DAVID S.K. TING

ENGINEERING DESIGN AND OPTIMIZATION OF THERMOFLUID SYSTEMS

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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.

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

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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 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.”

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

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.

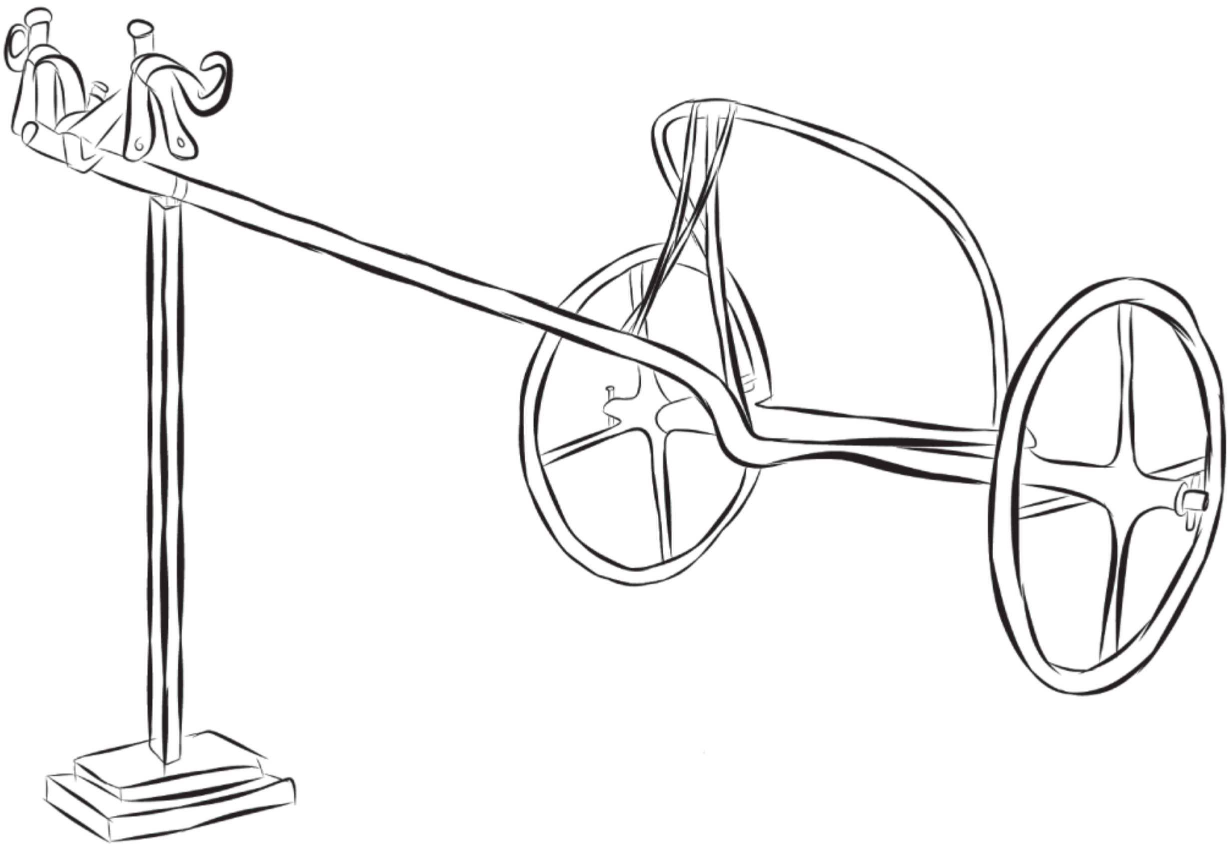

Figure 1.2 The millennia-old spoked wheel for horse chariots (created by S. Akhand). Shown are four-spoke chariot wheels resembling those found in the Red Sea, which are attributed to the powerful Egyptian army, as recorded in Exodus, Chapter 14.

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 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.