HEAT CONDUCTION AND MASS DIFFUSION

BENJAMIN GEBHART

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Benjamin Gebhart

University of Pennsylvania

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ABOUT THE AUTHOR

Benjamin Gebhart was born in Cincinnati and grew up in Miamisburg, Ohio. After a short stint as an apprentice tool maker, he joined the Marine Corps and spent two and a half years in the Pacific, in World War II. The GI Bill supported the BSE (ME) and MSE (ME) degrees at the University of Michigan. The Ph.D. degree was obtained at Cornell University and he remained there for twenty-four years. In 1975 he went to the State University of New York at Buffalo as a Leading Professor and became Chairman of Mechanical Engineering. In 1980 he was appointed the Samuel Landis Gabel Professor of Mechanical Engineering at the University of Pennsylvania. On leaves, he has been a professor at the University of California at Berkeley, the University of Marseille, Oregon State University, at the Ecole des Mines in France, and the Naval Post Graduate School, as the NAVSEA Research Chair Professor. He has also been associated widely in Europe, Scandinavia, Germany, and in the former USSR in research interactions.

The research over this period has been in many areas of buoyancy induced flows and transport. Other investigations have concerned mixed convection, mass diffusion, melting and freezing, flow interactions, density extrema effects, transport in pure and saline water, and microconfigured surface radiation and phase change processes. Earlier books were *Heat Transfer* (1961) and (1971) and *Buoyancy-Induced Flow and Transport*, with Professor Y. Jaluria, Professor R. L. Mahajan, and Dr. B. Sammakia. He is on the editorial boards of many archive journals and is listed in eight biographical references. He is a fellow of the ASME.

An interest for over three decades has been the assembly of land parcels into a large nature sanctuary near Ithaca, N.Y. Reforestation, wildlife habitat improvement, and soil restoration remain a continuing and strenuous activity there.

PREFACE

This book is a result of the author's activity in teaching conduction, with an added element of mass transfer. It provides a suitable text in conduction heat transfer and also includes much material concerning many kinds of mass diffusion processes. It demonstrates heat conduction and mass diffusion processes in terms of many and diverse engineering applications. Many excellent books have concerned the fundamental aspects of both conduction mechanisms and analysis. There are also a number of books which principally concern mass diffusion. These also include good coverage of additional and more diverse fundamental mechanisms which commonly arise in mass diffusion. A principal purpose here is to link analysis, application, and heat and mass diffusion.

Heat conduction and mass diffusion are very closely interrelated in both applied science and in technology. Many of the physical processes and methodologies are very similar. Their consideration together is well known to be an effective teaching strategy. The appropriate rate laws are often similar. Many direct analogies are commonly used in calculating transport. Considering heat and mass transfer together is an economy. It is also an advantage for students whose work will span these fields.

This book brings heat conduction and mass diffusion into a common treatment. The level is appropriate for a first advanced course. The total content of this book is beyond coverage in a single course. Choices are to be made in terms of the objectives of the particular instructor.

Both the content and presentations in this book are often different than common in past texts. Several objectives are followed throughout. A most important matter is a careful description of the physics of the many fundamental processes. For example, diffusion mechanisms are discussed in detail, in terms of the constituent microscopic processes.

Most solutions demonstrated here were chosen as characteristic of different applications. The separation of variables, the Laplace transform, and the Duhamel methods are given, along with some particularly useful solutions. Most graduate students are receiving instruction in applied mathematics. Therefore, the amount of such analysis, and the number of solutions, are considerably reduced here. This has made possible a broader representation of the diverse mechanisms and processes which are of increasing importance in our field. Abundant references also are given to the more specialized treatments available in many other excellent books and in the literature.

This book includes useful coverage of many typical and currently important processes and applications. Examples are composite materials, composite insulation, contact resistance, catalysis, moving sources, phase fronts, noncontinuum diffusion, effects of thermal stress, and shape factors. Combined and simultaneous processes of heat and mass diffusion, such as in transpiration cooling and porous region drying, are also treated.

Chapters 3, 4, and 5 concern steady-state and single and multidimensional unsteady-state processes. The results are commonly in terms of heat conduction bounding conditions, since many of the mechanisms do not have simple or direct mass diffusion analogs. Examples are contact resistance, moving phase fronts and moving sources.

The simplest treatments of the numerical methods used to generate approximate solutions are given in Chaps. 3, 4, and 5. These apply, in turn, to multidimensional steady-state, one-dimensional transients, and multidimensional transient processes. This divided treatment is used to emphasize the several distinct aspects of numerical modeling. Section 3.9 concerns the subdivision of a continuous region into the numerical simulation of regular boundary conditions, in steady state. Section 4.9 is the first consideration of the numerical simulation of an evolving transient response, including questions of calculational stability. Section 5.3 then combines these concepts, for multidimensional transients. Other numerical formulations and methodologies are thereafter considered in more detail in Chap. 9. Depending on the objectives of the instructor, and the previous preparation of the students, the material in Secs. 3.9, 4.9, and 5.3 may serve only as an initial review of some of the basic aspects of numerical representation.

Chapter 6 concerns many important mass diffusion mechanisms and processes which do not have very common or direct analogs in heat conduction. Section 6.1 concerns the equation transformations characteristic of mass diffusion, the concept of porous region permeability and the fundamental diffusion mechanisms of chemical species in gases, liquids, and solids. Section 6.2 examines the effects of changing mass diffusivity, D, over a region, due to its sensitivity to both local concentration and to region inhomogeneity. Section 6.3 treats transients, variable diffusivity, surface processes, and the measurement of diffusivity. Section 6.4 concerns interfaces and moving boundaries, in terms of surface region processes, such as surface oxidation layers and moving locations, or fronts, of abruptly changing diffusivity. Section 6.5 concerns distributed internal chemical reactions. Both chemically irreversible and reversible reactions are analyzed, to determine sorption and desorption rates. Section 6.6 concerns several kinds of combined heat transfer and mass diffusion mechanisms. These include the frequent thermal effects of internal species adsorption, chemical species diffusion in a flame front and the transpiration cooling of a hot surface. Non-Fickian transport, due to both noncontinuum and to surface-diffusion effects, is also analyzed.

The formulations and analyses in this book do not include either the Soret or Dufour effects. The Soret effect is the concentration gradient which sometimes arises from an imposed temperature gradient, as in saline water. The Soret effect would then cause saline diffusion. The Dufour effect is the inverse kind of process, thermal diffusion arising from an imposed concentration gradient. Similar simpler kinds of coupled processes arise in the mechanisms discussed in Sec. 6.6.

Chapter 7 concerns composite regions. Thermal transport contact resistance is quantified in detail, in recognition of its importance in many and diverse applications. It is also a good physical example of the interaction of parallel and series processes. The conductivity mechanisms of composite materials are discussed. The last section concerns composite insulation, and superinsulation in particular.

Chapter 8 is related to a group of important conduction-mediated applications. Extended surface heat transfer is treated in Sec. 8.2. Section 8.3 concerns welding, in terms of the internal conduction responses to concentrated moving energy sources. Thermal stresses, which arise in many processes, are also considered for several simple examples, in Sec. 8.4. Section 8.5 concerns the average heat conduction rate in randomly disturbed conduction environments. Section 8.6 concerns fluid flows in which the convection transport field is actually analyzed as a purely conductive process. The examples are liquid films and internal flows.

The treatment of numerical analysis in Chap. 9 presumes the background given in Secs. 3.9, 4.9, and 5.3. Section 9.1 contrasts the finite difference and finite element methods. Then finite difference formulations are given, in Sec. 9.2, along with the resulting errors due to truncation, discretization, and round-off. Examples of general higher-order estimates are also given. Section 9.3 concerns truncation errors and considerations of stability in transients. Common numerical methods are summarized. Section 9.4 treats important additional aspects of calculation techniques, including numerical iteration and the treatment of irregular boundaries. Section 9.5 concerns the effects of variable properties. Section 9.6 formulates the finite-element method of numerical analysis and gives a simple example.

This book covers a relatively wide diversity of heat and mass transfer processes, over a broad range of applications. The objective is to bring these considerations together in a consistent way, in a book of reasonable size. On the other hand, this material includes the treatment of many important mechanisms not commonly treated in text material concerning the heat and mass transfer mechanisms. Examples include moving phase interfaces, contact resistance, cryogenic insulation, composites, chemical processes, thermal stress, and random conduction effects.

The result here has been that the coverage of some commonly important matters is less detailed. One example is the material concerning finite-difference and finite-element implementation, in Chap. 9. Another is the relatively smaller scope given to classical analytical solution techniques. However, these treatments, along with many others, are widely available in the other literature referenced here.

A large number of problems are given. These cover most aspects of the material in the book. Appendix A gives conversion factors. Appendixes B, C, and D concern thermal properties, and E tabulates mass diffusivities for gases, liquids, and solids. Appendixes F, G, and H concern the error function, Laplace transform pairs, and piping and tubing dimensions. Both English and SI units are used in this book, since practice continues to indicate that the wide use of both systems is a continuing reality in our field.

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CHAPTER 1

INTRODUCTION

1.1 DIFFUSION PROCESSES IN SOLIDS

The study of heat and mass transport continues to be an increasingly intense concern in technology and in the earth sciences. In every field concerned with energy production and exchanges, the need to understand, to predict, and to optimize has led to increasingly detailed study of how thermal energy and chemical species are carried, distributed, and diffused in and by material.

This book concerns the rate of heat and chemical species diffusion through materials, by the mechanism called conduction or diffusion. This is idealized as a stationary region of material through which heat or chemical species diffuse. A common example of heat conduction is heating an object in an oven or furnace. The material remains stationary throughout, neglecting thermal expansion, as the heat diffuses inward to increase its temperature. A comparable chemical species diffusion process arises when a dry fibrous material is placed in a humid environment, to increase the water content of the fibers by inward vapor diffusion.

The common feature of both kinds of processes is that both the thermal and the mass diffusion often take place without an important effect on the configuration or volume of the material through which the diffusion occurs. These are simple conduction modes. However, there are many other transport processes in which both thermal and mass diffusion arise, wherein the material is flowing or in relative motion. These are convection processes. These are covered by the formulations developed here only for flow processes in which the motion does not influence the thermal or mass diffusion. This sometimes occurs when the flow is essentially parallel and also normal to the imposed gradient of temperature or concentration. Then the motion may not affect the diffusion process.

1.1.1 Heat Conduction and Thermal Conductivity

The rate of heat conduction through a material may be proportional to the temperature difference across the material and to the area perpendicular to heat flow and inversely proportional to the length of the path of heat flow between the two temperature levels. This dependence was established by Fourier and is analogous to the relation for the conduction of electricity, called Ohm's law. The constant of proportionality in Fourier's law, denoted by k, is called the thermal conductivity. It is a property of the conducting material and of its state. With the notation indicated in Fig. 1.1.1, Fourier's law is

$$q = \frac{kA}{L}(t_1 - t_2) \tag{1.1.1}$$

where kA/L is called the conductance of the geometry.

The thermal conductivity k, which is analogous to electrical conductivity, is a property of the material. It is equivalent to the rate of heat transfer between opposite faces of a unit cube of the material which are maintained at temperatures differing by 1°. In engineering units in the English system, k is expressed in

$$\frac{\text{Btu}}{\text{hr ft}^2\ {}^\circ\text{F/ft}} = \text{Btu/hr ft }{}^\circ\text{F}$$

in SI units, k is expressed as $\text{W/m}^2\ \text{K/m}$, or W/m K.

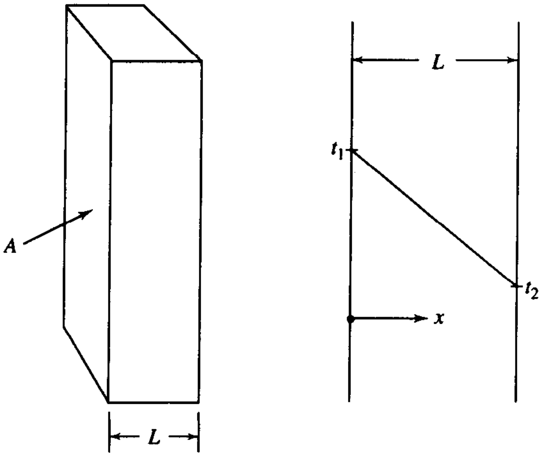

FIGURE 1.1.1
One-dimensional steady-state heat conduction.