Thermal Design

Heat Sinks, Thermoelectrics, Heat Pipes, Compact Heat Exchangers, and Solar Cells

HoSung Lee

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Preface

This book is written as a senior undergraduate or a first-year graduate textbook, covering modern thermal devices such as heat sinks, thermoelectric generators and coolers, heat pipes, compact heat exchangers, and solar cells as design components. These devices are becoming increasingly important and fundamental in thermal design in such diverse areas as microelectronic cooling, green or thermal energy conversion, thermal control and management in space, and so on. However, there is no textbook available that includes these topics, which is the rationale for the writing of this book. This book may be used as a capstone design course after students have finished the fundamental courses in areas such as thermodynamics, fluid mechanics, and heat transfer. The concept of this book is to give the student first an understanding of the physical mechanisms of the devices with detailed derivations, and second, practice in designing the devices with use of mathematical modeling, graphical optimization, and occasionally computational-fluid-dynamic (CFD) simulation. This is done through pertinent design examples developed using a commercial software, MathCAD. In other words, the design concept is embodied through the sample problems. The graphical presentation generally provides designers or students with rich and flexible solutions giving the optimal design.

This book is unique as a textbook of *thermal design* with the present topics and design methodology. It has been developed from the author's lecture notes. Since this book exhibits the fundamental framework of thermal design using modern thermal devices, the applications to the thermal systems associated with these devices are unlimited.

This book is self-contained. For example, an introduction to thermal radiation was added prior to the section of *fin design in space* for the readers who are not familiar with this subject. Many appropriate charts and tables were attached in the appendices so that readers need not look at other reference books. Detailed tutorials appropriate for use in CFD and MathCAD homework problems are also included in the appendices to help students.

Particular effort was made to create figures representing key concepts of the subject matter, keeping in mind that "one good figure is better than a thousand words." Needless to say, figures are important learning tools, focus attention and stimulate curiosity and interest.

In the past decade, a good deal of attention has been given to critically assessing traditional pedagogy and to exploring means by which students' learning may be enhanced. With respect to the development of educational tools and curricula, this assessment has stimulated serious consideration of *learning objectives* and the means of determining the extent to which prescribed objectives are being met. This textbook has three learning objectives:

1. The students should delineate physical mechanisms and transport phenomena for any process or system particularly associated with thermal devices such

as heat sinks, thermoelectric generators and coolers, heat pipes, compact heat exchangers, and solar cells.

2. The students should be able to develop mathematical models and graphical optimization for any process or system associated with the thermal devices or systems.
3. The students should be able to professionally design the thermal devices or systems using design tools.

As mentioned before, this book is self-contained. An attempt was made to include necessary background in thermodynamics, fluid mechanics, and heat transfer. Chapter 1 focuses on material needed in later chapters. Students can use this chapter as reference or review. The first and second laws of thermodynamics, internal and external convection flow, and heat transfer mechanisms were presented with essential formulas and empirical correlations.

Chapter 2 is devoted to *heat sinks*, which are the most common thermal devices for use in the electronics industry. They are used to improve the thermal control of electronic components, assemblies, and modulus by enhancing their exterior surface area through the use of fins. The governing formulas on heat dissipation and efficiency for single and multiple fins are derived and incorporated into the modeling and optimization of fin design. Particular effort was given to creating appropriate examples to reflect the design concept, which involves mathematical modeling and graphical optimization. Also in the chapter, fin design with thermal radiation (in space) was explored with two design examples.

Chapter 3 provides the fundamentals of the design of *thermoelectric generators* and *coolers*. The field of thermoelectrics has grown dramatically in recent years, but in spite of this resurgence of interest, there are very few books available. This may be the first book to deal with the design of thermoelectrics and heat pipes, providing the physical principles and fundamental formulas, which lead to mathematical modeling and graphical optimization. This chapter may prompt students to look for the waste energy recovery from the exhaust gases in automotive vehicles and power systems for spacecrafts using radioisotope thermoelectric generators (RTG). A design example at the end of the chapter was conceptualized and developed from a commercial product, which consists of two heat sinks, two fans and a thermoelectric cooler (TEC) module as a thermal system.

Chapter 4 is devoted to the design of *heat pipes*, which have been recently employed in numerous applications ranging from temperature control of the permafrost layer under the Alaska pipeline to the thermal control of optical surfaces in spacecraft. Today every laptop computer has a heat-pipe related cooling system. This book gives a clear understanding of the fundamentals of heat pipes, including the formulas, which allow modeling and optimization in design. This chapter deals with various heat pipes such as variable conductance heat pipe, loop heat pipe, micro heat pipe, and heat pipe in space. The end-of-chapter design example discusses the detailed design aspects: selecting materials and working fluid, sizing the heat pipe, selecting the wick, and performance map.

Chapter 5 discusses the design of *compact heat exchangers* including plate heat exchangers, finned-tube heat exchangers, and plate-fin heat exchangers. In order to discuss these complex exchangers, simpler heat exchangers such as a double-pipe heat exchanger and a shell-and-tube heat exchanger are also introduced. Usually, it takes a semester to cover the entire material of this chapter. However, the complex geometry and time-consuming work are incorporated into the illustrated models. This saves a lot of the students' time. Rather, students can put their efforts either into improving the model or implementing into the system design. Design tools such as MathCAD enable easy and precise minimizing of human errors in calculations.

Chapter 6 is devoted to *solar cell design*. It is often said that solar energy will be the energy in the future. Solar cells need to be developed in order to meet the formidable requirements of high efficiency and low cost. A solar cell is a technology-dependent device, wherein efficiency is a key issue in performance and design. The author believes that solar cells should be dealt with in undergraduate programs, when we consider their importance and huge demand in the future. Unfortunately, a solar cell involves many disciplines: physics, chemistry, materials, electronics, and mechanics (heat transfer). This book was written to provide the fundamentals of solar cells including both the physics and design with a ready-to-use model so that we may achieve our goal in a minimum of time.

Students or teachers should feel free to copy the ready-to-use models to suit their own purposes. This book was designed to provide profound theories and derivation of formulas so that students can easily make modifications or improvements according to their ability. For example, a student who is not strong in physics but is creative can produce a novel design using the ready-to-use models presented in this book.

Except for Chapter 1 ("Introduction"), each chapter is independent from other chapters so that it may be taught separately. Considering the volume of material in each chapter, any combination of three chapters would be appropriate for a semester's material. Chapter 1 may be skipped. For example, a thermal-oriented course would use Chapter 2, "Heat Sinks," Chapter 4, "Heat Pipes," and Chapter 5, "Compact Heat Exchangers." An electronic cooling–oriented course would use Chapter 2, "Heat Sinks," Chapter 3, "Thermoelectrics," and Chapter 4, "Heat Pipes." Intensive design can be sought with Chapter 5, "Compact Heat Exchangers," and Chapter 6, "Solar Cells." This book can be taught for one or two semesters. Note that many problems at the end of each chapter may require at least a week of work by students.

I would like to acknowledge the many suggestions, the inspiration, and the help provided by undergraduate/graduate students in the thermal design classes over the years. I also thank the College of Engineering and Applied Sciences at Western Michigan University for providing me the opportunity to teach the thermal design courses. Particular thanks to the Wiley staff for their support and their editing of the material. I also wish to thank anonymous reviewers for their suggestions and critiques that greatly improved the quality of this book. I am immensely indebted to Professor Emeritus Herman Merte, Jr. for his advice and support in the preparation of this book. My sincere appreciation is extended to Dr. Stanley L. Rajnak for his suggestions and his review in preparation of the manuscript. He reviewed the entire manuscript with his invaluable endeavors particularly finding errors in mathematics. Lastly I am truly indebted to my beloved wife, Young-Ae, for her support and forbearance during the preparation of this book, and also to my lovely daughter, Yujin, for her encouragement and assistance particularly in drawings. Without the supports mentioned above, this book would not be possible.

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