeneous on a macroscopic scale. A substance consisting of a single molecular species may exist in more than one phase by virtue of a nonhomogeneous physical structure, for example, ice and liquid water.

Pure substance: *A pure substance is a substance which on a macroscopic scale is both invariable and homogeneous in chemical composition.*

† The word *macroscopic* is used in this book to mean a size which is at least an order of magnitude greater than molecular size; *microscopic* is used to imply molecular size or smaller.

If a pure substance consists of a single molecular species, it can have more than one phase, but only one phase is allowed by the definition if the substance is a mixture.† Clean atmospheric air is a pure substance as long as the specific humidity remains constant and liquefaction is not encountered.

State: *The state of a substance is the condition of the substance, and is described in terms of properties.* The state of a system is fixed when the state and quantity of all matter constituting the system are fixed.

Process: *A process is that which occurs whenever matter changes state.* Processes are generally described on an operational basis; that is, they are described in terms of the restraints to which the process is subject. Thus we speak of constant-volume processes, constant-pressure processes, adiabatic (no heat transfer) processes, etc.

Equilibrium: *A system is in equilibrium if a spontaneous change of state is not possible.* When a system is in equilibrium, at least an infinitesimal disturbance, or change in the conditions imposed by the surroundings, is required in order to change the state.

Property: *A property is any characteristic which has a value that is uniquely determined by the state.* The value depends only on the state, and not on the process by which the state was achieved.

1-2 DISCUSSION OF STATE AND PROPERTY

The words *state* and *property* represent fundamental concepts. A critical examination of their "definitions" reveals that neither term is actually defined, for the definitions are interdependent. Nevertheless, we are able to sense something of their meaning.

This rather indefinite situation, which is characteristic of fundamental concepts, can be made more definite if we define as *primary* properties[2] those perceptible characteristics for which there are well-established procedures of measurement. Examples are mass, volume, pressure, temperature, and elevation. When values are prescribed for a number of primary properties of a specified system, the values of some additional primary properties become fixed; i.e., arbitrary values can no longer be assigned to them. By this occurrence, an aspect of state is established. As values are prescribed for additional sets of primary properties, additional aspects of state are fixed.

Many useful functions which are not perceptible characteristics of a system acquire unique values when one or more aspects of state are fixed. These functions we call *deduced properties.*[3] Examples are the specific

† An azeotropic mixture under constant pressure is an exception; its composition remains constant during a phase change.

heats, kinetic energy, and the product of pressure and volume. All properties are classified as either primary or deduced, but once deduced properties have been recognized, there is no need to maintain the classifications. Deduced properties, as well as primary properties, can be prescribed in fixing aspects of state.

The important distinction to be made is between dependent and independent properties. The properties chosen to fix an aspect of state must be *independent* properties; i.e., it must be possible to prescribe an arbitrary value for each. Once a set of independent properties has been selected, all other properties associated with the aspect of state become *dependent.*

It is seldom, if ever, that all aspects of state need to be established. When it is clear from the specification of the system and its processes that none of the properties associated with a particular aspect of state are significant, there is no need to fix that aspect. For example, if a system is specified as the air within a horizontal cylinder and the air is to be compressed, the elevation and potential energy of the system are not involved, and the aspect of state with which they are associated does not have to be fixed. On the other hand, if the cylinder were vertical and the piston were included in the specified system, potential energy might be significant, and its corresponding aspect of state would have to be fixed by specifying the weight and elevation of the piston.

In order to refer conveniently to the aspects of state with which we are frequently concerned, the following terminology is used. All significant aspects of state which can be fixed without regard for the size or extent of the system are included in the term *intensive state.* Pressure, temperature, and velocity are examples of intensive properties. *Extensive state* includes intensive state, but in addition, it implies concern with the extent or size of the system. Mass, volume, momentum, total energy, etc., are extensive properties. *Internal state* includes all significant aspects of state which can be fixed without specifying a spatial coordinate reference system. Aspects of *external state* require such a reference system. Pressure and temperature are internal properties, whereas velocity and elevation are external properties.

Combinations of the above terminology can be used. Intensive internal state would imply that even though extensive and external properties are significant in the total problem, they are not of concern in the immediate context. Similar meanings would be associated with other combinations. When *all significant* aspects of state are to be included, we shall simply refer to *the state.*

1-3 DIMENSIONS AND UNITS

The dimensions of an entity are those characteristics of the entity to which units of measure can be assigned. The familiar concept of dimensions associated with the linear characteristics of an object is extended to include other variables. The area of a geometric figure, the velocity of a moving object, the thrust of a rocket—these too are dimensions. Through definitions and physical laws any dimension can be expressed in terms of a chosen set of primary dimensions. An algebraic expression for any area can be formulated in such a way that each term of the expression contains the product of two lengths; the dimension of area is thus equivalent to the dimension of length squared. The definition of velocity establishes the quotient of length and time as the dimension of velocity. Similarly, the dimension of acceleration is the quotient of length and the square of time.

The number and choice of primary dimensions are somewhat arbitrary. *Force, mass, length, time,* and *temperature* are chosen as primary dimensions throughout this book. Charge would be included if electrical phenomena were to be considered. As we shall see, the choice of primary dimensions influences the form of equations expressing physical relationships.

For each primary dimension an arbitrary unit of measure is chosen. In English-speaking countries, engineers generally select the following units for the dimensional system under consideration.

Dimension	Dimensional symbol	Unit	Unit symbol
FORCE	F	pound force	lbf
MASS	M	pound mass	lbm
LENGTH	L	foot	ft
TIME	T	second	sec
TEMPERATURE	θ	degree Fahrenheit	°F

Through dimensional relationships consistent units for all other dimensions are derived from the chosen units. To illustrate, consider mass flow rate per unit area. Its dimension is M/TL^2, and the consistent unit in our chosen set is the lbm/sec-ft^2.

It is often desirable to change from one set of consistent units to another. To do this, we employ unit equivalents: ratios in which the numerator and denominator each express the same magnitude of a dimension, but in different units.

$$\frac{12 \text{ in.}}{1 \text{ ft}} = 1 \qquad \frac{3600 \text{ sec}}{1 \text{ hr}} = 1$$

To express 1 lbm/sec-ft^2 in terms of lbm/hr-in.^{2} we multiply by unit equivalents so that the unwanted units cancel.

$$1 \text{ lbm/sec-ft}^2 \left(\frac{3600 \text{ sec}}{1 \text{ hr}}\right)\left(\frac{1 \text{ ft}^2}{144 \text{ in.}^2}\right) = 25 \text{ lbm/hr-in.}^2$$

Units that do not belong to any consistent set can be handled in the same way. To express 110 hp in the consistent unit of our chosen set, we use the equivalent, 1 hp = 550 ft-lbf/sec.

$$110 \text{ hp} \left(\frac{550 \text{ ft-lbf}}{1 \text{ hp-sec}}\right) = 6.05 \times 10^4 \text{ ft-lbf/sec}$$

The differences in the dimensional systems that are commonly used arise from the various possibilities in handling the dimensions of force and mass, and the constant of proportionality in Newton's second law of motion. With the constant of proportionality denoted by $1/g_c$, Newton's law is written

$$F = \frac{1}{g_c} ma$$

When force, mass, length, and time are all chosen as primary dimensions (the *FMLT* system), the *dimension* of g_c is uniquely determined.

$$[g_c] = \left[\frac{ML}{FT^2}\right]^\dagger$$

The numerical *value* of g_c depends on the choice of units. For our chosen set, g_c is approximately equal to 32.2 lbm-ft/lbf-sec². This follows immediately from the definition of a pound force as the force required to give a pound mass an acceleration equal to the standard acceleration of gravity.

In other dimensional systems either force or mass is omitted from the set of primary dimensions, and unity is *chosen* as the value of g_c. Newton's second law is then written $F = ma$.

In the *MLT* system, force is not a primary dimension; its dimension is derived: $[F] = [ML/T^2]$. With the kilogram, meter, and second selected as primary units, the consistent unit of force is the kg-m/sec², which is called a *newton*.

In the *FLT* system the dimension of mass is derived: $[M] = [FT^2/L]$. With the pound force, foot, and second chosen as primary units, the consistent unit of mass is the lbf-sec²/ft, which is called a *slug*.

An examination of the definitions of the slug and the pound force reveals that a slug is approximately 32.2 times larger than a pound mass.

† Brackets used in this context symbolize "the dimension of."

If the slug is chosen as a primary unit in the *FMLT* system,

$$g_c = 32.2 \text{ lbm-ft/lbf-sec}^2 \left(\frac{1 \text{ slug}}{32.2 \text{ lbm}}\right) = 1 \text{ slug-ft/lbf-sec}^2$$

Note that g_c is not equal to unity, even though its numerical value is 1. It is not dimensionless, even though the slug is generally associated with a dimensional system in which g_c is dimensionless. The definition of the slug has been changed. Here it is defined as a prescribed multiple of the pound mass:

$$1 \text{ slug} = 32.2 \text{ lbm (approximately)}$$

Its two definitions are physically consistent, but each definition is dimensionally consistent only in its own system.

There is no need to have all the systems of dimensions and units that are in use today, but we have them, nevertheless. Each specialized branch of engineering practice finds certain advantages in the system which it uses, and no concerted effort has been made to adopt a single system. Consequently, the engineer must learn to work with all the common systems, and he must be able to change from one to another with facility.

The *FLT* system of dimensions is used in engineering mechanics; the *FMLT* system is used in engineering thermodynamics. Since this text encompasses both subjects, a choice has to be made between the two systems. The choice of the *FMLT* system is based primarily on two considerations: (1) The need to use tables of thermodynamic properties makes it desirable to use the same system of dimensions and units as is used in the tables. (2) In the *FMLT* system of dimensions, g_c appears explicitly in all the equations which are in any way associated with Newton's second law of motion. To change from the *FMLT* system to the *FLT* system, one simply sets g_c equal to unity wherever it appears. To make a change in the other direction, g_c must be introduced into the equations; where to place it is not always apparent.

1-4 PROBLEM SOLUTION

Even though engineering problems differ greatly in nature, certain principles of solution are applicable to all of them.

1. *Recognition of the problem.* Before a problem can be solved its existence must be recognized. A textbook problem is recognized simply by a careful reading of the problem statement, but in actual practice there must be an awareness of the undesirable and the imagination to visualize improvement.

2. *Definition of the problem.* Once a problem has been recognized, it