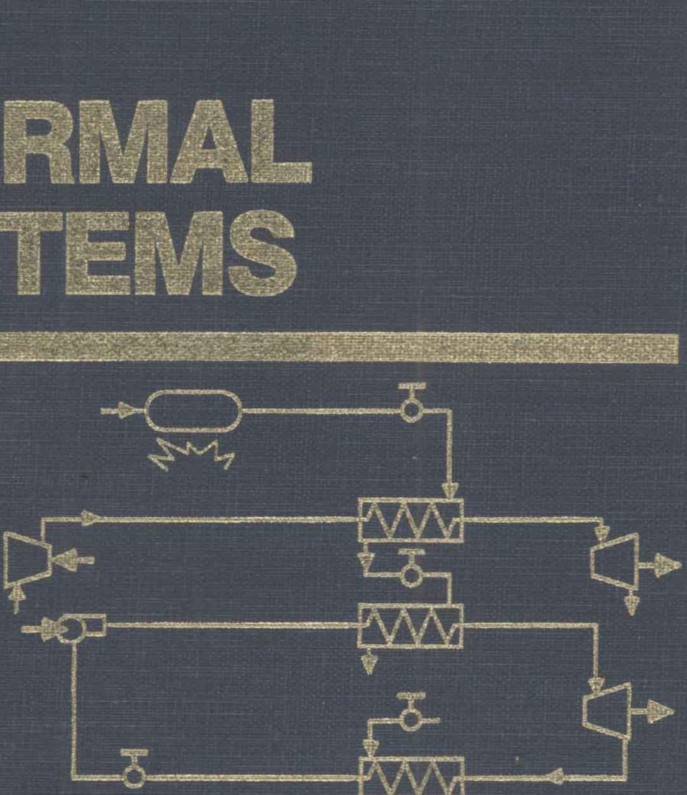
DESIGN ANALYSIS OF THERMAL SYSTEMS



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John Wiley & Sons

New York · Chichester · Brisbane · Toronto · Singapore

To Marcia, Debbie, Chris, and the Corvairs, who keep my life full and my wallet empty.

Library of Congress Cataloging-in-Publication Data:

Boehm, R. F.

Design analysis of thermal systems.

Includes bibliographies and index.
1. Heat engineering. 2. Engineering design. I. Title.
TJ260.B57 1987 621.402 86-32609
ISBN 0-471-83204-9

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

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PREFACE

This book is an outgrowth of my teaching of a senior-level thermal systems design course over the last several years at the University of Utah. Generally, the courses in design are difficult for many people to teach, and this one was that way for me. There were two complicating factors. First, I started putting this course together as a fairly green assistant professor. I had had some industrial experience with a few years at the General Electric Atomic Power Equipment Department (later called Nuclear Energy Division) and a number of summer engineering jobs. But it was still a difficult transition from being a doctoral student to being a professor who is supposed to know all things about all things.

Second, there were new currents moving in the field. Computers were proving their value as an engineering tool in everything from characterizing materials to guiding us to the moon. But it seemed that the field of thermal systems was among the last to reap the benefits of this technology. Certainly there were exceptions. Finite difference and, later, finite element techniques were proving to be key tools in many heat transfer analyses. Modeling of fluid flow in a variety of fields was given a considerable boost from a number of breakthroughs during the space race and the associated technological binge the world was experiencing. Even the modeling of control systems seemed to move along rapidly. Power plants, however, were still designed by "hand." Even today, cooling towers continue to be designed by many companies from graphical techniques developed before most of us can remember.

Hence, to aid my own education on thermal systems, and to see where the field might go if computer-aided design techniques were applied, I began studying this field with more than a little interest. It finally got to the point where the file was overflowing with material, and I had to make the decision to do something with it. In 1984-1985 I went on sabbatical leave and began this book.

A general concept of the course and this book developed quite naturally. In this concept, it seemed that the book should draw heavily on the basic analysis courses that students have in the sophomore, junior, and senior years of their engineering curricula. Second, the text should give insights to some of the practical aspects of design that too often are not found in the analysis courses Overall, the course should generally deal with topics in a computer-aided context. Finally, the student should be introduced to the thermal design literature so that the full power of the various techniques can be studied in detail, if desired.

From my course work in thermal systems design, I had ideas about what specific topics I wanted to include in the text. Of course, there should be a discussion of the practical aspects of equipment selection. Of particular concern were some keys to choices between various types of available heat exchangers. For example, too many students leave school without knowing the difference between a floating-head heat exchanger and a U-tube heat exchanger. I addressed questions of this sort with information on selection criteria and costs in a concise format. In this regard, I appreciated Gael Ulrich (of the University of New Hampshire) allowing me to borrow some of his excellent material.

I felt there should be some information on the old, but newly "rediscovered," topic of availability analysis. Workers around the world were showing the value of this concept for the analysis of complex systems where design choices had to be made between energy in various forms. Of course, the cogeneration example is one that illustrates the concept of economic trade-offs between heat and work, and this is used in the text. I think availability will become more of a generally applied tool as we all better understand the concepts and their power in the solution of a wide range of problems.

Flowsheeting is a topic that is given little thought in the systems analysis performed in an introductory thermodynamics course. However, as the system becomes larger and more complicated, the definition of an appropriate flowsheet can be an extremely critical step in the analysis of a system. Many of the questions involved in setting up an appropriate flowsheet have been addressed in the development of powerful codes like ASPEN, and this is an area where research continues. An introduction to flowsheeting ideas is also included.

One topic that is not often covered in basic courses is costs and their effects on the appropriate design selections. Cost data are very difficult to encapsulate accurately, both at a given point in time and in a few pages of a book. The approach used here is the simplified power function form used in the chemical engineering literature. One of the problems with this approach is that the student may view the limited data to be both precise and all inclusive and thus not be aware of the vast differences in costs that can result from various materials of construction, surface finish, or all of the other aspects that can have profound effects on costs. In spite of all of the admitted limitations, the method presented here is chosen as a good "first-cut" approach to the problem of trying to attach costs to components shown on a block diagram. Even the question of which components' prices should be included is a perplexing one. A large number of types of equipment are given in Appendix D, but key items are almost certainly missing. In spite of this, the problem of gathering cost information to perform preliminary design analysis with this information should be greatly simplified compared with starting from "scratch."

Estimates of future costs of energy are likewise very difficult to predict, but this topic is also important to the choices of design options. The data given here are the best estimates of people who make the prediction of prices in their business. Those of us who have watched energy prices through the 1970s and 1980s know how unpredictable these data can be. As the energy cost estimates included here become more dated, users of the book should seek more current information.

A brief chapter on general economic analysis is included. At many schools, these ideas are covered much more thoroughly in an engineering economy course than is the case in this text.

Numerical analysis topics are covered in the text. Included are curve fitting and equation solving in Chapter 4 and optimization techniques in Chapter 9. These chapters share with all of the others the fact that complete texts have been written on subtopics of each chapter. I have attempted to distill the information to give a qualitative feel for approaches represented by the various techniques. Not all techniques are necessarily included. Some that may be very important to various instructors undoubtedly do not appear. Hence, in these topics, as well as in virtually all others, the instructor should supplement the information given here to emphasize important points to him/her.

Curve fits or other correlation information to be used for the prediction of properties are given in Appendix B. At one time or another, we have all curve fit thermophysical properties. In the tabulations included here, I have attempted to make available published data to simplify this thrust.

From the initial stages of the drafting of this book, the plan was to make it concise and qualitative in its approach to the variety of topics covered. However, I wanted to give the student/worker insight to the rich literature spanning both the mechanical and chemical engineering fields. Hence, you will find that every chapter addresses topics that could be covered in complete texts (most, in fact, are the topic of complete books elsewhere), as well as a number of design related papers that may not have found their way into the archival literature. On the other hand, each references section has many more entries than most students will be inclined to consult. Students will find that this book does not have all the information they may want stated explicitly, but they will be able to find it through the use of this text, if they so desire. Some may not want to be bothered by supplementing this text with library materials, but to understand a given topic fully this will usually have to be done.

Several items are not in the text because they have purposefully been left out. Perhaps most obvious is the almost total lack of concepts covered in engineering fundamentals courses. For example, do not look for treatments of the LMTD or Effectiveness-NTU techniques of heat exchanger analysis. They are not here. This is not to imply that there is no need for this information in a design course, but rather it is a recognition that this information is conveniently available elsewhere to students. In fact, I usually review some of the basic material in this course. There are problems in the most chapters that are of a review nature.

In my view, the most important aspect of the student experience in design is the application of the various concepts in a project setting. The book does not carry this aspect through to completion. Only on a teacher-worker level can this work. Decisions may have to be made at each step of the way regarding directions, approximations, desired results, and so on. We may someday find thermodynamics and other courses taught by programmed learning (through computer interaction or special text), but the application of these learning concepts to the design of systems will be among the last to make this transition. There is no replacing the professor or experienced engineer in the day-to-day development of a design. This text addresses topics that should facilitate the process, but these cannot replace the process.

I want to acknowledge people who were helpful in the development of this text, realizing that not all will be mentioned who should be. It all started with John Wiley & Sons' willingness to take on the project, and I want to thank them first. Engineering editors Bill Stenquist and, later, Charity Robey were great facilitators in the overall process. Numerous people at Sandia National Laboratories, Livermore, where I was on sabbatical leave when the drafting began, were willing to take time from their own to look over preliminary notes and make comments. Chuck Hartwig, Jack Swearengen, Joe Iannucci, Jim Dirks, and others are among those in this group. Sandy Baum, an industrial engineering colleague of mine, looked over the engineering economy section. He eliminated several serious errors I had there. I only wish I could capture his enthusiastic expositions on those topics. A number of students, including the brave ones who took the ME 562 course or assisted me when the notes were developing, are especially appreciated. I note particularly Turhan Çoban.

Most importantly, though, I acknowledge my prime proofreader, wife, and friend, Marcia. She gave considerable amounts of both time and encouragement thoughout the whole process. Without her, this book would not have been completed.

My whole career in general and this book in particular have benefited from the guidance and examples set by several advisers and colleagues. Included are Chang-Lin Tien, John Lienhard IV, Frank Kreith, and H. R. (Bob) Jacobs. Thanks, guys.

A final note. Items that probably should have been included in the text were not. Errors are present, but I do not know where they are now. I will appreciate feedback on both aspects of the book.

May your design experiences be among your best.

January 1987 *Robert F. Boehm*

A Note on the Production of this Text

This text, with the exception of Figures 3-10 and 6-1, was produced entirely on an Apple Macintosh personal computer and printed on an Apple Laserwriter. The computer was the 512 k memory machine with dual single-sided disk drives (affectionately referred to by some as the "hummer"). Software applications used were MacWrite for word processing, MacDraw for rendering the line diagrams, and Microsoft Chart for the plotting done in Chapter 6. In all cases the application Switcher was used to go between other applications and the word processer. Printing was done entirely in Geneva 9, 10, and 12 point fonts with laser font substitution. Final rendering was done on 8 1/2 by 14-in. sheets, which were used for reproduction at Wiley. Appreciation is expressed to the University of Utah for making this equipment available.

About the Author

Robert F. Boehm was born in Portland, Oregon in 1940 and was raised in the state of Washington. He attended Washington State University, receiving a B.S.M.E. degree in 1962 and an M.S.M.E. degree in 1964. He then joined the General Electric Company, Atomic Power Equipment Department. He left GE to pursue a Ph.D. at the University of California at Berkeley where he received the degree in 1968. He then accepted a position at the University of Utah where he is now Professor of Mechanical Engineering. During his tenure at the University of Utah he has served as chairman of the Mechanical and Industrial Engineering Department. The 1984-1985 academic year was spent at Sandia National Laboratories, Livermore, California, where this text was started. He is the author or coauthor of nearly 100 technical articles, 2 other texts, and approximately 10 chapters in texts on heat transfer and thermal systems. Research interests include experimental and numerical heat transfer studies and analysis of thermal systems, with particular emphasis in applications to energy conversion. He is a Fellow of the American Society of Mechanical Engineers and serves as Technical Editor of the ASME's *Journal of Solar Energy Engineering.* Dr. Boehm is a registered professional engineer in the state of California.

CONTENTS

CHAPTER 1

THE DESIGN ANALYSIS PROCESS

1.1 WHAT IS DESIGN?

Much has been written about the topic of design. Design has always been important in all engineering practice, but its relative importance as a distinct field in engineering curricula has ebbed and flowed over the years. Generally, the design process involves the application of concepts from engineering science topics in a generally specified manner coupled with a creative touch.

Successful design is a collection of several processes. First, insight into the desired end result is necessary. This step might be called *conception.* Second, the ways in which that end result might be accomplished must be defined. The term *synthesis* might be applied to this step. Finally, a significant amount of *analysis* is often needed to supplement the first two steps to bring the design to reality. Analysis can also supplement the synthesis function.

The insight noted in the first step depends very strongly on a hard-to-define characteristic called *creativity.* Does a person have creativity at birth, or is it something that can be learned? Since there are numerous successful inventors (invention can be a form of design) who do not have a formal education, it would seem that some people are born with a natural ability in this area. There are varying opinions about whether or not it can be learned. The second step, called synthesis, is obviously very important. It requires both learned information and creative insight. A person can come a long way in setting up a more efficient thermodynamic system by studying the various kinds of processes possible and the factors that influence their efficiency. From time to time, though, creative insight will render a clear breakthrough in a given design. Finally, the third step related to analysis is clearly something that can be learned. The analysis function can find application in the synthesis step, causing a gray area in the definition of these two terms.

Compare distinctions between mechanical design and thermal process design. Like many, this division may be somewhat arbitrary, but it is important to the thrust of this text. Some elaboration on this comparison as well as the elements of the creative aspect in each category are in order.

Suppose that a firm wants to manufacture and sell a new type of mechanical can opener. Suppose further that in order to have a market edge, the new device will have an operational advantage over existing designs and will sell for a competitive price (this may actually be a higher or lower price than the other openers on the market, depending upon the perceived operational advantage of the new design). Creative work must then occur in two areas. First, the operational advantage must be conceived and reduced to practice. Some people think that the creative procedures involved in this step are not, in general, easily categorized or learned. Once a device is designed, the processes used in the manufacturing steps must be determined. Although there are avenues to demonstrate creative genius in these aspects, several dimensions can be developed into a specific technology and can be categorized and learned. If the product is truly successful, hundreds of thousands might be manufactured and sold, so the clever manufacturing of the device may be just as important as its original invention.

In the example of the can opener, as well as other more involved mechanical devices, creative aspects can be the most critical in the device conception stage and can be of somewhat lesser importance in the other facets of bringing the product to the consumer. The relative importance of the upfront creativity is lessened in more complicated mechanical systems and thermal systems where refinement of designs may make up a large portion of the creative process. In these examples, the modeling of the devices or systems may be extremely valuable, enabling the overall improvement of function and performance.

Computer-aided engineering can be of great value in the solution of mechanical design projects. Often this involves a graphical representation of the part or device via the computer. See the left-hand side of Figure 1.1. This can ultimately be used for assisting with the manufacture of the device. In addition, as the design and analysis functions take place, the graphical representations can be used for stress, electric/magnetic field, and/or temperature analyses of the device.

On the other hand, the simulation of thermal systems often involves the synthesis of components into an overall system. See the right-hand side of Figure 1.1. This is a subset of the overall category of process design. In contrast to mechanical design, the computer can be used here to simulate processes. Both fields can share a need for optimization and other types of numerical analysis, but there is a fundamental difference between the two.

Consider applications to the design of thermal devices and systems. A system may be very large and have a single application. An example of this is a giant mine-mouth power plant in Wyoming. Alternatively, it could be some system produced in large numbers, such as a new refrigeration unit to be applied as an automobile air conditioner.

What are some points of contrast between most thermal systems and the simple mechanical devices as illustrated above with the can opener