BASIC HEAT & MASS TRANSFER

SECOND EDITION

A. F. MILLS

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Second Edition

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About the Cover: The columns supporting portions of the trans-Alaska oil pipeline system are gravity-flow ammonia heatpipes (see Chapter 7). In winter, the ground underneath the columns is warmer than the environment. Ammonia liquid evaporates inside the base of a column and condenses at the top, with the enthalpy of vaporization dissipated to the environment by convection and radiation from the cooling fins. The heat extracted from the ground causes a large volume of ice to form underneath the columns and provides a solid foundation for the pipeline. The Arctic summer is not warm enough to completely melt this permafrost before the next winter.

To Brigid
For your patience and understanding.

PREFACE

Basic Heat and Mass Transfer has been written for undergraduate students in mechanical engineering programs. Apart from the usual lower-division mathematics and science courses, the preparation required of the student includes introductory courses in fluid mechanics and thermodynamics, and preferably the usual junior-level engineering mathematics course. The ordering of the material and the pace at which it is presented have been carefully chosen so that the beginning student can proceed from the most elementary concepts to those that are more difficult. As a result, the book should prove to be quite versatile. It can be used as the text for an introductory course during the junior or senior year, although the coverage is sufficiently comprehensive for use as a reference work in undergraduate laboratory and design courses, and by the practicing engineer.

Throughout the text, the emphasis is on engineering calculations, and each topic is developed to a point that will provide students with the tools needed to practice the art of design. The worked examples not only illustrate the use of relevant equations but also teach modeling as both an art and science. A supporting feature of *Basic Heat and Mass Transfer* is the fully integrated software available from the Prentice-Hall website at www.prenhall.com. The software is intended to serve primarily as a tool for the student, both at college and after graduation in engineering practice. The programs are designed to reduce the effort required to obtain reliable numerical results and thereby increase the efficiency and effectiveness of the engineer. I have found the impact of the software on the educational process to be encouraging. It is now possible to assign more meaningful and interesting problems, because the students need not get bogged down in lengthy calculations. Parametric studies, which are the essence of engineering design, are relatively easily performed. Of course, computer programs are not a substitute for a proper understanding. The instructor is free to choose the extent to which the software is used by students because of the unique exact correspondence between the software and the text material. My practice has been to initially require students to perform various hand calculations, using the computer to give immediate feedback. For example, they do not have to wait a week or two until homework is returned to find that a calculated convective heat transfer coefficient was incorrect because a property table was misread.

The extent to which engineering design should be introduced in a heat transfer course is a controversial subject. It is my experience that students can be best introduced to design methodology through an increased focus on equipment such as heat and mass exchangers: *Basic Heat and Mass Transfer* presents more extensive coverage of exchanger design than do comparable texts. In the context of such equipment one can conveniently introduce topics such as synthesis, parametric studies, tradeoffs, optimization, economics, and material or health constraints. The computer programs HEX2 and CTOWER assist the student to explore the consequences of changing the many parameters involved in the design process. If an appropriate selection of this material is taught, I am confident that Accreditation Board for Engineering and Technology guidelines for design content will be met. More important, I believe that engineering undergraduates are well served by being exposed to this material, even if it means studying somewhat less heat transfer science.

More than 300 new exercises have been added for this edition. They fall into two categories: (1) relatively straightforward exercises designed to help students understand fundamental concepts, and (2) exercises that introduce new technology and that have a practical flavor. The latter play a very important role in motivating students; considerable care has been taken to ensure that they are realistic in terms of parameter values and focus on significant aspects of real engineering problems. The practical exercises are first steps in the engineering design process and many have substantial design content. Since environmental considerations have required the phasing out of CFC refrigerants, R-12 and R-113 property data, worked examples and exercises, have been replaced with corresponding material for R-22 and R-134a.

Basic Heat and Mass Transfer complements *Heat Transfer*, which is published concurrently. *Basic Heat and Mass Transfer* was developed by omitting some of the more advanced heat transfer material from *Heat Transfer* and adding a chapter on mass transfer. As a result, *Basic Heat and Mass Transfer* contains the following chapters and appendixes:

1. Introduction and Elementary Heat Transfer

2. Steady One-Dimensional Heat Conduction

3. Multidimensional and Unsteady Conduction

4. Convection Fundamentals and Correlations

5. Convection Analysis

6. Thermal Radiation

7. Condensation, Evaporation, and Boiling

8. Heat Exchangers

9. Mass Transfer

A. Property Data

B. Units, Conversion Factors, and Mathematics

C. Charts

In a first course, the focus is always on the key topics of conduction, convection, radiation, and heat exchangers. Particular care has been taken to order the material on these topics from simpler to more difficult concepts. In Chapter 2 one-dimensional conduction and fins are treated before deriving the general partial differential heat conduction equation in Chapter 3. In Chapter 4 the student is taught how to use convection correlations before encountering the partial differential equations governing momentum and energy conservation in Chapter 5. In Chapter 6 radiation properties are introduced on a total energy basis and the shape factor is introduced as a geometrical concept to allow engineering problem solving before having to deal with the directional and spectral aspects of radiation. Also, wherever possible, advanced topics are located at the ends of chapters, and thus can be easily omitted in a first course.

Chapter 1 is a brief but self-contained introduction to heat transfer. Students are given an overview of the subject and some material needed in subsequent chapters. Interesting and relevant engineering problems can then be introduced at the earliest opportunity, thereby motivating student interest. All the exercises can be solved without accessing the property data in Appendix A.

Chapters 2 and 3 present a relatively conventional treatment of heat conduction, though the outdated and approximate Heissler and Gröber charts are replaced by exact charts and the computer program COND2. The treatment of finite-difference numerical methods for conduction has been kept concise and is based on finite-volume energy balances. Students are encouraged to solve the difference equations by writing their own computer programs, or by using standard mathematics software such as Mathcad or MATLAB.

In keeping with the overall philosophy of the book, the objective of Chapter 4 is to develop the students' ability to calculate convective heat transfer coefficients. The physics of convection is explained in a brief introduction, and the heat transfer coefficient is defined. Dimensional analysis using the Buckingham pi theorem is used to introduce the required dimensional groups and to allow a discussion of the importance of laboratory experiments. A large number of correlation formulas follow; instructors can discuss selected geometrical configurations as class time allows, and students can use the associated computer program CONV to reliably calculate heat transfer coefficients and skin friction coefficients or pressure drop for a wide range of configurations. Being able to do parametric studies with a wide variety of correlations enhances the students' understanding more than can be accomplished by hand calculations. Design alternatives can also be explored using CONV.

Analysis of convection is deferred to Chapter 5: simple laminar flows are considered, and high-speed flows are treated first in Section 5.2, since an understanding of the recovery temperature concept enhances the students' problem-solving capabilities. Mixing length turbulence models are briefly discussed, and the chapter closes with a development of the general conservation equations.

Chapter 6 focuses on thermal radiation. Radiation properties are initially defined on a total energy basis, and the shape factor is introduced as a simple geometrical concept. This approach allows students to immediately begin solving engineering radiation exchange problems. Only subsequently need they tackle the more difficult directional and spectral aspects of radiation. For gas radiation, the ubiquitous Hottel charts have been replaced by the more accurate methods developed by Edwards; the accompanying computer program RAD3 makes their use particularly simple.

The treatment of condensation and evaporation heat transfer in Chapter 7 has novel features, while the treatment of pool boiling is quite conventional. Heatpipes are dealt with in some detail, enabling students to calculate the wicking limit and to analyze the performance of simple gas-controlled heatpipes.

Chapter 8 expands the presentation of the thermal analysis of heat exchangers beyond the customary and includes the calculation of exchanger pressure drop, thermal-hydraulic design, heat transfer surface selection for compact heat exchangers, and economic analysis leading to the calculation of the benefit-cost differential associated with heat recovery operations. The computer program HEX2 serves to introduce students to computer-aided design of heat exchangers.

Chapter 9 is an introduction to mass transfer. The focus is on diffusion in a stationary medium and low mass-transfer rate convection. As was the case with heat convection in Chapter 4, mass convection is introduced using dimensional analysis and the Buckingham pi theorem. Of particular importance to mechanical engineers is simultaneous heat and mass transfer, and this topic is given detailed consideration with a focus on problems involving water evaporation into air.

The author and publisher appreciate the efforts of all those who provided input that helped develop and improve the text. We remain dedicated to further refining the text in future editions, and encourage you to contact us with any suggestions or comments you might have.

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Some of the material in *Basic Heat and Mass Transfer,* in the form of examples and exercises, has been adapted from an earlier text by my former colleagues at UCLA, D. K. Edwards and V. E. Denny (*Transfer Processes* 1/e, Holt, Rinehart & Winston, 1973; 2/e Hemisphere–McGraw-Hill, 1979). I have also drawn on material in radiation heat transfer from a more recent text by D. K. Edwards (*Radiation Heat Transfer Notes,* Hemisphere, 1981). I gratefully acknowledge the contributions of these gentlemen, both to this book and to my professional career. The late D. N. Bennion provided a chemical engineering perspective to some of the material on mass exchangers. The computer software was ably written by Baek Youn, Hae-Jin Choi, and Benjamin Tan. I would also like to thank former students S. W. Hiebert, R. Tsai, B. Cowan, E. Myhre, B. H. Chang, D. C. Weatherly, A. Gopinath, J. I. Rodriguez, B. P. Dooher, M. A. Friedman, and C. Yuen.

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NOTES TO THE INSTRUCTOR AND STUDENT

These notes have been prepared to assist the instructor and student and should be read before the text is used. Topics covered include conventions for artwork and mathematics, the format for example problems, organization of the exercises, comments on the thermophysical property data in Appendix A, and a guide for use of the accompanying computer software.

ARTWORK

Conventions used in the figures are as follows.

 Conduction or convection heat flow

 Radiation heat flow

 Fluid flow

 Species flow

MATHEMATICAL SYMBOLS

Symbols that may need clarification are as follows.

$\simeq$ Nearly equal

$\sim$ Of the same order of magnitude

$|_x$ All quantities in the term to the left of the bar are evaluated at x

EXAMPLES

Use of standard format for presenting the solutions of engineering problems is a good practice. The format used for the examples in *Basic Heat and Mass Transfer,* which is but one possible approach, is as follows.

Problem statement

Solution

Given:

Required:

Assumptions: 1.
2. etc.

Sketch (when appropriate)

Analysis (diagrams when appropriate)

Properties evaluation

Calculations

Results (tables or graphs when appropriate)

Comments

1.

2. etc.

It is always assumed that the problem statement precedes the solution (as in the text) or that it is readily available (as in the *Solutions Manual*). Thus, the *Given* and *Required* statements are concise and focus on the essential features of the problem. Under *Assumptions*, the main assumptions required to solve the problem are listed; when appropriate, they are discussed further in the body of the solution. A sketch of the physical system is included when the geometry requires clarification; also, expected temperature and concentration profiles are given when appropriate. (Schematics that simply repeat the information in the problem statements are used sparingly. I know that many instructors always require a schematic. My view is that students need to develop an appreciation of when a figure or graph is necessary, because artwork is usually an expensive component of engineering reports. For example, I see little use for a schematic that shows a 10 m length of straight 2 cm–O.D. tube.) The analysis may consist simply of listing some formulas from the text, or it may require setting up a differential equation and its solution. Strictly speaking, a property should not be evaluated until its need is identified by the analysis. However, in routine calculations, such as evaluation of convective heat transfer coefficients, it is often convenient to list all the property values taken from an Appendix A table in one place. The calculations then follow with results listed, tabulated, or graphed as appropriate. Under *Comments*, the significance of the results can be discussed, the validity of assumptions further evaluated, or the broader implications of the problem noted.

In presenting calculations for the examples in *Basic Heat and Mass Transfer*, I have rounded off results at each stage of the calculation. If additional figures are retained for the complete calculations, discrepancies in the last figure will be observed. Since many of the example calculations are quite lengthy, I believe my policy will facilitate checking a particular calculation step of concern. As is common practice, I have generally given results to more significant figures than is justified, so that these results can be conveniently used in further calculations. It is safe to say that no engineering heat transfer calculation will be accurate to within 1%, and that most experienced engineers will be pleased with results accurate to within 10% or 20%. Thus, preoccupation with a third or fourth significant figure is misplaced (unless required to prevent error magnification in operations such as subtraction).

EXERCISES

The diskette logo next to an exercise statement indicates that it can be solved using the *Basic Heat and Mass Transfer* software, and that the sample solution provided to the instructor has been prepared accordingly. There are many additional exercises that can be solved using the software but that do not have the logo designation. These exercises are intended to give the student practice in hand calculations, and thus the sample solutions were also prepared manually.

The exercises have been ordered to correspond with the order in which the material is presented in the text, rather than in some increasing degree of difficulty. Since the range of difficulty of the exercises is considerable, the instructor is urged to give students guidance in selecting exercises for self-study. Answers to all exercises are listed in the *Solutions Manual* provided to instructors. Odd- and even-numbered exercises are listed separately; the instructor may choose to give either list to students to assist self-study.

PROPERTY DATA

A considerable quantity of property data has been assembled in Appendix A. Key sources are given as references or are listed in the bibliography. Since *Basic Heat and Mass Transfer* is a textbook, my primary objective in preparing Appendix A was to provide the student with a wide range of data in an easily used form. Whenever possible, I have used the most accurate data that I could obtain, but accuracy was not always the primary concern. For example, the need to have consistent data over a wide range of temperature often dictated the choice of source. All the tables are in SI units, with temperature in kelvins. The computer program UNITS can be used for conversions to other systems of units. Appendix A should serve most needs of the student, as well as of the practicing engineer, for doing routine calculations. If a heat transfer research project requires accurate and reliable thermophysical property data, the prudent researcher should carefully check relevant primary data sources.

SOFTWARE

The *Basic Heat and Mass Transfer* software has a menu that describes the content of each program. The programs are also described at appropriate locations in the text. The input format and program use are demonstrated in example problems in the text. Use of the text index is recommended for locating the program descriptions and examples. There is a one-to-one correspondence between the text and the software. In principle, all numbers generated by the software can be calculated manually from formulas, graphs, and data given in the text. Small discrepancies may be seen when interpolation in graphs or property tables is required, since some of the data are stored in the software as polynomial curve fits.

The software facilitates self-study by the student. Practice hand calculations can be immediately checked using the software. When programs such as CONV, PHASE, and BOIL are used, properties evaluation and intermediate calculation steps can also be checked when the final results do not agree.

Since there is a large thermophysical property database stored in the software package, the programs can also be conveniently used to evaluate these properties for other purposes. For example, in CONV both the wall and fluid temperatures can be set equal to the desired temperature to obtain property values required for convection calculations. We can even go one step further when evaluating a convective heat transfer coefficient from a new correlation not contained in CONV: if a corresponding item is chosen, the values of relevant dimensionless groups can also be obtained from CONV, further simplifying the calculations.

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