DAVID S.K. TING

# ENGINEERING DESIGN AND OPTIMIZATION OF THERMOFLUID SYSTEMS

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*DAVID S.K. TING*
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*Engineering design is the synthesis of science and art for practical applications. Engineering Design and Optimization of Thermofluid Systems is very much a subset of engineering as described by J.A.L. Waddell, "Engineering is the science and art of efficient dealing with materials and forces … it involves the most economic design and execution … assuring, when properly performed, the most advantageous combination of accuracy, safety, durability, speed, simplicity, efficiency, and economy possible for the conditions of design and service."*

> *The difference between science and the arts is not that they are different sides of the same coin… or even different parts of the same continuum, but rather, they are manifestations of the same thing. The arts and sciences are avatars of human creativity.*
>
> *– Mae Jemison*

> *After a certain high level of technical skill is achieved, science and art tend to coalesce in esthetics, plasticity, and form. The greatest scientists are always artists as well.*
>
> *– Albert Einstein*

*This book is dedicated to the everyday artistic engineers who unceasingly put into effect human creativity to forge a better future for the generations to come.*

# Contents

# Preface

This book is primarily designed for senior undergraduate engineering students interested in Engineering Design and Optimization of Thermofluid Systems. It invokes basic undergraduate mathematics, thermodynamics, fluid mechanics, and heat transfer concepts. The book aims at stimulating every keen mind to appreciate design and optimization of engineering thermofluid systems.

David S-K. Ting
June 20, 2020

# Acknowledgments

This book would have remained an ambitious dream, if not for the overflowing help from above and around the author. From above, timely and sufficient grace inspirited the author all the way through, from onset to finish. The earlier than anticipated completion is nothing short of a miracle. Each and every individual mentioned below played a pivotal yet unique role in this miracle.

The striving and fulfillment of this dream starts at home. The Turbulence and Energy (T&E) Laboratory (http://www.turbulenceandenergylab.org/) is the home for forging enthusiasts into experts, including many artistic engineering experts. These skillful T&E experts are recognized in the captions of their creative figures. Yang Yang and Xi Wang also assisted in overcoming a few technical hurdles that severely tangled the decrepit author. Gnanesh Nagesh deserves a special mention for fashioning the many top-notch figures. Dr. Mehdi Ebrahimi sympathetically furnished practical details associated with the compressed air energy storage project.

The eagle eyes of Dr. Jacqueline A. Stagner captured every tilde littered throughout the manuscript, from Preface to Appendix. Dr. JAS' contribution far exceeds proofreading; she also inspired Project A.7 Desert Expedition in the Appendix. It would be a huge loss if the reader misses the opportunity to time travel with her in Starship T&E.

The recessive gene inherited from mom and dad has made possible the creation of idiosyncratic humor fastidiously placed throughout the book. The author is convinced that environmental factors, i.e., his three sisters, brother, and the enchanting rainforest of Borneo, are to blame for these puns that may be above the appreciation threshold of some readers. The author is aware that he has to work on designing better jokes and optimizing the placement of these buffooneries to maximize students' learning. Another thought-to-be childish dream, the Allinterest Research Institute (https://allinterestresearchinstitute.ca/ ), has bridged daydreaming with reality. Thanks to many naive fantasies, some dreams do become reality.

Mother Teresa is right, "If you want to change the world, go home and love your family." The endeavor was fueled, from the beginning to the end, by love from Naomi, Yoniana, Tachelle, and Zarek Ting. As with all engineering systems, there are many constraints to overcome, so also, true love is woven with many constructive criticisms and sarcasms for the visionary to exercise his faith muscles. The quality of the book was thus substantially enhanced. Surely there is still much room for further improvement. As with optimization, this book has been optimized within the constraints of life. The future is yet filled with hope of eventual perfection, with progressive betterment to tread.

This book is accompanied by a book companion site: www.wiley.com/go/ting

# 1

# Introduction

*To develop a complete mind: Study the science of art; Study the art of science.*
– Leonardo da Vinci

**Chapter Objectives**

- Understand what design and optimization of thermofluid systems mean.
- Differentiate engineering from science.
- Discern development, design, and analysis.
- Become familiar with the design process.
- Be aware of the existing books on thermofluid system design and/or optimization.
- Appreciate the organization and contents of the book.

## Nomenclature

| | |
|---|---|
| HVAC | heating, ventilation, and air conditioning |
| $I_{dir}$ | direct radiation on a horizontal surface |
| KISS | keep it simple, stupid |
| LED | light-emitting diode |
| PV | photovoltaic |
| UWCAES | underwater compressed air energy storage |
| X, x | (design) variables or influencing parameters |
| Y | a variable, the objective function |

## 1.1 What Are Design and Optimization of Thermofluid Systems?

Design and optimization of thermofluid systems are

> the design and, subsequently, optimization of the design of engineering systems involving significant fluid flow, thermodynamics, and/or heat transfer.

To more fully understand Design and Optimization of Thermofluid Systems, we need to clearly comprehend the four main terms:

1) design
2) optimization
3) thermofluid[1]
4) systems.[2]

Within this context,

1) *design* is the creation of an engineering system which will provide the desired result, and
2) *optimization* is taking the workable design one step further, attaining not just a better but the best design.

There usually exist a few unavoidable constraints, putting practical limits within which the optimal design is bounded. The optimal car may be the one performing the best in terms of mileage. For a typical middle-class engineer with four mouths to feed, however, the price of the car may be the deciding factor, limiting the selection to within a low-budget ceiling.

### Example 1.1 *Design a residential solar thermal energy storage system*

#### Given

An engineering student living in a temperate climate region wishes to store the thermal energy harnessed from the sun when it shines during the day, for residential use during the night.

#### Find

An appropriate storage system.

#### Solution

A workable design is running a glycol-water line from the solar thermal collector into an adequately large insulated water tank. Glycol-water is appropriately employed to prevent freezing. The temperature of the stored fluid has to be sufficiently high for the intended usage. Reasonable drops in the temperature from the solar collector to the storage tank and to the delivery end use must be accounted for, as some losses are inevitable.

The initial workable design, however, is probably not the best design as it may occupy the entire basement. The use of phase-change material will probably keep the size in check. Molten salt is also worth exploring, especially when dealing with larger utilization, such as a multiple-housing residence. Comparing different existing options, such as off-the-shelf tank sizes and storage media to achieve the best option is called optimization. Since the budget, as well as the available space for the storage tank, are likely limited, the optimization of the residential solar thermal energy storage system is thus subjected to budget, space, and other constraints.

Example 1.1 hints that a *workable design* does not necessarily need to be the best design. In fact, it typically is not. When the project is adequately large and there are (financial) backings for it, optimization is invoked to deduce the best design. Furthermore, for a company to compete in mass-selling of such systems, progressively better designs which are cheaper to manufacture are

---

[1] The term thermofluid encompasses thermodynamics, fluid mechanics, and heat transfer.

[2] A system is an orderly collection of integrated parts forming a unitary whole. An internal combustion engine is a familiar everyday engineering system.

**Figure 1.1** Workable versus optimal design of electricity-driven household light bulbs. Source: Photos taken by X. Wang and Y. Yang.

necessary. By and large, there will be budgetary, space, and other constraints. Other constraints for a thermal storage tank can be a maximum workable storage temperature, particular charging and discharging rates, etc. In some sense, moving from a feasible design to an optimum design is like progressing from an “ad hoc art and/or experience” to a “systematic scientific artistic endeavor.”

A familiar design versus optimization exemplification is the three types of light bulb for everyday usage, see Figure 1.1. The incandescent light bulb is a workable design, and it has been satisfying our need since Thomas Edison invented it in 1879. Much later, the fluorescent light bulb is optimized in terms of energy usage and cost. For this reason, the compact fluorescent light bulb has finally squeezed out its archetype after being in the market for a couple of decades, the duration for the price to drop to a competitive level. Over the long run, the LED (light-emitting diode) light bulb is the best, because the money saved due to its low wattage and very long life span far exceed the high initial cost. In short, the incandescent light bulb, with a typical life span of 1,000–2,000 hours, is a workable design. The compact fluorescent light bulb, which lasts on the ballpark of 10,000 hours and uses around 75% less energy, is currently the optimum design. The LED light bulb, which outlasts the fluorescent by up to 50,000 hours while using 90% less energy, is the fruit of the latest design and optimization endeavor, and it is expected to be the new optimum design in a few years, as its manufacturing cost drops.

## 1.2 Differentiating Engineering from Science

The challenging tasks associated with thermofluid systems’ design and optimization are only to be executed by individuals well educated and trained in engineering, i.e. competent engineers. But what is engineering? How does it differ from science? Science may be defined as the systematic knowledge of the physical world that is testable, repeatable, and predictable. Concisely,

> *Science* is the systematic knowledge of the physical world.

Simply put,

> *Engineering* is putting science into practice.

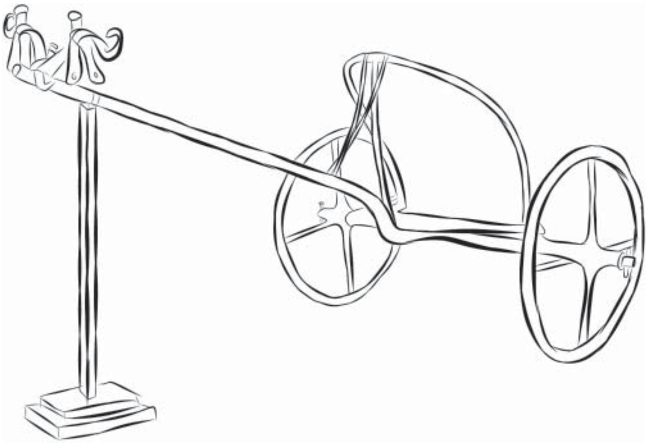

**Figure 1.2** The millennia-old spoked wheel for horse chariots (created by S. Akhand). Shown are four-spoke chariot wheels resembling those found in the Red Sea, which are attributed to the powerful Egyptian army, as recorded in Exodus, Chapter 14.

By and large, engineering was initiated for, and still is, the exploitation of science to create practical systems to make life easier for society. In relation to the context of the material covered in this book,

> Engineering is the science and art of efficient dealing with materials and forces … it involves the most economic design and execution … assuring, when properly performed, the most advantageous combination of accuracy, safety, durability, speed, simplicity, efficiency, and economy possible for the conditions of design and service.
>
> J.A.L. Waddell

Let us look briefly at the millennia-old wheels, sketched in Figure 1.2. Horse chariots date further back than the Old Testament, where the Pharaohs were largely feared because of their vast number of powerful horse chariots. Durable wood was the material adopted, and the forces at play included the load on the chariot and the required torque. As per “economic design and execution,” the wood has to be readily available locally, or relatively accessible and affordable to acquire from a not-too-distant land, or from subject nations as tributes under one’s dominance. Accuracy may be viewed as the wood that does not expand or contract excessively with moisture and/or changes in the weather. Safety and durability may be perceived as keeping the soldiers from falling off as they charge the chariots forward into partially-rocky or muddy fields[3] at great speeds. Note that speed, to a large extent, decides the fate of the riding warriors. Simplicity and efficiency can easily be inferred from the spoke design, including the number of spokes. This becomes particularly obvious when contrasted with the predecessor of the spoked wheels, the clumsy, spoke-less, solid wood wheels; see Figure 1.3. For war chariots, securing sharp weapons on the outer side the (spoked) wheel further illustrates ingenious, effective design for the intention.

Further to the differentiation between science and engineering, a scientist is an expert in science, whereas an engineer creatively converts the scientific findings into useful applications. A good scientist indiscriminately strives to improve all kinds of knowledge, irrespective of any potential

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[3] It is worth mentioning that these powerful chariots can become handicapped on muddy and/or hilly ground. For this reason, foot soldiers prevail in mountainous battlefields.

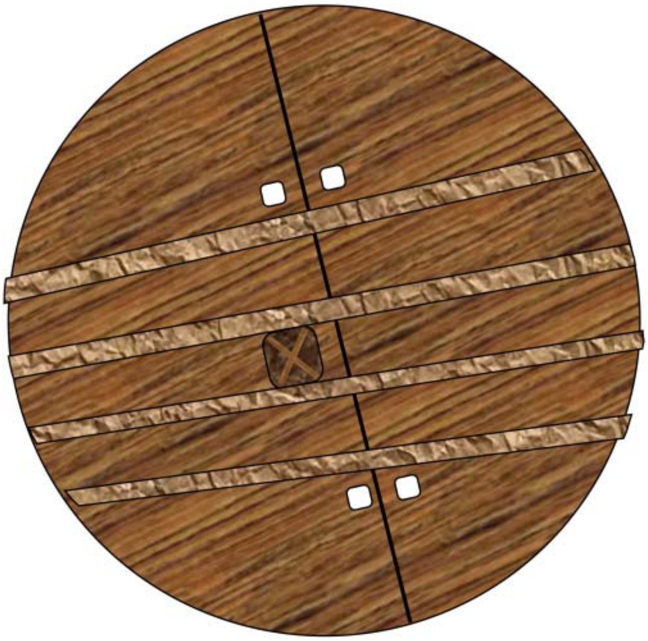

**Figure 1.3** A sketch of, presumably, the world's oldest wheel, the Ljubljana Marshes Wheel, found in the Ljubljana Marshes in 2002 (Gasser, 2003). It has been radiocarbon-dated to before 3100 BCE. Source: Y. Yang.

usage, of the physical world. An applied scientist undertakes only applications-oriented scientific endeavors. This includes an engineering researcher who develops ideas that advance the frontiers of knowledge but may not be applied for a number of years. In other words, good engineers are not short-sighted; the prospective applications need not be immediately cognizable. Engineers may be regarded as professionals who design and develop, creatively converting theoretical concepts into useful applications on a daily basic. What exactly do engineers do? They link theory with practical applications. Bona fide engineers possess an extensive theoretical knowledge, the ability to think creatively, and a knack for obtaining practical results. The materials covered in this book aim at fostering the forging of amateur engineering students into fully-fledged creative engineers. While thermofluids is the subject of coverage, much of the knowledge delineated in this book, especially the core element, optimization, can equally be employed to improve solid mechanics and also process and production line processes. The aforementioned wheels for horse chariots clearly fall under the solid mechanics, not thermofluids, stream. Designing sound wheels for muddy thoroughfares, however, would encompass solid mechanics, thermofluids, and dynamics.

## 1.3 Development, Design, and Analysis

*Development* is the initial phase of an intended venture, where different methods through which a project may be realized are explored, analyzed, compared, and tested. Once the basic method is decided, design takes place. *Design* is the establishment of the exact way the various relating parts are to be put together so that the entire system functions properly. It generally involves the employment of concepts from engineering science coupled with a creative touch to make it work, and work elegantly. As such, to design is to create, devise, and/or forge artistically. To design is to invoke fundamental principles to an open-ended problem to procure one or more possible solutions. This is different from *analysis*, which is the application of fundamental principles to a well-defined problem to attain the solution. Note that there is a lack of openness and creativity in analysis.

## 1.4 The Design Process

In general, the design process may be roughly divided into the following steps.

1) *Identify the need*. What is the problem we have to solve? Keep in mind that engineers are problem-solvers.
   Let us assume the need is the stabilization of an intermittent renewable energy grid.
2) *Conception*. Establish an insight into the desirable end result and define the project.
   The end result is a stable grid which balances supply with demand.
   Energy storage can be utilized to mitigate the intermittence of the existing renewable energy grid.
3) *Synthesis*. Synthesize one or more possible ways to accomplish the end result.
   Pumped hydro, compressed air, underwater compressed air, flywheel, battery, hydrogen, etc., or a combination of some of these are all possible solutions. Assume that we wish to explore the underwater compressed air option as there is a body of water available, but not the elevation to permit pumped hydroelectric storage. Put the major pieces such as the motor, the compressor, the piping network, the underwater accumulator, the expander, and the generator together. Note that to realize this, the engineer should have acquired the required knowledge essential to the pieces of the engineering system puzzle involved.
4) *Operation conditions and limits*. Outline the operating conditions and spell out the constraints.
   Estimate the values of the major parameters. Storage capacity: how much energy storage is needed? What are the required storing and discharging rates? Storage duration: how long should the energy be stored? How much money can be spent? How deep is the water?
5) *Analysis*. Analyze the conceptual solution to deduce its feasibility. If it is infeasible, evaluate alternative plan(s). Analytical, numerical, or experimental analyses may be invoked.
   Perform the basic thermodynamics and fluid mechanics analyses. For example, are the available depth and volume of water adequate?
   Construct and test a pilot-scale system. Perform a parametric study, if appropriate and feasible.

**Example 1.2** ***Design a daily routine for maximizing life span***

### Given

A large pool of data correlating exercise and diet with life span of a typical human being is available.

### Find

The healthiest (longest) life span of an average human being, based on the available data.

### Solution

1) The objective function, $Y$ = life span.
2) $Y = f(X_1, X_2)$, where $X_1$ is the number of hours of exercise per week, and $X_2$ is the amount of food in kilograms consumed every week.
3) In the considered case, $X_i = x_i$, and thus, $Y = f(x_1, x_2)$.

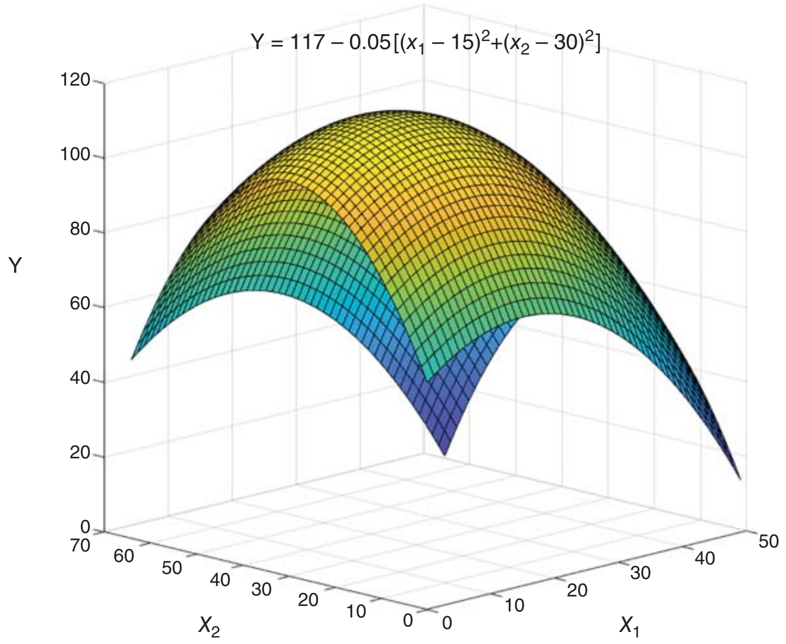

**Figure 1.4** Life span as a function of exercise and diet. Source: Y. Yang.

4) $0 < x_1 < 63$ hours, $0 < x_2 < 77$ kg.
   The premise is that only someone who is dead is doing absolutely no exercise. Also, no one can work out for more than 63 hours (9 hours per day) every week. Furthermore, an average human being has to eat at least some food every day to stay alive, and no one can consistently consume more than 77 kg (11 kg per day) of food every week. In other words, an individual is expected to expire outside of these limits.

After compiling the available data, curve (surface) fitting leads to

$$Y = 117 - 0.05\ \left[(x_1 - 15)^2 + (x_2 - 30)^2\right]$$

This is plotted in Figure 1.4.

We see that the longest life span is 117 years, i.e., $Y = 117$ years at $x_1 = 15$ hours and $x_2 = 30$ kg.

It is noted that in this design, which happens to be the optimization of human life span, type and intensity of the exercise and contents of the food have not been considered. Other design parameters, such as quantity and quality of sleep, also demand our attention. The mental, psychological, or spiritual aspects also come into play, not to mention our typical complaint regarding our many problems associated with the inheritance of some bad genes.

One could protest that 117 years is simply too old to be considered as a good optimum, and dyeing of hair, along with cosmetic surgery etc., can only uplift the façade. This is very much in line with the view of Steve Jobs, who argued that "Design is not just what it looks like and feels like. Design is how it works." The sound functioning of the life span optimization stratagem is built into this groove. In other words, if a 100+year-old person can perform a couple of hours of sound exercise, along with savoring a couple of kilograms of victuals every day, the individual must also have no problem conducting the regular washroom business, and thus, the living being is not old but lively. Pointedly, the design is working!

In real life, it is not always feasible to optimize the design, especially under the pressure of money and time, both are essential for the survival of the company. Nevertheless, engineers should adopt the habit of striving for quality in their designs. Steve Jobs correctly said, "Be a yardstick of quality. Some people aren't used to an environment where excellence is expected."

### Example 1.3 *Stabilize the intermittent renewable energy grid*

**Given**

The increase in renewable energy into the power grid causes a heightened grid stability challenge. To rephrase it, the sporadic supply of natural energy, such as that harnessed by a wind turbine, mismatching with irregular demand introduces unprecedented challenges.

**Find**

A solution to mitigate the grid intermittence.

**Solution**

Possible steps in the design and optimization process are:

1) Identify the need.
   To stabilize the intermittent renewable energy grid.
2) Develop a conceptual solution.
   Battery, compressed air, hydrogen, flywheel?
3) Estimate values of major parameters.
   How much energy/power? For how long (storing, releasing)? How much will it cost?
4) Construct, test, and modify.
   Try out a scaled model.
5) Management and financial review.
   Financially feasible? Environmentally acceptable?
   The cost may depend on the size and the volume (numbers of units to be sold), and the length of the payback period.
6) Refine and optimize parameters.
   Efficiency is a major concern, how and how much can we improve; availability/cost of materials used, size, number of accumulators, etc.?
7) Field test for meeting performance, reliability, and safety goals.
   UWCAES (underwater compressed air energy storage) prototype, identifying shortcomings, opportunities for improvement.
8) Manufacture and market.
   Sampling/monitoring users' experiences – failure rates, failure modes, life expectancy, etc.

Iterate as needed.

A good engineer should never forget common sense. Sketching the disposition of physical parts and possible relative positions is generally a valuable aid. The KISS (Keep It Simple, Stupid) design philosophy is always a helpful guide. As the case may be, it seems like some advanced thinking is required to keep it simple. Richie Norton stated that, "Simplicity is complex. It's never simple to keep things simple. Simple solutions require the most advanced thinking." There is an upper limit, beyond which we would be overdoing it. This is nicely put by Albert Einstein, "Make everything as simple as possible, but not simpler."

## 1.5 Existing Books on Thermofluid System Design and/or Optimization

Some existing books which expound, with varying degree of details, on particular aspects of the materials discussed in this book include:

Arora, J.S. (1989). *Introduction to Optimum Design*. New York: McGraw-Hill.
Balaji, C. (2011). *Essentials of Thermal System Design and Optimization*. New York: CRC Press.
Bejan, A., Tsatsaronis, G., and Moran, M. (1996). *Thermal Design and Optimization*. New York: John Wiley & Sons, Inc.
Boehm, R.F. (1987). *Design Analysis of Thermal Systems*. New York, John Wiley & Sons, Inc.
Burmeister, L.C. (1998). *Elements of Thermal-Fluid System Design*. Upper Saddle River, NJ: Prentice-Hall.
Dhar, P.L. (2016). *Thermal System Design and Simulation*. Cambridge, Academic Press.
Edgar, T.F. and Himmelblau, D.M. (1988). *Optimization of Chemical Processes*. Part II. Boston, McGraw-Hill.
Jaluria, Y. (1998). *Design and Optimization of Thermal Systems*. New York McGraw-Hill.
Penoncello, S.G. (2015). *Thermal Energy Systems: Design and Analysis*. Boca Raton, FL: CRC Press.
Stoecker, W.F. (1989). *Design of Thermal Systems*, 3rd ed. New York: McGraw-Hill.
Suryanarayana, N.V. and Arici, Ö. (2003). *Design and Simulation of Thermal Systems*. New York: McGraw-Hill.

Arora (1989) and its later versions are very comprehensive and far-reaching in scope, covering a wide range of engineering designs, including many non-thermofluid systems. The optimization methods covered in Balaji (2011) are somewhat unconventional. Bejan et al. (1996) offer a more advanced book which is not quite suited for an undergraduate engineering curriculum. While the title of Boehm's (1987) book does not spell out optimization, it is briefly covered as the final chapter. Edgar and Hummelblau's book (1988) is a specialized monograph geared for chemical engineering students. Burmeister (1998), Dhar (2016), Jaluria (1998) and their newer editions, and Stoecker (1989) are probably the four textbooks which are closest to covering the subject matter on design and optimization of thermofluid systems, with Stoeker (1989), or, more correctly, its first edition published by McGraw-Hill in 1971, as the classic text. Penoncello (2015) deals extensively with thermal systems analysis and design. Optimization is only briefly mentioned in the last chapter. It is worth noting that the second edition of this book is also available (Penoncello, 2018). Suryanarayana and Arici (2003) comprehensively review thermodynamics, fluid mechanics, and heat transfer, but optimization is not included in their textbook. There are other books on design and/or simulations of thermofluid systems. They, however, do not typically cover optimization. This book aims at balancing the coverage of the essential elements; engineering economics, the prevailing thermofluid systems and devices and their modeling, and generic and selected advanced optimization methods.

The following books may also be of interest:

Fox, R. (1971). *Optimization Methods for Engineering Design*. Reading, MA: Addison-Wesley.
Goldberg, D. (1989). *Genetic Algorithms in Search, Optimization, and Machine Learning*. Boston: Addison-Wesley.
Rao, S. (1996). *Engineering Optimization*. New York: Wiley-Interscience.

## 1.6 Organization of the Book

Money talks and, thus, basic engineering economics is conveyed in Chapter 2. Common thermofluid devices such as valves, ducts, pipes, and fittings are reviewed in Chapter 3. Chapter 4 presents the fundamentals of heat exchangers. The focus is on the most prevailing indirect-contact heat exchangers. To enable modeling, the system under consideration must be accurately described by mathematical equations. Therefore, equations are covered in Chapter 5, where pertinent curve fittings are highlighted. Once the mathematical model is established, we move on to thermofluid system simulation in Chapter 6. Most prevalent, robust sequential, and simultaneous solution methods are expounded. With the functioning of the system simulated, the problem can be formulated for optimization. Chapter 7 delineates the formulation of the concerned system, clearly defining the objective function and relevant constraints. For differentiable objective functions, the calculus approach discussed in Chapter 8 can nail the optimum via rigorous differentiation. For constrained problems, the Lagrange Multiplier can convey the sensitivity of the solution with respect to modest relaxation of, or changes in, the constraint. The beef of the curriculum is Chapter 9, where the standard search approaches are detailed. With the bullet-proof Exhaustive Search as the base, versatile single-variable elimination methods, Dichotomous Search, the Fibonacci search and the Golden Section search are explained. For multi-variable problems, Lattice Search, Univariate Search, Steepest Ascent/Descent methods are viable for unconstrained problems. Penalty-function and Search-along-a-constraint methods can be resorted to for constrained multi-variable problems. For thermofluid systems, the objective function and the constraints can often be expressed as sums of polynomials. As elaborated in Chapter 10, geometric programming is especially suited for solving this kind of problems. A few large-scale, real-world, as well as some envisioned, projects are included in the Appendix.

## Problems

**1.1 Hot water storage**
Assume that the necessary storage energy for Example 1.1 is 2 kJ and water is the medium. How big is the required storage tank?

**1.2 Water temperature leaving a solar thermal collector**
The solar radiation is 1500 W/m$^2$. Water ($c_p \approx 4.2$ kJ/kg·K) at 12°C enters a solar thermal collector at 0.1 kg/s. The available surface area for collecting the solar radiation is 20 m$^2$. What is the (ideal, maximum) temperature of the water leaving the solar collector?

**1.3 Sizing a solar thermal water tank**
Assume the daily solar irradiance (direct radiation on a horizontal surface), $I_{dir}$, for Los Angeles is equal to that of May 1, 1990 as summarized in Table 1.1.

**Table 1.1** Solar irradiance for Los Angeles on May 1, 1990.

| Time | 8:00 | 9:00 | 10:00 | 11:00 | 12:00 | 13:00 | 14:00 | 15:00 | 16:00 | 17:00 |
|---|---|---|---|---|---|---|---|---|---|---|
| $I_{dir}$ [kJ/h·m$^2$] | 109 | 915 | 1332 | 2108 | 2480 | 2889 | 2521 | 1821 | 837 | 128 |

Design a solar thermal system (collector) to supply 0.003 $m^3/s$ of 50°C hot water between 9:00 a.m. and 3:00 p.m., where the makeup water is at 20°C. What is the required collector area? If the maximum available collector area is 200 $m^2$, what is the size of the required hot water storage tank?

### 1.4 Battery storage for a solar photovoltaic system

Assume the daily solar irradiance (direct radiation on a horizontal surface), $I_{dir}$, for Los Angeles is equal to that in Table 1.1. Design a solar photovoltaic (PV) system using common commercial PV panels to supply a total of 10 kJ of electricity in a day. How many panels are needed? What is the required area? If the maximum available collector area is 200 $m^2$, and a minimum of 1 kW of power is needed between 9:00 a.m. and 3:00 p.m., what is the size of the required battery storage?

### 1.5 Improve the horse chariot wheels

You are asked to improve the design of a horse chariot such as that for the powerful biblical pharaoh. How would the performance of the horse chariot vary with the number of spokes, say, from 2 to 200 spokes? What is the proper sequence concerning development, design, optimization, and research? What do you call the process of varying the number of spokes in an effort to improve performance?

### 1.6 Thermoelectric wristwatch

Design a wristwatch that runs on thermoelectric power based on the temperature difference between the human body and the ambient temperature. Follow the steps delineated in this chapter. Estimate the needed power and size the thermoelectric power generator accordingly. See Synder (2019) for an overview of this sexy technology.

### 1.7 Sleeping Beauty's life span

Suppose additional data on sleeping hours and life span is available, modify the equation in Example 1.2 to include $x_3$, the number of hours of sleep per month. Create a new equation so that the same maximum life span is achieved at $x_3 = 240$ hours.

### 1.8 Water transport network

Water from a reservoir is to be transported at 0.07 $m^3/s$ via a 15-cm diameter commercial steel pipe piping network with three flanged elbows and to be discharged into the open atmosphere at 25 m above the free surface of the water in the reservoir. A pump is to be located at 5 m below the free water surface. What is the required head which needs to be supplied by the pump?

Hint: Invoke the conservation of energy for pipe flow. The equations can be found in Chapter 3 on Thermofluid Devices, where fluid transport in a piping network is recapped. For example, from the inlet of the pump to the discharge outlet into the open atmosphere at 25 m above the free surface of the water in the reservoir, conservation of energy can be written as

$$P_1/\rho g + ½U_1^2/g + z_1 + h_{pump} = P_2/\rho g + ½U_2^2/g + z_2 + h \qquad (1.1)$$

where P is pressure, ρ is density, g is gravity, U is average velocity, z is elevation, $h_{pump}$ is head supplied by the pump, $h_L$ is head loss associated with the piping network. The head loss consists of the major head loss in the straight pipe sections and the minor head loss associated with the fittings. The major head loss can be deduced from

$$h_L = f \left(L_{pipe}/D\right) \left(\tfrac{1}{2}U^2/g\right) \tag{1.2}$$

where f is the friction factor, and D is the diameter of the pipe. The minor losses can be estimated from

$$h_{L,minor} = K_L \; \tfrac{1}{2}U^2/g \tag{1.3}$$

where $K_L$ is the loss coefficient.

**1.9 Storing energy underwater**
An underwater air accumulator is needed to store 70 kJ of energy during the low-demand hours when there is plenty of wind to harness energy from a wind turbine. Provide two workable options in terms of the size of the accumulator and the depth at which it is placed underwater. See Wang et al. (2016) to appreciate the background of this promising technology.

**1.10 Cool a solar photovoltaic panel to boost efficiency**
The energy conversion efficiency of a solar photovoltaic (PV) panel is known to decrease as the PV cell temperature increases (Wu et al., 2018; Fouladi et al., 2019; Yang et al., 2019). Devise a passive turbulence generator which can effectively lower the cell temperature by 2°C, at solar noon on July 1, in Windsor, Ontario, Canada, or the location where you reside, assuming that the wind is prevailing at 7 m/s over the PV panel.

**1.11 Renewable water desalination system**
Design a workable renewable energy system for remote water desalination for a typical family of four in Bathurst Inlet, Nunavut, Canada. Soni et al. (2017) estimated a typical case for India with approximately 100 liters of water consumption per capita per day. They presented a simple four-stage still for the water desalination process based on reduced vapor pressure. Their wind and solar driven system for a solar flux of 850 W/$m^2$ for six hours a day and 1–5 m/s wind can meet the fresh water needs of rural and urban communities.

**1.12 Seasonal thermal storage for a heating greenhouse**
Design a seasonal thermal energy storage system for heating a one-acre greenhouse in South Western Ontario, or another temperate location. For the South Western Ontario setting, see Semple et al. (2017).

## References

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