

1 Introduction

The “big picture” mentioned at the conclusion of the Preface can be best described in an analogy to the Russian nesting doll (*matryoshka*) comprising a set of wooden dolls of decreasing size placed one inside another.

- The biggest, outermost doll is the electric power industry.
- The second doll represents heat engines in electric power generation.
- The third doll represents gas turbine power plants in the realm of heat engines.
- The fourth doll is the gas turbine itself.
- The fifth to seventh dolls are major gas turbine components: compressor, combustor, and expander.
- The remaining dolls represent individual building blocks of each component: vanes, blades, disks (wheels), combustor cans, tie rods, turbine rings, etc.

Consider a design engineer working on the first turbine stage stator vane design using a proprietary 3D computational fluid dynamics code. In case you are wondering, original equipment manufacturers (OEMs) deploy teams of engineers for the stage-by-stage design of an advanced gas turbine’s “hot gas path.” Each engineer, many of them with PhDs in thermofluids from prestigious universities, specializes in one part among many using highly complex software to solve, say, the full Reynolds-averaged Navier–Stokes equations in three dimensions, which describe the flow of hot combustion gas across rows of vanes and blades in each stage of the turbine. It is easy to imagine the requisite skill and knowledge to perform such tasks adequately.

Yet even more knowledge and skill (and experience) are required to assess the impact of a particular tweak to, say, the stage 1 nozzle vane geometry on the efficiency and output of the gas turbine in question, in a simple or combined cycle, and, in turn, the impact of said gas turbine’s operation in the field on the overall generation portfolio’s, say, carbon footprint.

This book is not about how to design a particular part; there are tomes written on the underlying theory of governing aerothermodynamic principles (they will be mentioned later in the book). Specialized and highly proprietary knowledge is available in OEM design practices, theory manuals of specific software packages, and, to a certain extent, in archival papers published in academic journals (containing mostly results and few background details). Even if one is armed with all of these tools and resources, nobody sets out to design an entire heavy-duty industrial or aeroderivative gas turbine (or one of

its components or one of the parts thereof) from a proverbial “blank sheet” on his or her own anymore.

This book is about the first four “dolls” of the *matryoshka* described above. The fifth to seventh dolls will be covered in sufficient detail for one to gain a good grasp of the impact of particular design decisions on the first four. Finally, the remaining dolls will be touched upon briefly mainly to illustrate where the technology is, where it came from, and how far it can go.

Electric power is the lifeblood of contemporary human civilization. Electricity consumption per capita is shown to have a strong correlation with key social development and economic indices (i.e., human development index, gross domestic product per capita, etc.). This simple fact is both a boon and a bane simultaneously, as evidenced by the great disparity between developed and underdeveloped countries. Consider that China and India, two up-and-coming countries with populations well above one billion each, lag well behind, say, the USA in this key measure: about 4,000 and 600 kWh/person for China and India, respectively, vis-à-vis more than 12,000 for the USA! There is increasing concern that the unstoppable striving of these two giants of the so-called Third World toward a better life standard will push fossil fuel-based electricity production to levels where the global drive to limit carbon dioxide emissions will become an exercise in futility. It is not a stretch to assume that readers of these lines are already well versed in the dangers of global warming and its connection to anthropomorphic greenhouse gas emissions, of which CO₂ is by far the biggest culprit.

This brings us to the subject of electric power (or electricity) generation from burning a particular fossil fuel – namely, natural gas – in advanced gas turbine-based power plants. At the time of writing, natural gas-fired power plants, primarily in the form of combined cycles, are by far the most efficient means of electric power generation via combustion of fossil fuels. Their *rated* performance (i.e., similar to the sticker performance of a passenger car) is more than 60 percent net thermal efficiency at power outputs of 500–1,000 MWe or even more. Best-in-class power plants can reach 56–57 percent thermal efficiency during actual field operation. The average efficiency of all natural gas-fired power plants in the USA in 2015 was about 46 percent, vis-à-vis about 33 percent for all coal-fired plants (as reported by the US Energy Information Administration [EIA]). Furthermore, in terms of specific CO₂ emissions (i.e., pounds of CO₂ emitted per MWh of electricity generated), coal-fired generation is by far the worst culprit, at nearly 150 percent more than that by natural gas-fired generation (again, in 2015 per the EIA).

In 2015, natural gas and coal each accounted for about a third of all US electricity generation, with more than 1,700 power plants utilizing the former and more than 500 power plants utilizing the latter. Almost all natural gas-fired power plants are based on gas turbine technology. Finally, in several months of 2016, US natural gas-fired electricity generation surpassed coal-fired generation. The top two driving factors leading to this trend are low natural gas prices due to the shale gas boom and the much more favorable emissions characteristics of natural gas vis-à-vis coal and all other types of fossil fuels.

Increasing penetration of intermittent renewable technologies (i.e., solar and wind) into the electricity generation portfolio requires readily available backup from fossil fuel-fired generating capacity. In the USA, the contribution of wind and solar to electricity generation in 2015 was about 5 percent (mostly from wind). When wind stops blowing, especially on short notice, the most efficient, clean, and fast-responding power plants to pick up the slack are natural gas-fired gas turbine power plants. In the early years of the second decade of the twenty-first century, this dynamic was thought to be a very important driver of gas turbine-based electricity generation.

In the age of the Internet, it is pointless to cite a lot of statistics, which will be obsolete within the span of a few years (if not sooner), in a print book. All sorts of numbers are readily available online. Barring a “black swan” event of a catastrophic nature (e.g., an accident associated with shale gas extraction via fracking leading to huge loss of life) or of a fortuitous one (e.g., successful culmination of cold fusion research into the large-scale commercialization of it in electric power generation), heavy-duty industrial gas turbines will play a significant role in electric power generation in the USA, Europe, and many other places in the world in the remainder of the twenty-first century.

Nevertheless, it is difficult to guess the magnitude of the aforementioned “significant role.” Around 2010, it was foreseen that there would be about 300 large gas turbines sold each year, but in 2013, just 212 were ordered worldwide. In 2017, this number was 122. Major OEMs reported declining sales and, even worse, the most advanced turbines were being sold at no margin or sometimes at a loss. At the time of writing (late 2017), it is difficult to gauge whether the decline in industrial gas turbine sales is just a cyclical problem or whether there is a structural problem in the industry.

The underlying technology is more than a century old and its basic features are not expected to change drastically. There are many excellent treatises of the gas turbine theory out there, going back to the monumental work of Aurel Stodola in the early twentieth century. This book does not intend to retread the path of giants in the field. In fact, they constitute the foundation with which any serious student of the subject matter must be familiar. Herein, core scientific principles of mechanical, electrical, operational, and economic aspects of the land-based gas turbine generator are going to be distilled into easily usable “bites” to help the practitioner and student alike in their daily work.

The book is divided into four parts (plus Appendices):

- I. Prerequisites
- II. Fundamentals
- III. Extras
- IV. Special Topics

Part I includes material that the reader must be familiar with in order to derive the maximum benefit from the book and ends with a brief history of the gas turbine (Chapter 4). This chapter will start with three “vignettes” covering three historical gas turbines.

It is interesting to note that the concept of a gas turbine has been around much longer than is commonly realized. In his treatise *Mathematical Magick* of 1648 (a second

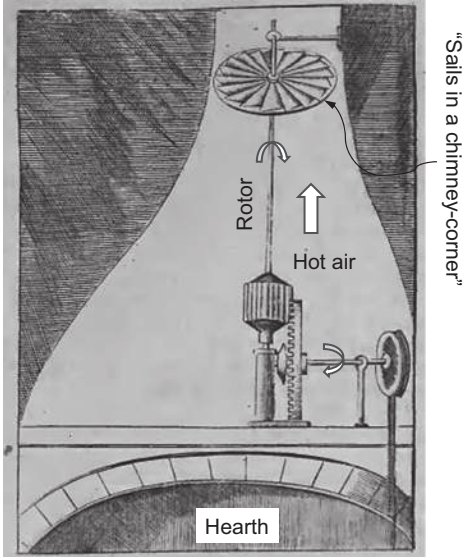


Figure 1.1 “Chimney gas turbine” described by John Wilkins, Lord Bishop of Chester.

edition was published in 1683), English clergyman, natural philosopher, polymath, and author, John Wilkins (1614–1672), Lord Bishop of Chester, described “a better Invention to this purpose, mentioned in Cardan, whereby a Spit may be turned (without the Help of Weights) by the Motion of the Air that ascends the Chimney.”¹ The “moving of Sails in a Chimney-corner” (i.e., a “chimney gas turbine”), as depicted in Figure 1.1, is the purpose that Wilkins refers to.² Bishop Wilkins indicated that the “invention” was mentioned in the 1559 treatise *De Varietate Rerum* by the Italian polymath, Gerolamo Cardano (“Cardan” as Wilkins calls him), who is well known for his achievements in algebra, but was also an inventor of mechanical devices such as the combination lock. While the contraption in Figure 1.1 is unmistakably a gas turbine, the aforementioned “vignettes” are bona fide examples of turbomachinery, which laid the foundation for the modern-day variant.

Once the historical foundations of the gas turbine are laid down, the current state of the art is going to be assessed in realistic terms. The “class hierarchy” of heavy-duty industrial gas turbines will be established in this chapter as well.

¹ The complete title is *Mathematical Magick, or, The wonders that may by performed by mechanical geometry: in two books, concerning mechanical powers [and] motions. Being one of the most easie, pleasant, useful (and yet most neglected) part of Mathematicks. Not before treated of in this language* (London: Printed for J. Nicholson, at the Kings-Arms in Little Britain; A. Bell, at the Croft-Keys in Cornhill; B. Tooke, at the Middle-Temple-Gate in Fleetstreet; and R. Smith under the Piazza’s of the Royal-Exchange. MDCCVIII).

² According to Wilkins, “the Motion of these Sails may likewise be serviceable for sundry other Purposes; for the Chiming of Bells, for the Reeling of Yarn or the Rocking of a Cradle, with diverse the like domestick Occasions.”

Part II comprises fundamental material one has to be thoroughly familiar with in order to be conversant in more advanced subject matter related to the design and operation of gas turbines for electric power generation.

In Chapter 5, it will be shown that the basic gas turbine concept logically follows from the second law of thermodynamics (even though, in reality, the evolution of heat engines and the science of thermodynamics went pretty much hand in hand). Once that logical path is established, it is amazing how many practical calculations, which typically require hours of analysis with sophisticated heat balance simulation software, can be distilled into a few simple formulae amenable to simple spreadsheet analysis.

From the thermodynamic cycle to the final end product (Chapter 14), there are several intermediate steps. They separate “concept” from “reality.” In a roughly logical order, they comprise aeromechanical design of compression and expansion (turbine) sections to achieve particular cycle conditions (Chapters 10 and 11), combustion with minimal or – even better – no harmful emissions (Chapter 12), and the availability and selection of suitable materials of construction (Chapter 13). All of these individual design and development steps must be undertaken with a keen eye on cost, operability, maintainability, and reliability.

Part III comprises subject matter of a more advanced nature, which one has to master in order to claim comprehensive knowledge of industrial gas turbines for electric power generation. Note that the coverage in the book does *not* deliver the said mastery; that requires many years of active involvement in the field. The goal herein is simply to shed light on the path to be taken toward that goal.

At the end of the day, the gas turbine itself generates mechanical (shaft) power. The synchronous alternating current machine, which transforms the shaft power into electric power, is an integral part of the system (i.e., the gas turbine generator). In the past, when gas turbines were primarily utilized for peaking duties (i.e., a few hundred hours annually) or for base load duties in a combined cycle configuration, treatment of the generator was barely an afterthought (i.e., generator efficiency was 98.9 percent – that’s it!). Modern grid requirements such as grid code regulations and reactive power support necessitate a closer look at the alternating current machine and its ramifications for running the gas turbine efficiently and reliably. A whole chapter in Part III will be devoted to this (Chapter 15).

Other chapters in Part III deal with:

- Reliability, availability, and maintainability (Chapter 16)
- Combined cycle power plant (Chapter 17)
- Off-design operation (Chapter 18)
- Transient operation (Chapter 19)
- Economics (Chapter 20)
- The Hall of Fame (Chapter 21)

The last chapter in Part III is a deep dive into the “latest and greatest” in gas turbine technology, as of the end of 2017, via the flagship products of four major OEMs.

Part IV comprises chapters on unique applications of gas turbine technology:

- Closed cycle gas turbines (Chapter 22)
- Aeroderivative gas turbines (Chapter 23)

Finally, now that the reader is equipped with a trove of knowledge on the state of the art, a glimpse into future development possibilities will conclude the treatise. The final, concluding chapter will recap the status of gas turbine technology and look into the future with a keen eye on the past.

With this brief introduction complete and without further ado, it is time to move on to the nitty-gritty details of large, stationary gas turbines for electric power generation.

Part I

Prerequisites

2 The Tool Chest

Let us state the obvious first: this is a book for engineers and engineering students. A solid understanding of the key concepts of thermodynamics, fluid mechanics and heat transfer is more than a prerequisite; it is a *must*. Without that, slogging through the material covered in this book will become a tedious chore (which is definitely *not* the author's intention).

One does not have to hold a degree in advanced mathematics to be a good gas turbine engineer. Nevertheless, a strong foundation in calculus is requisite to understanding the laws of thermodynamics, especially the second one. Furthermore, the foundation of the thermal design of power plants in general and gas turbines in particular consists of the famous “TdS” equations. The reader must be readily conversant in them and in Maxwell relationships (if you draw a blank here, it is time to pick up your thermodynamics textbook and blow the dust off its cover) – simply put, there is no shortcut around it. If your math skills are rusty, the excellent book by Zel'dovich and Yaglon is the perfect resource for getting up to speed [1].

It also helps greatly to have an adequate understanding of basic statistical concepts, which, in turn, require a firm grasp of calculus. This is imperative for understanding the difference between “engineering” and “commercial” performance (i.e., commercial “margins”). It is also very handy in order to prevent being lured into unrealistic expectations by the proverbial “fool's gold.” A very useful tool to help you in statistical analysis is the Oracle Crystal Ball, which is a Microsoft Excel-based software for predictive modeling, forecasting, Monte Carlo simulation, and optimization.¹ Monte Carlo simulation in particular is a very valuable tool to differentiate between substantial and insignificant differences when comparing design options. Its use will be demonstrated later in the book (see Chapter 20).

2.1 Computer Software

In order to derive the maximum benefit from this book to impact your daily work, you need to perform calculations. Some of the equations developed in the following chapters are amenable to quick implementation with a pen, a piece of paper, and a \$10 drugstore

¹ For more information about Crystal Ball, visit www.oracle.com/crystalball (last accessed by the author in December 2017).

calculator (or the calculator app on your smartphone). Once you go beyond a few “back of the envelope”-type estimates, you will probably need to implement quite a few such equations in an Excel spreadsheet. Nevertheless, at a certain point, you will realize that it is a good idea to distill some of your calculations into compact snippets of computer *code*. This is where the real fun starts.

It is highly recommended that you are well versed in at least one of the following programming languages²:

1. Visual Basic (VB; especially VBA in Excel)
2. C or C++
3. FORTRAN
4. Matlab (from MathWorks[®])

The last one is extremely popular among the younger generation – students *and* practitioners. Even though the author has not had extensive experience with it, he is aware that it is a very simple and powerful tool for computational purposes. The most beneficial one in this author’s opinion, which is also quite easy to learn and implement, is VB. In particular, VBA (Visual Basic for Applications) is the programming language of Excel and other Microsoft Office programs. (It is highly unlikely that the reader of this book does *not* have access to Microsoft Office and Excel through his or her organization or on his or her own.) If you are not already familiar with VBA, you can get started by automating tasks in Excel by using the Macro feature, which essentially records a sequence of your Excel spreadsheet actions in a VB function.

An alternative to Microsoft Office is Apache OpenOffice (AOO), which is an open-source office productivity software suite. It contains a word processor (Writer – equivalent to Microsoft Word), a spreadsheet (Calc – equivalent to Microsoft Excel), and a presentation application (Impress – equivalent to Microsoft PowerPoint), among others. Readers who are more familiar with it can of course substitute the AOO variant for Excel, which is the software program most familiar to the author.

If you are already familiar with C++ and/or FORTRAN and, even better, if you already have old programs that you had developed earlier in your educational and/or professional career, you can easily translate them into VB. It is very intuitive and easy. Another way to capture such legacy code in Excel or similar software programs is via converting them into a *dynamic-link library* (DLL; i.e., an executable file encapsulated in a DLL).

In Appendix C of the book, some examples of Excel VBA code based on the formulae developed for the subject matter hand will be provided. You can use them in your own applications *as is* or as starting points. For the younger generation of readers, these code snippets (or formulae and methods contained therein) can be used as building blocks or starting points to design your own “apps.”

However, at some point, for serious work, the calculations requisite for accurate and reliable engineering design analysis require specialty software. This is especially true

² There are many new computer languages out there. Whatever works for you is just fine.

for transient (dynamic) analysis of the power plant for operability analysis and control system development. The software used for the latter task is extremely complex, with a steep learning curve (and it is very expensive, of course), and it requires a huge number of man-hours to develop and execute fully functional power plant models. It is no exaggeration to state that some people spend an entire career on such programs and associated tasks. Unfortunately, there are no shortcut calculation methods to replace them (which require the solution of combinations of partial differential equations), and even simplified approaches to estimate their outcomes are quite complicated and require a deep engineering knowledge of the underlying phenomena. This will be touched upon again in Chapter 19.

Software for steady-state performance calculations are commonly known as “heat balance simulation tools.” The name derives from the fact that the underlying fundamental principle is the first law of thermodynamics (also known as conservation of energy) along with mass continuity (also known as conservation of mass). These two laws of conservation are applied to the individual pieces of equipment comprising the power generation system in question. In the end, a “balance” is established between the two forms of energy transfer – work and heat – and mass transfer across the entire system (i.e., the “control volume”).

There are several steady-state, heat balance simulation tools widely used in the industry:

1. **GateCycle.** Gate, as it is commonly known, is a PC-based simulation software with a graphical user interface that allows the user to build a system by interconnecting individual components, which are available as icons (compressor, combustor, expander, etc.). In 2000, Enter Software was fully acquired by General Electric. Since then, however, marketing and support activities for Gate continuously dropped until 2013 or 2014, when, for practical purposes, GE Enter all but ceased to function. Some readers might be familiar with Gate and have access to its legacy (and functional) copies through their organizations.
2. **Thermoflow Suite.** This is a suite of several software packages, developed by Thermoflow, Inc., since 1987, which are classified into the following two distinct groups:
 - a. **Application-specific software.** A special-purpose tool focusing exclusively on a specific type of power plant. The program includes a general model, from which the user selects a subset via a guided, structured procedure. They comprise:
 - i. **GT PRO** and **GT MASTER** for gas turbine combined-cycle and cogeneration (i.e., combined heat and power, or CHP as it is commonly known in Europe) design and off-design performance.
 - ii. **STEAM PRO** and **STEAM MASTER** for fossil plant (e.g., coal-fired boiler and steam turbine generator) design and off-design performance.
 - b. **Fully flexible software.** A general-purpose tool that allows the user to construct any real or conceptual power plant model by connecting