ENGINEERING HEAT TRANSFER

SECOND EDITION

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Preface to First Edition

The aim of this book, which is a revised edition of a book previously published by McGraw-Hill, is to introduce the reader to the subject of heat transfer. It will take him sufficiently along the road to enable him to start reading profitably the many more extensive texts on the subject, and the latest research papers to be found in scientific periodicals. This book is therefore intended for students of engineering in universities and technical colleges, and it will also be of assistance to the practising engineer who needs a concise reference to the fundamental principles of the subject. The engineering student will find most, if not all, aspects of the subject taught in undergraduate courses and, thus equipped, he will be in a position to undertake further studies at postgraduate level.

The aim throughout has been to introduce the principles of heat transfer in simple and logical steps. The need for an easily assimilated introduction to a subject becomes more urgent when the subject itself continues to grow at an ever-increasing rate. It is hoped that the material selected and presented will be of value at all levels of readership. Indebtedness is acknowledged to all those, past and present, who have contributed to the science of heat transfer with their original work, and as far as possible detailed references are given at the end of each chapter. Also grateful thanks are extended to various persons and organizations for permission to use certain diagrams, tables, and photographs; credit for these is given at appropriate points throughout the text.

It is also hoped that in this edition the changes made will further enhance the value of the book. Greater attention has been given to numerical methods in conduction, and some basic procedures in digital computing are included. The chapter on radiation has been extended to include an introduction to non-luminous gas radiation and a short section on solar radiation. Numerous small changes have been made throughout in the light of reviews and criticisms received. New worked examples are included to extend the range of applicability, and some of the original problems set have been replaced by more recent ones. SI units are now used exclusively, and conversion factors for British units are included in appendix 2.

Many of the problems included are university examination questions; the source is stated in each case. Where necessary the units in the numerical examples have been converted to SI. Indebtedness is acknowledged to the owners of the copyright of these questions for permission to use them, and for permission to convert the units. The universities concerned are in no way committed to the approval of numerical answers quoted.

Much of the material in this book has been taught for a number of years at undergraduate level to students at The City University. Grateful thanks are due to Professor J. C. Levy, Head of the Department of Mechanical Engineering, and to Mr B. M. Hayward, Head of the Thermodynamics Section. Discussions with colleagues at City and elsewhere have also contributed in numerous ways, and for this help sincere thanks are expressed.

Finally, thanks are due to Malcom Stewart, of The Macmillan Press, who has been responsible for the production of both editions, and also to my wife, who has typed the manuscript revisions.

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Preface to Second Edition

The essential aims of this new edition remain unchanged. While the subject matter of heat transfer at undergraduate level has not greatly altered, the student now has a powerful computational tool available to him, which in its use enables him to plot, explore and appreciate the mechanisms of heat transfer and their contributions in solving engineering problems. The use of the personal computer is increasing in all subject areas of undergraduate courses; and with growing emphasis on Design as an essential concept in the presentation of undergraduate studies, the introduction of computing methods into this edition forms the essential new material.

Relatively elementary computing procedures may be introduced in the subject matter of steady state and transient conduction, extended surfaces and heat exchangers, and the bulk of the new material lies in these areas. Since a considerable amount of valuable and relatively simple computing practice is possible in the field of cross flow heat exchange and in rotary regenerators, new sections have been added in these areas, and in order to make room for all the new computing material the chapter on mass transfer has been removed. More advanced computing techniques arise in convection studies and this subject is well covered in the literature. It is hoped that this new edition will help the student become familiar with the possibilities of computer literacy in the more elementary aspects of the subject of heat transfer.

The language of the computer listings is BASIC, which is the most popular language in use in the programming of personal and microcomputers. Some minor editing may be required to enable the given listings to run on particular machines. No claim is made for elegance in the programming presented; it is intended merely to present relatively simple examples with which the majority of students may gain in computing experience.

Some of the older problems have been removed and new ones introduced. At the same time, some earlier misprints and one or two misconceptions have been rectified. The author is grateful for comments and suggestions received since the first edition appeared, and he is grateful, too, for the support received which has made this second edition possible.

JOHN R. SIMONSON

Nomenclature

a	distance increment
A	area
b, l, t, w	linear dimension
C	capacity ratio of heat exchanger
C, K	constants of integration
Cd	average friction factor
Cf	skin friction coefficient
c_p	specific heat at constant pressure
C_p	volumetric specific heat at constant pressure
d	diameter
E	effectiveness of heat exchanger
f	friction factor
F	geometric configuration factor
$\mathscr{F}$	geometric emissivity factor
f_D	drag factor
g	gravitational acceleration
G	irradiation, mass velocity
Gz	Graetz number, $Re\ Pr(d/x)$
h_R	convection coefficient
H	product hA
h_{fg}	latent enthalpy of evaporation
h_r	radiation coefficient
i	current density
I	current
I	intensity of radiation
J	radiosity
k	thermal conductivity
L, D, T, W	linear dimension
L, M, T, θ	dimensions of length, mass, time, temperature
m	mass flow, or mass in transient conduction
$\dot{m}$	mass flow, where a non-flow m also occurs
n	coordinate direction
n	frequency of temperature variation
NTU	number of transfer units
$p, P, \Delta p$	pressure, difference of pressure
P	perimeter
PN	plate number
q	heat transfer per unit area and time
q'	heat generation per unit volume and time
Q	heat transfer per unit time, or a physical variable in dimensionless analysis

r	radius, radial direction
r	residual value
R	resistance
R_m	universal gas constant
S	scaling factors in electrical analogy
S_i	electrical shape factor
S_q	thermal shape factor
t	temperature
T	absolute temperature
t, Δt, T	time, time increment, time constant
U, U_A, U_L	overall heat transfer coefficients
U	velocity of temperature wave
v	velocity
v	specific volume
V	electrical potential, volume
x, y, z	coordinate direction, linear dimension
X	length of temperature wave
α	thermal diffusivity
α	absorptivity
β	coefficient of cubical expansion
δ	boundary layer thickness
δ_b	thickness of laminar sub-boundary layer
δ_t	thermal boundary layer thickness
δ_t'	equivalent conducting film thickness
ε	emissivity
ε	eddy diffusivity
ε_q	eddy thermal diffusivity
η_f	fin effectiveness
η_{fe}	equivalent effectiveness of finned surface
θ, θ_m	temperature difference, logarithmic temperature difference
θ	angle in cylindrical coordinate system
λ	wave-length
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
ρ	electrical resistivity
ρ	reflectivity
σ	Stefan–Boltzmann constant, surface tension
τ	shear stress
τ	transmissivity
τ_t	turbulent shear stress
ϕ	angle in spherical coordinate system

Dimensionless groups

F	Fourier number, $\Delta t\alpha/a^2$
Gr	Grashof number, $\beta g\theta\rho^2 l^3/\mu^2$
J	Colburn J-factor, $St.\ Pr^{2/3}$
Nu_l	Nusselt number, hl/k

Pr	Prandtl number, $c_p \mu / k$
Ra	Rayleigh number, $Gr.Pr$
Re_l	Reynolds number, $\rho v l / \mu$
St	Stanton number, $h / \rho v c_p$

Suffices

a	at axis of tube
b	black body
b	limit of laminar sub-boundary layer
c	cold fluid
C	convection
d, l, x	length terms used in dimensionless groups
e	equivalent
f	fluid
h	hot fluid, heated length
i, o	inlet, outlet (in heat exchangers)
l	liquid
m	mean value
M	metal, in heat-exchanger wall
n	direction of component
O	datum length
p	constant pressure
r	radial direction, or radial position
R	radiation
s	surroundings, of free stream
sat.	saturated temperature
t	temperature, turbulent
v	constant volume, vapour
w	wall
x, y, z	direction of component
θ	angular component
λ	monochromatic

Superscript

—	average value

Contents

1

Introduction

One of the primary concerns of the engineer is the design and construction of machines many times more powerful than himself or any of his domestic animals. The development of this skill over the centuries has been fundamental to the growth of civilization. Man's early efforts to harness the power of wind and water owed very little to engineering science, and indeed the early steam engine was a practical reality *before* the science of thermodynamics was firmly established. In contrast, there is now a vast fund of engineering knowledge behind the present day prime movers.

Much engineering activity is directed to the controlled release of power from fossil and nuclear fuels, and with making that power available where it is needed. The laws of heat transfer are of the utmost importance in these activities. The generation of power from the energy changes of chemical and nuclear reactions involves the transfer of vast quantities of thermal energy. Further, chemical processes of combustion yield temperatures at which most constructional materials would melt; adequate protection by heat transfer processes is therefore vital. The distribution of energy as electricity is accompanied, at all stages, by certain wastages manifested as rising temperature of the equipment. Heat transfer considerations enable these temperatures to be controlled within safe limits.

The laws of heat transfer find application in many other fields of engineering. Chemical and process engineering, and manufacturing and metallurgical industries are examples. In addition, the civil and constructional engineer and environment control engineer need considerable knowledge of the subject. Large city buildings must be economically heated and insulated, and air conditioning is increasingly necessary.

To the mechanical engineer heat transfer is a subject closely allied to applied thermodynamics. The first and second laws of thermodynamics state the relations between the physical entities of heat and work, and the limit to the amount of work that may be obtained from any source of heat. Even this limit cannot be reached in practical engineering processes because of their inherent irreversibility. These irreversibilities may be accounted for in calculations but, even so, thermodynamics alone leaves a lot of questions unanswered. There is no time scale and, consequently, thermodynamics will not permit the calculation of physical sizes necessary to achieve a given objective. In a steam power plant it is necessary to transfer the thermal energy of the hot combustion gases of the burnt fuel to the water in the boiler tubes. The actual rate of transfer to produce a required flow rate of steam may be known, but without the laws of heat transfer and knowledge of the properties of the engineering materials to be used, it is not possible to calculate the size and surface area of the tubes required. From an economic point of view, the boiler must be made as small as possible, hence the heat transfer rate must be as high as possible. Elsewhere in the plant, heat transfer considerations are necessary in insulating the steam delivery lines and in condensing the low pressure turbine exhaust.

Heat transfer processes, then, are described by equations which relate the energy to be transferred in unit time to the physical area involved. Other factors entering the equations are the temperatures, or the temperature gradient, and some coefficient which depends on various physical properties of the system and on the particular mechanism of heat transfer involved. Three basic mechanisms of heat transfer are recognized. They may occur separately, or simultaneously. Separate equations may be written to describe each mechanism, and when two or more mechanisms occur simultaneously it is sometimes possible to add the separate effects; but sometimes it is necessary to consider the equations of the participating mechanisms together. The subject matter thus conveniently sub-divides itself into the separate basic mechanisms of heat transfer, and the combinations of them.

Heat is transferred by conduction, convection, and radiation. Before describing these processes, it is desirable to clarify what is meant by 'heat'. In the study of thermodynamics, heat is defined as an energy transfer between communicating systems, arising solely from a temperature difference. Thus a heat transfer is strictly a phenomenon occurring only at *boundaries* of systems, and a heat transfer elsewhere in a system is more correctly a redistribution of internal energy within the system. As it is convenient to keep to the conventional language of heat transfer, this should be kept in mind, and the word heat will not in most cases be in accord with the thermodynamic usage.

Conduction is the mode of heat transfer in a solid material and occurs by virtue of a temperature difference between different parts of the material. Conduction also occurs in liquids and gases but is generally associated also with convection, and possibly with radiation as well in the case of gases. Conduction within a solid is a transfer of internal energy; this energy is, in fact, energy of motion of the constituent molecules, atoms, and particles of which the material consists. The kinetic energy of the motion is proportional to the absolute temperature; molecular collisions lead to energy transfer to regions of lower kinetic energy. Under steady conditions a molecule will pass on the same amount of energy that it receives. Under non-steady conditions the flow of energy is governed by the changing energy levels.

The theory of conduction heat transfer was established by Joseph Fourier whose work was published in Paris in 1822,[1] but pioneer work was done by Biot in 1804[2] and 1816.[3] Conduction is described by an equation known as the Fourier rate equation

$$Q_x = -kA\frac{\mathrm{d}t}{\mathrm{d}x} \tag{1.1}$$

The rate of heat flow (in only the x-direction, see Fig. 1.1) is proportional to the product of the area of flow and the temperature gradient, the constant of proportionality being the thermal conductivity k which is a property of the material. The negative sign results from the convention of defining a positive heat flow in the direction of a negative temperature gradient. The property k may be a function of temperature and direction of heat flow. Materials with directional dependence of thermal conductivity are said to be anisotropic.

The units involved depend on the system chosen. In the SI system, the unit of heat or internal energy is the joule, hence rate of heat transfer is measured in J/s or W. However, the kilojoule, (kJ), and kilowatt, (kW), are accepted multiples of the SI unit, and to be consistent with general usage in thermodynamics, the kJ and kW are the preferred units in this book. With the area in m^2 and the temperature gradient in K/m, the units of k are kW/(m K). This follows the British Standards recommendation[4] for the presentation of complex units.