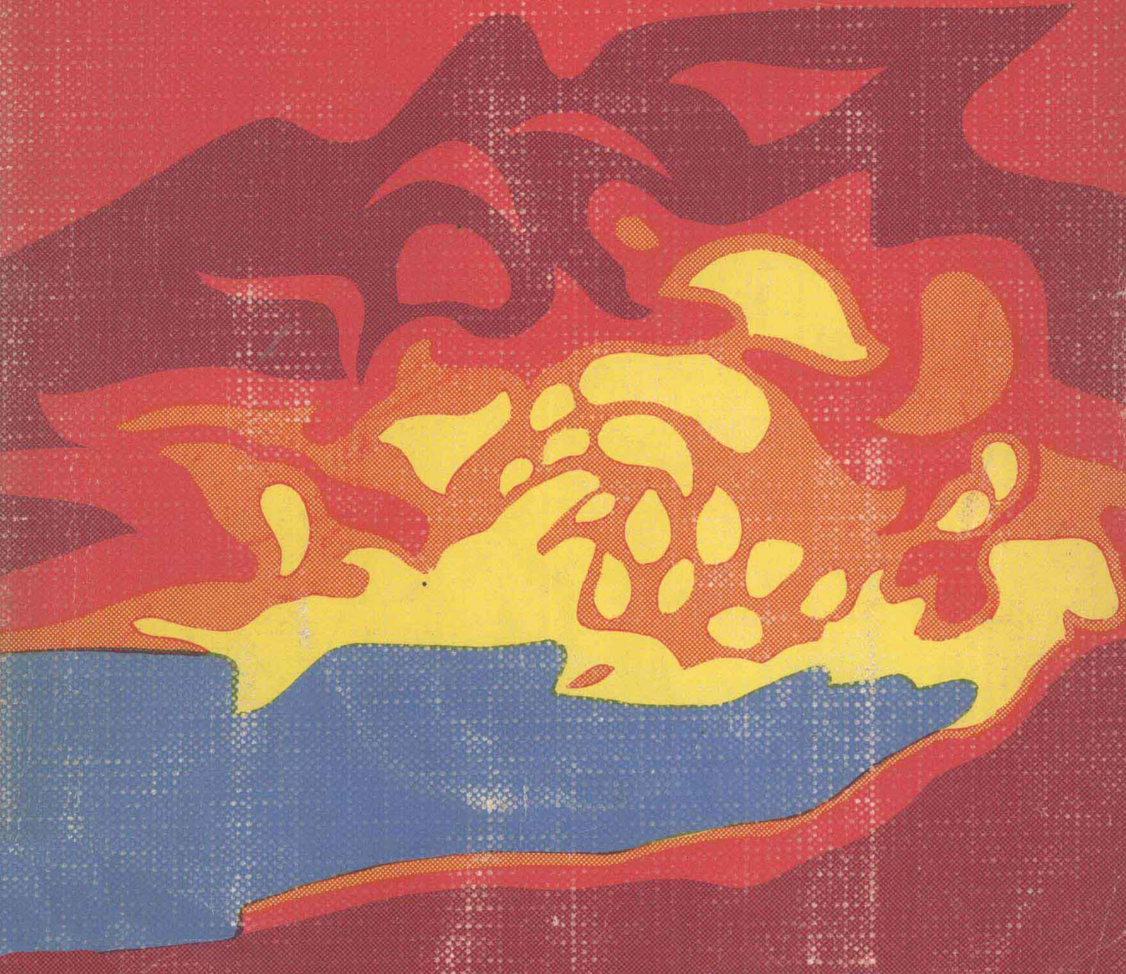
THE FLOW OF HEAT

in S.I. units

K. CORNWELL



VAN NOSTRAND REINHOLD

The Flow of Heat

To my Parents

Preface

In recent years there has been an increasing awareness that man is rapidly depleting the available energy resources. This awareness has not only initiated efforts to find new coal and oil reserves and use direct solar energy, but has also inspired attempts to reduce our energy consumption, both industrially and domestically. Most of the energy we use and most of the energy we waste is in the form of heat. In countries with a temperate or cold climate, a major proportion of the energy is used for heating human beings and there has recently been much publicity aimed at reducing domestic consumption. As a result of this energy-saving campaign and a general increase of interest in technical subjects, the ranks of those who desire some knowledge of heat and the flow of heat have swollen from the original group of thermal engineers and scientists. They now include the economy-minded factory or office manager, the enthusiastic layman who insulates the attic of his home and the thrifty housewife who reduces the central heating load in the centre of the day.

This book on the flow of heat, or heat transfer as the subject is often called, is written for two categories of readers. These are the professional students of the subject and the technically inclined laymen or those of other technical disciplines who desire some knowledge of the topic. For the first category the book is a student text suitable for diploma and degree courses and covers all the material generally included up to engineering honours degree level. Part I is sufficient for students of lower level courses or for those who discontinue the subject in one of the earlier years of their degree course. Part II contains the essence of the book for those studying the subject to higher levels. The treatment is in SI units and is particularly sympathetic to the reader, with emphasis on important points and many worked examples. For the second category of reader Part I forms a readable introduction to the topic and requires only limited knowledge of physics and mathematics. Part II may be used as a reference for further knowledge of specific areas and for this purpose a summary of important heat transfer relationships is included. The flow of heat is not a subject which is only worthy of study as a means to an end. It has an intrinsic interest which I shall attempt to illustrate by application to everyday situations, by mention of historical aspects and, here and there, by a little wandering from the direct and well-worn path.

I am indebted to the authors of the many textbooks, reference books and technical papers that have been used in the preparation of the book. Name and date identification is given in the text and full location details are included in the reference list. I am much obliged to my colleagues at Heriot-Watt University and particularly to Dr. A. J. Addlesee for his many helpful comments. Finally I wish to thank Mrs. Anne Edward for typing and retyping the manuscript, Mrs. J. Burnett for preparing the drawings and my wife for tolerating many evenings of non-communication.

Keith Cornwell,
North Berwick,
May, 1976

Introduction

What is energy? We know certain things about it. We know for example that it can flow in various forms such as heat energy, electrical energy and mechanical work. It may also be stored in various forms such as strain energy in a compressed spring, internal energy in a hot body and chemical energy in a fuel. Furthermore, Einstein showed at the beginning of the twentieth century that it is interconvertible with mass itself; that is to say the whole physical world is really a manifestation of energy. The characteristics of the various forms of energy can be identified. We could say for example that heat energy flows due to a temperature difference or express the internal energy of a material in terms of the activity of its atoms, but this brings us no nearer to answering the question: What is energy?

The fact is that we do not really know the answer. Most scientific and technological subjects commence with an acceptance of the concept of energy and treat the various forms of energy and mass as the stuff of the universe. Questions regarding the basic nature and existence of energy are more appropriate to the fields of philosophy and religion. Science cannot give reasons for the existence of energy or the presence of the physical universe. We ourselves are part of this physical universe, part of the energy which we seek to understand and due to this it may be inherently impossible for us to comprehend the existence of energy. However, this daunting thought need not deter us from studying the various characteristics of energy. Man has largely progressed to his present state of civilization by gleaning knowledge about it.

The subject of this book concerns just one of the many manifestations of energy, that of heat. It is further restricted to a study of the rate of flow of heat, a topic often called heat transfer. We are not concerned here with the conversion of heat into other forms of energy, such as the conversion of heat to work, called thermodynamics or the conversion of heat to electricity, called thermoelectrics. It was mentioned earlier that heat is the form of energy which flows due to a temperature difference and the subject of heat transfer is therefore only applicable to systems which involve different temperatures.

A popular science textbook used in the latter part of the nineteenth century was entitled *Deschanel's Natural Philosophy* (1888). In Part 2 Professor Deschanel concisely summarized the methods of heat flow to surrounding air:

'The cooling of a hot body exposed to the air is effected partly by radiation and partly by conduction of heat from the surface of the body to the air in contact with it. The activity of the surface conduction is greatly quickened

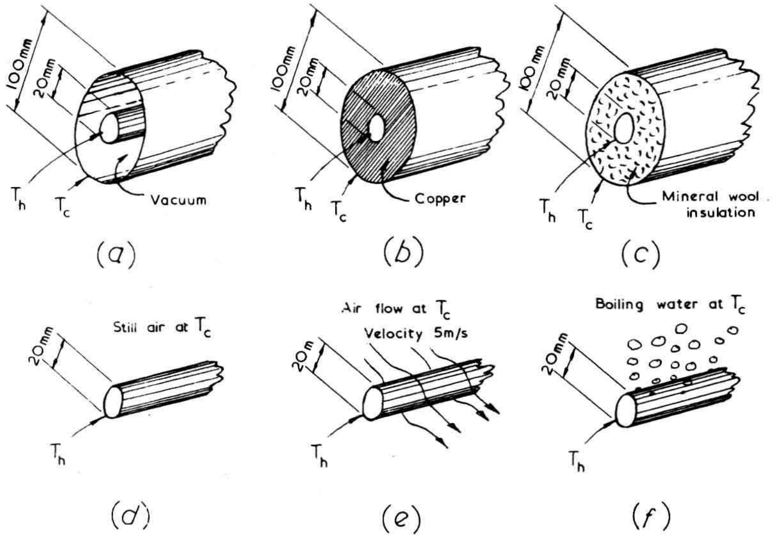


Figure 1 Heat transfer from a rod under various conditions.

	Predominant heat transfer mechanism	*Dependence on temperatures*	*Heat transfer at steady state per* m *length with* $T_c = 0\,°C$, $T_h = 100\,°C$
a	Radiation (blackbody)	$(T_h^4 - T_c^4)$	0.05 kW
b	Conduction	$(T_h - T_c)$	150 kW
c	Conduction	$(T_h - T_c)$	0.02 kW
d	Natural convection	$(T_h - T_c)^{1.25}$ approx.	0.07 kW
e	Forced convection	$(T_h - T_c)$ approx.	0.3 kW
f	Nucleate boiling	$(T_h - T_c)^3$ approx.	20 kW (with $T_c = 100\,°C$, $T_h = 120\,°C$)

by wind, which brings continually fresh portions of cold air into contact with the surface, in place of those which have been heated.'

We shall proceed to examine heat flow by these methods and in the same order, that is radiation, conduction and the activity of surface conduction or convection as it is called today. Furthermore, we shall not only consider the cooling of a hot body in air but also the heat flow from bodies in a vacuum, the heat flow through insulation, the heat flow from fluids in pipes and condensers and even the heat flow from our own human bodies.

Radiation and conduction are two basic and fundamentally different mechanisms. Radiation involves the propagation of energy through space at the speed of light and, like the transfer of light and radio waves, is an electromagnetic phenomenon. The situation in which radiation is the sole means of heat transfer only occurs when heat flows through a vacuum. On the other hand, conduction necessarily requires the existence of matter and depends upon molecular activity within the matter. Thermal convection is not a basic heat flow mechanism like radiation or conduction and mainly involves conduction together with the physical movement of matter. Professor Deschanel correctly described it as the activity of surface conduction, because the heat flow from a surface to a fluid (gas or liquid) is governed by the conduction process through a thin layer of the fluid adjacent to the surface. Convection heat transfer is subdivided into forced convection, where the fluid is forced over the surface by a blower or pump, and natural convection, where the temperature of the surface itself causes the convection currents. Convection mechanisms involving phase changes lead to the important fields of boiling and condensation. A rough indication of the magnitude of heat flow under various conditions is given in Fig. 1 and the accompanying table.

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PART II — AN INTRODUCTION TO THE ANALYSIS OF HEAT FLOW

The Fundamentals of Heat Flow

Heat Flow Through a Vacuum

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1.1 Vibrations and Voids

The awareness of heat radiation has been with us ever since our primeval descendants delighted in the rays of the sun or in the cosiness of their cave fires. However, it was not until the beginning of the twentieth century that any understanding of its nature was attained. Radiant heat energy was originally considered to propagate from a heat source rather like the ripples on a pond propagating from a point of disturbance. It could be shown that these ripples transferred energy by allowing the vertical oscillation of a float to operate a ratchet mechanism and raise a weight. In a similar way, it was assumed that radiation waves also transferred energy owing to their vibratory motion. Unfortunately, this did not account for the most significant aspect of radiation; its ability to pass through a vacuum. This ability was originally shown by Count Rumford using a thermometer situated in an evacuated glass chamber. Application of the wave theory requires some form of matter between the radiating bodies to enable transmission of the vibrations, or in other words there must be something to wave.

To circumvent this paradox, nineteenth century scientists postulated the existence of a gas called 'ether' which permeated all space (thus allowing for solar radiation) and penetrated the vacuum jars in their laboratories. Professor Deschanel in the aforementioned treatise writes:

'It is now generally admitted that both heat and light are due to a vibratory motion which is transmitted through space by means of a fluid called ether.' Perhaps the cautious manner in which he opens the sentence is significant. This was not the first time our forefathers had bridged the gap between their theories and experimental facts by postulating an invisible, weightless fluid with singular properties. Less than half of a century before, heat had been considered as a fluid named 'caloric' which flowed between bodies under conditions of 'heating by fire, rubbing or hammering'. When the possibility of converting heat into other forms of energy was demonstrated the concept of caloric was gradually abandoned although, as was mentioned earlier, energy is not really definable in general terms. Further progress with the wave theory of radiation was therefore severely hampered by the passage of radiation through a vacuum and, as we shall see later, it was not until the introduction of the quantum theory that the problem was resolved.

On another front, however, research was progressing satisfactorily, based on the concept of radiation as atomic particles. These particles formed a radiation gas, not a mysterious weightless gas, but one with characteristics and properties similar to a perfect gas. Radiation was known to pass through a vacuum at the velocity of light and, since this velocity is finite, there must be a finite amount of energy in transit at any time in the space between radiating surfaces. That is to say there must be a radiant energy density or radiation 'gas' occupying the space. By analysis of this gas along exactly similar lines to the classical kinetic theory of perfect gases Boltzmann showed in 1884 that the heat energy emitted by radiation from any surface is proportional to its absolute temperature to the fourth power:

$$E = CT^4$$

In this equation E is the quantity of energy emitted per unit area and per unit time by the surface and is termed the emissive power. The term T is the temperature, which is always measured in absolute units in radiation work, and C is a constant. This relationship confirmed the conclusions drawn by Stefan (1879), based on experiments conducted by Tyndall on radiation from hot platinum wire. Ironically Stefan's conclusions were rather inaccurate as it has since been shown that radiation from untarnished electrically conducting metals is more nearly proportional to T^5.

The emissive power of a surface is found to depend upon a number of parameters among which are the surface material and roughness. In order to formulate general radiation relationships, it is helpful to define a surface which is a perfect emitter and emits the maximum power possible at a particular temperature. We shall later show that a surface which is a perfect or ideal emitter may also be called a black surface. For a perfect emitter the previous expression becomes

$$E_b = \sigma T^4 \tag{1.1}$$

where E_b is the emissive power of the perfect emitter at temperature T. This equation is termed the Stefan–Boltzmann law and the Stefan–Boltzmann constant σ has the value of 56.7×10^{-12} kW/m² K⁴. The emissive power of an actual surface is expressed as a proportion of E_b:

$$E = \varepsilon E_b \tag{1.2}$$

The proportion ε is termed the emissivity of the surface and its value depends upon surface characteristics and temperature.

1.2 Symbols and Surfaces

Radiation involves the use of many technical terms and definitions and before proceeding further we shall introduce the more important of these terms. The total radiant energy falling on a surface is called the incident radiation and the incident radiation per unit time and area is termed the irradiation H. There are three possibilities open to radiation striking a body; it may be absorbed, reflected or transmitted. The following parameters are accordingly defined:

Absorptivity α—the proportion of incident radiation absorbed

Reflectivity ρ—the proportion of incident radiation reflected

Transmissivity τ—the proportion of incident radiation transmitted

and it follows that

$$\alpha + \rho + \tau = 1 \tag{1.3}$$

Solids generally transmit no radiation unless the material is of very thin section. Metals absorb radiation within a fraction of a micrometre and electrical insulators within a fraction of a millimetre. Even substances such as liquids and glasses absorb most of the radiation within a millimetre. Solids and liquids therefore are generally assumed to have a transmissivity of zero in which case:

$$\alpha + \rho = 1 \tag{1.4}$$

On the other hand, most elementary gases such as hydrogen, oxygen and nitrogen (and mixtures of these such as air) have a transmissivity of practically unity; i.e., their reflectivity and absorptivity are nearly zero. For this reason radiation transfer through air is generally estimated using the relationships for radiation through a vacuum. Gases with a more complex structure, such as steam and carbon dioxide, generally absorb and emit as well as transmit radiation.

The reflection of radiation from a solid surface may be of a specular or diffuse nature. Specular reflection occurs at a surface which is very smooth, such as a mirror, and an image of the radiation source is projected. The optical laws apply and, in particular, the angle of reflection is equal to the angle of incidence. Diffuse reflection occurs when the surface is rough and there is no preferential direction of reflection. No actual body is perfectly specular or diffuse but it is often useful to approximate to one of these ideal surfaces.

Equation (1.3) indicates that when a body is such that no incident radiation is reflected or transmitted all the radiant energy must be absorbed. A body of this type is called a blackbody (and a surface which has this property is termed a black surface). For a blackbody therefore

$$\rho + 0,\ \tau = 0 \text{ and } \alpha = 1$$

No actual body is perfectly black; if there were such a body it would not be possible to see it, except as a silhouette. Some surfaces are nearly black and it is possible to artificially create an almost perfectly black area by forming a cavity in a material, as shown in Fig. 1.1. Radiation passing through the hole into the cavity is repeatedly absorbed and reflected at the cavity walls until it is all absorbed. An even better black surface is provided by distant surroundings such as the night sky, but in this case one is restricted to the particular

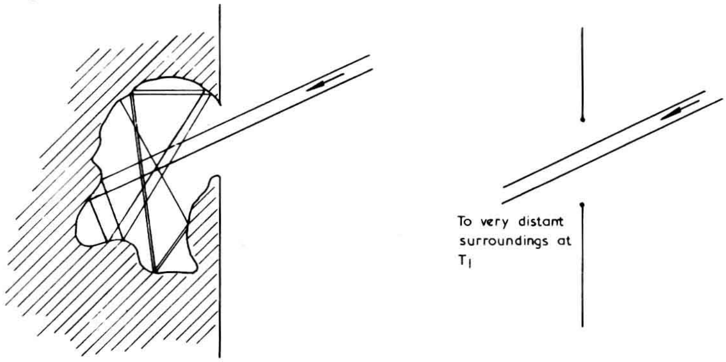

Figure 1.1 The black 'surface'.

temperature of the surroundings. It should be pointed out that surfaces which are nearly black, for radiation purposes, are not necessarily black to visible light, because the visible light wavelength range is only a small part of the overall thermal radiation range. White paper, for example, is nearly radiation black with an absorptivity of 0.97.

Let us now turn our attention to radiation leaving a surface rather than radiation falling on a surface. The total radiation leaving a surface per unit time and area is termed the radiosity, B. The radiation leaving a surface may be divided into two parts: that which is reflected by the surface, and that which is emitted by the surface due to its temperature. The former part is equal to ρH where H, it will be recalled, is the irradiation or the total incident radiation per unit time and area. The latter part is the emissive power E which was introduced earlier as the energy emitted per unit time and area. Substituting $E = \varepsilon E_b$ from equation (1.2) where E_b is the maximum possible emissive power, the radiosity becomes

$$B = \rho H + \varepsilon E_b \tag{1.5}$$

A little thought now shows that a blackbody is also a perfect emitter. Consider a blackbody in thermal equilibrium with surroundings at tempera-