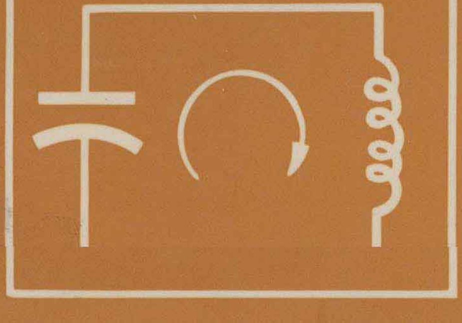
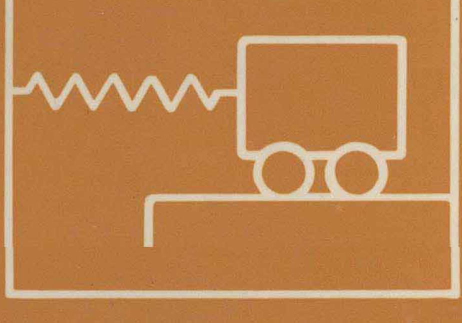
ENGINEERING TECHNOLOGY/3

ELEMENTS OF THERMAL TECHNOLOGY

JOHN H. SEELY





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MARCEL DEKKER, INC. New York and Basel

Library of Congress Cataloging in Publication Data

Seely, John H.
Elements of thermal technology.

Includes index.
1. Thermodynamics. 2. Heat -- Transmission.
I. Title.
TJ265.S457 621.402'1 81-1577
ISBN 0-8247-1174-2 AACR2

MARCEL DEKKER, INC.
270 Madison Avenue, New York, New York 10016

Current printing (last digit):
10 9 8 7 6 5 4 3 2 1

PRINTED IN THE UNITED STATES OF AMERICA

ELEMENTS OF THERMAL TECHNOLOGY

ENGINEERING TECHNOLOGY

A Series of Textbooks

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Wichita, Kansas

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PREFACE

All types of engineering systems--mechanical, electrical, thermal, chemical, and fluid--are affected by the manner in which heat is transferred. For example, temperature levels inside electrical components determine the efficiency and effectiveness of circuits made from the components. Many fluid properties such as viscosity, density, and surface tension are highly thermophysical in nature. Strength considerations, friction forces, and clearances between parts are functions of temperature in mechanical systems, while the manner and rate of reaction between the elements of chemical systems also depend on temperature.

The purpose of this book is to outline the elements required by a technologist to analyze or synthesize engineering systems from the viewpoint of thermal technology. Material in this book covers the thermal equilibrium conditions normally treated in classical thermodynamics, and nonequilibrium conditions that constitute the subject of heat transfer. Other sections are devoted to discussions of thermophysical properties, that is, the properties of a system that depend upon temperature.

Although some knowledge of calculus is required to understand the equations used in thermal technology, an effort has been made to minimize the level of mathematics used in presenting the subject matter. Most students who have completed at least one full year of college mathematics should have no difficulty in following the text. Extensive use is made of techniques and empirical equations based on curves, charts, and diagrams.

SI units are used throughout this book. Since many of the references that the technologist will have to use will not be in SI units, appropriate conversion methods are presented where necessary.

The text has been written expressly for students in four-year engineering technology programs. However, it is applicable to the needs of many junior college students and will serve as convenient review material for practicing engineers and engineering technologists.

I am greatly indebted to my wife, Marcella, for excellent typing and proofreading, but most of all for her constant encouragement.

John H. Seely

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THERMODYNAMIC DEFINITIONS AND CONCEPTS

1.1 INTRODUCTION

Engineering thermodynamics is the study of energy transfer between systems and the effects of temperature level on the transfer process. Although the subject can be developed from purely macroscopic postulates, knowledge of microscopic concepts helps to develop an understanding of the nature of the matter which is responsible for the macroscopic properties of a substance.

The microscopic approach assumes that matter is particulate and is made up of electrons, protons, neutrons, etc. Each of the particles can be assumed to have a characteristic mass, energy, momentum, and electric charge. The macroscopic approach assumes that matter is continuous and distributed throughout space. A continuum has the same kinds of characteristics as particles, but additional characteristics such as pressure, temperature, mass flow rate, and electric current can also be considered.

1.2 THERMAL EQUILIBRIUM

From the continuum viewpoint, properties such as temperature and pressure are considered to be constant throughout a volume that consists of many different particles; such a consideration implies that the entire system is in equilibrium.

Equilibrium can generally be defined as a condition in which all tendencies for change are equally and oppositely balanced by other tendencies for change. Engineering applications, however, require a more precise definition. An engineering system is said to be in *thermodynamic equilibrium* if it is in mechanical, thermal, electrical, and chemical equilibrium

1. Mechanical equilibrium connotes the absence of any pressure gradients within a system.
2. Thermal equilibrium connotes the absence of any temperature gradients within a system.
3. Electrical equilibrium connotes the absence of any voltage gradients within a system.
4. Chemical equilibrium connotes the absence of any tendency for chemical combination within a system.

The concept of equilibrium presents something of a dilemma. Macroscopic properties, for example, describe the condition of a system when the system is in equilibrium. How, then, can we apply these properties to a system undergoing an energy transfer process, which by definition is a nonequilibrium condition? The problem is resolved by means of an idealization called a *quasistatic* or *quasi-equilibrium* process. Such a process is defined as one in which there is an infinitesimal deviation from thermodynamic equilibrium at each point in the process; however, all states in a quasistatic process can be considered to be equilibrium states.

Consider the system shown in Fig. 1.1 in which the internal pressure of the gas is balanced by the weights; consequently, the piston is stationary. If any of the weights are removed, mechanical equilibrium no longer exists and the piston will rise until equilibrium is reestablished. A quasistatic process can be assumed for the system if the weights are taken to be very small and are removed one at a time. Obviously, if all the weights are removed at once, the piston will rise rapidly and equilibrium will not exist during any part of the process.

Many engineering systems are not too far removed from a quasistatic process, and application of this concept can greatly simplify thermodynamic analysis.

1.3 SYSTEM CONCEPT

A *system* is an entity whose overall performance can be monitored and analyzed. It can be a region in space, a quantity of matter, a group of creatures, or a series of interacting elements. Everything external to the system is the *environment*, and the interface between the system and its environment is the *boundary*. Macroscopic and/or microscopic characteristics of a mechanical, thermal, electrical, or chemical nature can be associated with the system, its boundary, and the environment. These characteristics can change with time or they may be constant while the system is functioning. Outside the realm of technology, the characteristics can be psychological economic, political, or philosophic in nature.

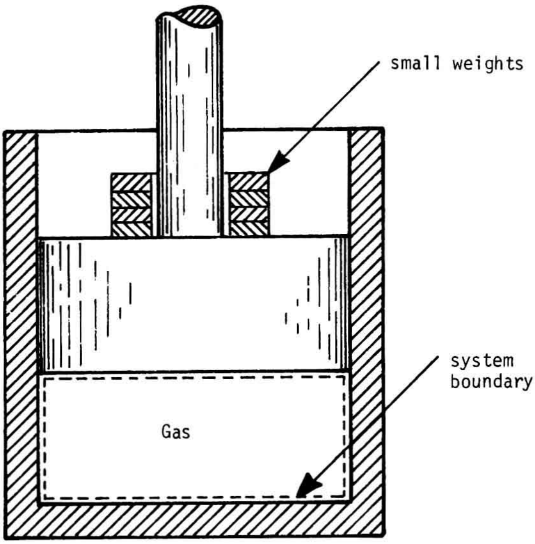

FIGURE 1.1 Gas in the cylinder undergoes a quasistatic process when small weights are removed one at a time.

A *subsystem* is an assemblage of interrelated components, or other subsystems, which make up a system. A *component* is an element which is used to build systems or subsystems, but which does not have to be designed or constructed in the context of a system synthesis or analysis.

In engineering thermodynamics three types of systems are distinguished: open, closed, and isolated systems. In an *open system* both energy and matter can cross the system boundary. Examples of open systems are pumps, turbines, fans, and combustion processes open to the environment. A *closed system* does not allow the passage of matter; only energy can cross its boundaries. Examples of closed systems are electric motors, integrated circuits, mechanical springs, furnaces, and calorimeters. An *isolated system* is completely uninfluenced by its surroundings; it has a fixed mass and no form of energy can cross the boundary. Examples are pumps, electronic circuits, or structural elements that are redundant or which are used in a standby capacity. In some of the literature the closed system is referred to as simply a system and the open system is called a control volume.

The first step in every thermodynamic analysis is to identify the system. This is customarily done by drawing a dotted line that approximates the boundary between the system and its environment.

Figure 1.2 shows an arrangement in which a motor-driven centrifugal pump transports a liquid from one region to another. An integral part of the arrangement is a redundant or standby motor/pump combination which, by definition, is an isolated system. Liquid enters the pump at the suction level and leaves at the discharge level. In addition, work crosses the boundary of the pump, and so it is identified as an open system. In the case of the motor, only electrical and mechanical energy cross the boundary, and so it is a closed system.

1.4 STATE OF A SUBSTANCE

The condition of a substance in a system is referred to as its *state*. If the condition is changed in any way by a transfer of energy, the

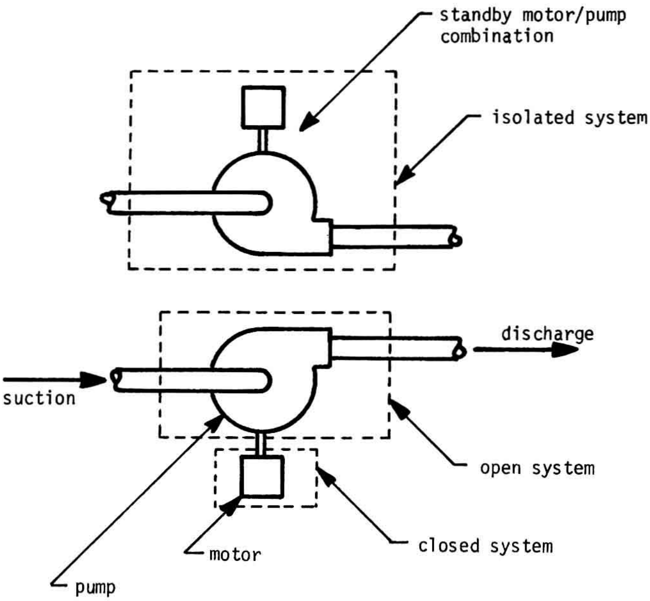

FIGURE 1.2 Schematic of a motor driven centrifugal pump and standby motor/pump combination showing examples of open, closed, and isolated systems.

system is said to have experienced a *change of state*. When a system passes through a succession of states, it goes through a *process*. If a system passes through a succession of processes and returns to the initial state, it has gone through a *cycle*.

A *phase* is a quantity of matter which is homogeneous in physical and chemical composition. The important phases in engineering thermodynamics are solid, liquid, and gaseous; in material science a variety of phases are encountered within the solid condition, but they are not generally considered for thermodynamic analyses. A change in phase such as the transformation from a solid to a liquid or from a liquid to a gas is a special case of a change in state.

A *pure substance* is a quantity of matter that retains the same chemical composition even when it experiences a phase change. Water is a classic example of a pure substance since it has the same chemical identity in the solid, liquid, or gas phase, or in mixtures of