ENGINEERING THERMODYNAMICS

WORK AND HEAT TRANSFER

By

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PREFACE

This book is intended for engineering students and covers the fundamentals of applied thermodynamics courses up to Honours Degree standard. The following presentation has been adopted.

An exposition of the principles of thermodynamics is given in Part I without reference to the behaviour of any particular substance. Part II opens with a discussion of the properties of fluids, and the principles of Part I are then applied to closed and open systems assuming that the properties are best related (a) in tables and (b) by simple equations. This is followed by an analysis of power and refrigeration cycles. Part II ends with a study of gas and vapour mixtures and combustion processes.

Parts I and II are chiefly concerned with relations between fluid properties and the quantities of work and heat which accompany changes of state. The way in which the work and heat transfers are effected in practice are described in Parts III and IV respectively. Part III is divided broadly into work transfers associated with (a) positive-displacement machines and (b) nonpositive-displacement machines. For the latter, a more detailed analysis of flow processes is required than is given in Parts I and II, and therefore a chapter on one-dimensional flow is included. This chapter is designed as a bridge between the sciences of thermodynamics and fluid dynamics and, to avoid obscuring the fundamental links, concepts such as total temperature and Mach number have not been used. The usual classification of modes of heat transfer is adopted in Part IV, with the emphasis placed on methods of approach rather than on the presentation of established empirical data.

We do not suggest that our order of presentation is suitable as a direct introduction to the subject, and the book is not designed as a substitute for a course of lectures. Most students are best introduced to a subject by a careful juxtaposition of principle and application, and the book leaves it open to the lecturer to choose any preferred order of presentation. But, although a mixture of principle and application is necessary in a lecture course, it can leave the student with serious misconceptions, and it by no means follows that he will gain a sufficient grasp of the principles to be able to tackle unfamiliar problems. Our object has been to produce a book which will enable the student to distinguish principle from application: a reading of the first six chapters, as revision late in his first year, should enable him to make this distinction. It should also help him to appreciate the elegance and power, as well as the limitations, of the science he is using.

Our second concern has been to provide a book of reference to which the student can turn for the elucidation of difficult points. A rigorous approach cannot often be used in a lecture course, partly for lack of time and partly because it would be inappropriate when introducing the student to a new idea. In this book, however, a rigorous proof or explanation is given wherever practicable for the benefit of the better student who is not satisfied with simplifications.

A few words are necessary about two of the appendixes. Many of the problems provided in Appendix B are intended to amplify points only touched on in the text. To this extent they should be regarded as an integral part of the book. The answers to the problems, and to the worked examples in the text, have been obtained using the abridged tables of properties arranged by us and published separately—*Properties of Fluids and Other Data* (Basil Blackwell, 1957). Most of the references, given in Appendix C, are to be regarded as suggestions for further reading and also as acknowledgement of sources. A few classical papers of academic interest are also included.

Finally we wish to acknowledge our particular indebtedness to two books which we have found a source of inspiration: J. H. Keenan's *Thermodynamics* (Wiley, 1941), and E. R. G. Eckert's *Introduction to the Transfer of Heat and Mass* (McGraw-Hill, 1950). We also wish to thank our colleagues at Bristol—Dr. B. Crossland, Mr. T. V. Lawson, and Dr. P. Woodward—for their useful suggestions after reading parts of the manuscript. Mr. C. J. Spittal, of the University Library, has been most helpful in obtaining papers and checking the references.

G. F. C. R.

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PART I

PRINCIPLES OF THERMODYNAMICS

INTRODUCTION

Thermodynamics is the science dealing with the relations between the properties of a substance and the quantities 'work' and 'heat' which cause a change of state. Before a satisfactory analysis of such changes can be made, it is necessary to introduce some carefully defined concepts.

The idea of a *system* plays an important part in thermodynamics; it may be defined as a region in space containing a quantity of matter whose behaviour is being investigated. This quantity of matter is separated from its surroundings by a *boundary*, which may be a physical boundary, such as the walls of a vessel, or some imaginary surface enveloping the region. Before any thermodynamic analysis is attempted it is essential to define the boundary of the system, because it is across the boundary that work and heat are said to be transferred. The term *surroundings* is restricted to those portions of matter external to the system which are affected by changes occurring within the system. When the same matter remains within the region throughout the process under investigation it is called a *closed system*, and only work and heat cross the boundary. An *open system*, on the other hand, is a region in space defined by a boundary across which matter may flow in addition to work and heat.

Part I is primarily concerned with the behaviour of a particular form of matter—a fluid. The fluid may be a gas (e.g. air), a vapour (e.g. steam), a liquid, or a mixture of these substances provided they do not react chemically with one another. Closed and open systems containing such fluids are the main concern of engineering thermodynamics. Chemical and physical thermodynamics deal with a wider variety of systems and phenomena, e.g. solids, surface films, electric cells, mixtures undergoing chemical reactions, thermoelectric effects, and magnetic substances [see Refs. (5) and (8)]. These are not the concern of this book, although some consideration is given in Part II to the chemical reactions involved in the combustion of fuel.

Here, therefore, a system may be defined less generally as a region in space containing a quantity of fluid. If the fluid is flowing into, out of, or through the region, it is an open system. Some examples are (1) a gas expanding from a container through a nozzle, (2) steam flowing through a turbine, and (3) water entering a boiler and leaving as steam. Examples of a closed system are (1) a mixture of water and steam in a closed vessel, and (2) a gas expanding in a cylinder by displacing a piston. From the last example it will be seen that the boundary separating a closed system from its surroundings need not be fixed; it may expand or contract to accommodate any change of volume undergone by the fixed quantity of fluid. The processes undergone by the fluid in a closed system are described as *non-flow processes*, whereas those undergone by the fluid in an open system are referred to as *flow processes*.

Since chemical, surface tension, electrical and magnetic effects are absent, any closed system considered here can only change its condition or 'state' for one or both of the following reasons: (1) there will be a change of state if a part of the boundary is displaced by a force so that some mechanical work is done, e.g. when a force is applied to a piston to compress a gas; (2) there will be a change of state if the system is brought into contact with a portion of the surroundings which is at a different temperature, i.e. if heat is allowed to flow across the boundary. Thus the engineer is concerned to know the way in which the state of a system changes when work and heat cross the boundary.

The *state*† of a system at any given instant is determined by the values of its *properties* at that instant. The sort of characteristic which can be used to describe the condition of any object under investigation must always be found by experience, and will depend upon the nature of the investigation. From the standpoint of thermodynamics, many observable characteristics will be irrelevant, e.g. shape and colour are irrelevant characteristics of the systems considered in this book. On the other hand, shape would be an important characteristic of any thermodynamic system involving surface tension effects. Those characteristics of a system which can be used to describe its condition or state, and which are relevant to the investigation, are termed the properties of the system. These properties are not all independent of one another, e.g. for a perfect gas it is known that the temperature must have a definite value if the pressure and volume are fixed, in accordance with the well-known equation of state $pv = RT$. Classical thermodynamics has been built up from a study of closed systems, and it has been found by experiment‡ that *only two properties are necessary and sufficient to determine the state of a closed system containing a simple fluid*. This state may be termed the *thermodynamic state* of the fluid, and the properties of the fluid from which these two may be chosen are called the *thermodynamic properties*. When the thermodynamic state has been determined by a knowledge of two thermodynamic properties, any third thermodynamic property can be found from a relation expressing it as a function of the two known properties. It will be assumed in Part I that these relations have been determined by experiment for all the fluids likely to be used in engineering systems; the equation of state of a perfect gas is merely one such relation.

The study of open systems is complicated by the fact that the fluid is

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† The term 'state' is sometimes used in textbooks on heat to refer to the solid liquid or vapour form of a substance, but these forms are referred to as 'phases' in thermodynamics.

‡ Advanced students will find an interesting logical analysis of this procedure in Ref. (2), Chapter 1.

in motion. If attention is concentrated on a portion of the fluid entering the system, it will be realised that it possesses a relevant *mechanical state* in addition to a thermodynamic state. The *mechanical properties* necessary to determine its mechanical state are (1) velocity relative to the fixed boundary of the system and (2) position in the gravitational field, i.e. height above some datum level. Both these characteristics may change during the passage of the fluid through the system, and they may affect events which occur within the system and the work and heat which cross the boundary; they cannot therefore be omitted from an analysis of open systems. The two mechanical properties are independent of one another and, moreover, are independent of the thermodynamic properties. For example, the fact that a perfect gas is flowing through a pipe with a certain velocity in no way changes the fact that at any point the pressure, volume and temperature of an element of the gas are related by $pv = RT$. All the relations between the thermodynamic properties which will be developed in the following pages are similarly independent of whether the fluid is in motion or changing its position in the gravitational field. Thus the mechanical state is something which can be superimposed upon the thermodynamic state without disturbing the relations between the thermodynamic properties. It will appear later that this makes it possible for the body of knowledge built up from a study of closed systems to be applied to the analysis of open systems.

We are now in a position to summarise the contents of Part I, which present the fundamentals *without reference to any particular fluid.* Firstly, we note that experiment has shown that the state of a closed system is determined when two thermodynamic properties are known, and that all the other thermodynamic properties are then determined. We shall assume that sufficient experimental information is available to enable any third thermodynamic property to be found if two are known. Secondly, the state of a system changes when work or heat cross the boundary. Thermodynamics provides a means of relating the quantities of heat and work with the change of state, i.e. with the variation of the properties of the fluid. The structure of thermodynamics rests upon two important principles called the First and Second Laws of Thermodynamics. These cannot be proved and are treated as axioms; their validity rests upon the fact that neither they, nor any deductions made from them, have ever been disproved by experience.

The First Law is initially stated with reference to closed systems, and it is applied to various processes which such systems may undergo. It is then applied to open systems. The First Law is an expression of the principle of the conservation of energy. With the aid of this law it is possible to calculate the quantities of heat and work which cross the boundary of a system when given changes in properties occur, e.g. the work done by steam expanding through a given range of pressure in a turbine, the work required to produce a given pressure rise in an air compressor, or the heat required to generate steam at a given pressure in a boiler.

A second class of problems is concerned with how much of the heat, normally supplied by burning fuel, can be converted into work by a heat engine. Or, again, how much work is required to extract a given amount of heat from a body in a refrigerator. These are problems concerning the efficiency of power plant, and they can be solved with the aid of the Second Law of Thermodynamics. The Second Law is an expression of the fact that it is impossible to convert all the heat supplied to an engine into work; some heat must always be rejected, representing a waste of energy. As with the First Law, the Second is enunciated with reference to closed systems, and then its consequences for open systems are deduced.

In the final chapter, *which may be omitted on a first reading*, some important general relations between the thermodynamic properties are deduced from the First and Second Laws.

CHAPTER 1

FUNDAMENTAL CONCEPTS

Before the basic structure of thermodynamics can be outlined, it is necessary to define some of the concepts more thoroughly than has been attempted in the Introduction, paying particular attention to temperature, work and heat. Accordingly, this chapter is devoted to a discussion of such fundamental concepts.

1.1. Thermodynamic Properties

The idea of a system has been presented in the Introduction. A closed system is fully defined when the following details are known:

(a) the fluid, e.g. whether air, hydrogen, water, etc.,
(b) the boundary between the fluid under consideration and its surroundings,
(c) the mass of fluid within the boundary.

The state of the system has yet to be determined; for this a knowledge of its properties is required.

To define the state of a closed system, only the thermodynamic properties of the fluid are relevant. Any such property must be some characteristic that can be measured, and it must have a unique numerical value when the fluid is in any particular state. Pressure, volume and temperature are obvious examples. The value of a property must be independent of the process through which the fluid has passed in reaching that state. It follows that a change in the value of a property depends only on the initial and final states of the system, and is independent of the process undergone by the system during the change of state.

Using pressure as an example, a gas at state 1 may have a pressure of 50 lb/in², and after a compression process to state 2 a pressure of 80 lb/in². The change in pressure is an increase of 30 lb/in² however the compression is carried out. If $\mathrm{d}P$ is any infinitesimal change in a property during a process, the total change between states 1 and 2 can be written as

$$\int_1^2 \mathrm{d}P = P_2 - P_1.$$

Mathematically speaking, $\mathrm{d}P$ is an *exact differential*.†

Consider the following mechanical analogy. A cyclist travels from point 1, z_1 ft above sea level, to point 2 on a hill z_2 ft above sea level.

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† The concept of an exact differential is defined in Chapter 7.

Treating the cyclist as the system, his height above sea level can be regarded as a property of the system because the change in height $(z_2 - z_1)$ is independent of the path, i.e. the process, by which the cyclist travels from 1 to 2. The work done by the cyclist, however, is not independent of the process; it clearly depends upon whether he has chosen a short or long route between 1 and 2 and whether he has a following or head wind. Consequently the work done, although a measurable quantity, is not a property. If, during any infinitesimal part of a process, a measurable quantity which depends upon the process is denoted by $\mathrm{d}X$, $\mathrm{d}X$ is not an exact differential and

$$\int_1^2 \mathrm{d}X \neq X_2 - X_1.$$

When the quantity is not a property, the integration between state 1 and state 2 must be written as

$$\int_1^2 \mathrm{d}X = X_{12} \text{ (or simply as } X\text{).}$$

Further discussion of quantities which are not properties will be deferred to section 1.3, which deals with the concepts of work and heat.

We have already noted the experimental fact that when the values of two properties are known, the state of a closed system is completely determined. An important assumption is implicit in this statement, i.e. that the system is in *thermodynamic equilibrium*. A system is said to be in thermodynamic equilibrium if no further changes occur within it when it is isolated from the surroundings in such a way that no heat and work can cross the boundary. The properties, such as pressure and temperature, must be uniform throughout the system when it is in equilibrium. If the pressure is not uniform, due to turbulence for example, spontaneous internal changes occur in the isolated system until the turbulence has died down and the pressure has become uniform. Similarly, if there are temperature gradients in the isolated system, a spontaneous redistribution of temperature occurs until all parts of the system are at the same temperature. Only under conditions of equilibrium can single values of pressure and temperature be ascribed to the system, and thus be used to determine its state. It will always be assumed in this book that the system is in equilibrium at the beginning and end of any process, and therefore the end states are determined when the values of two properties are fixed.

It follows that the initial and final states of any closed system can be located as points on a diagram using two properties as coordinates. If the system is imagined to pass through a continuous series of equilibrium states during the process, the intermediate states could also be located on the diagram, and a line representing the *path* of the process could be drawn through all the points. Such a process is called a *reversible process*; it will be found to be an ideal process analogous to the frictionless process so often referred to in mechanics. In all real processes, however, the system is not in equilibrium in any of the intermediate states. These states cannot be located on the coordinate diagram because the properties do not have single unique values throughout the system. Such processes are called *irreversible processes*. They are best represented on a diagram by a dotted line joining the initial and final state points, to indicate that the intermediate points are indeterminate. The full significance of the ideas of reversibility and irreversibility will appear later.

Pressure, specific volume and temperature are three properties observable by the senses. Pressure p is defined as the force exerted by the fluid on unit area of the boundary, and the units† employed are normally lb/in². The specific volume v is the volume of unit mass of fluid, usually quoted in ft³/lb. It is the reciprocal of the density, defined as mass per unit volume, but it is conventional to use specific volume rather than density as one of the properties in thermodynamics. Temperature is a property deserving special attention and it will be introduced in section 1.2. Three more thermodynamic properties—internal energy, enthalpy and entropy—will emerge as consequences of the First and Second Laws of Thermodynamics. Although they are not directly observable by the senses they are essential to the structure of thermodynamics.

From these six properties, two may be selected to determine the state of a closed system in thermodynamic equilibrium, and the values of the remaining four are then fixed. Care must be taken to see that the two chosen properties are independent of one another, i.e. it must be possible to vary one of these properties without changing the other. Obviously density and specific volume are not independent properties because one is simply the reciprocal of the other; this fact is recognised in that density is not included in the six properties to which reference was made. But, less obviously, pressure and temperature are not always independent properties: when a liquid is in contact with its vapour in a closed vessel it is found that the temperature at which the liquid and vapour are in equilibrium is always associated with a particular pressure and one cannot be changed without the other. Pressure and temperature cannot be used to determine the state of such systems, although other pairs, such as pressure and specific volume, may be so used.

As stated in the Introduction, it will be assumed throughout Part I that if any two independent properties are known, the others can be found from experimental data relating to the particular fluid under consideration. If, for example, p and v are known, any third property x must be a function of these two, i.e. $x = \phi(p, v)$. For some fluids the functions are simple, and algebraic equations are used to relate the properties; for others the function is complicated and the experimental data are most conveniently presented in tabular form. Fig. 1.1 shows such

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† A full discussion of dimensions and units is given in Appendix A.

a table, the dots denoting values of temperature corresponding to the various combinations of p and v. Similar tables can be prepared with internal energy, enthalpy or entropy as the third property. It is assumed in Part I that either a set of equations or a set of tables is available for each fluid likely to be encountered in engineering systems.

	v_a	v_b	— — — — — — —	v_y	v_z
p_a	•	•		•	•
p_b	•	•		•	•
¦			Values of temperature (or internal energy or enthalpy or entropy)		
p_y	•	•		•	•
p_z	•	•		•	•

Fig. 1.1 Table of Properties

1.2 Temperature

Two systems are said to have *equal temperatures* if there is no change in any of their observable characteristics when they are brought into contact with one another. Consider a system A consisting of a gas enclosed in a vessel of fixed volume fitted with a pressure gauge. If there is no change of pressure when this system is brought into contact with a second system B, say a block of metal, then the two systems are said to have the same temperature. Experiment shows that if the system A is brought into contact with a third, C, again with no change of pressure, then B and C when brought into contact will also show no change in their characteristics. That is, if two bodies are each equal in temperature to a third body they are equal in temperature to each other. This principle of *thermal equilibrium* is sometimes called the 'zeroth law of thermodynamics'; the possibility of devising a means of measuring temperature rests upon this principle.

The temperatures of any group of systems may be compared by bringing a particular system, known as a thermometer, into contact with each in turn. System A performs this function in the foregoing example. Such a system must possess an easily observable characteristic termed a thermometric property, e.g. the pressure of a gas in a closed vessel, the length of a column of mercury in a capillary tube, or the resistance of a platinum wire. A scale of temperature could be defined by assigning numbers to divisions