Gas Turbine Engineering Handbook

Meherwan P. Boyce

- Design
- Operation
- Maintenance

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To the memory of my father, Phiroz H. J. Boyce.

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Preface

Gas Turbine Engineering Handbook discusses the design, fabrication, installation, operation, and maintenance of gas turbines. The book has been written to provide an overall view for the experienced engineer working in a specialized aspect of the subject and for the young engineering graduate or undergraduate student who is being exposed to the turbomachinery field for the first time. The book will be very useful as a textbook for undergraduate turbomachinery courses as well as for in-house company training programs related to the petrochemical, power generation, and offshore industries.

The use of gas turbines in the petrochemical, power generation, and offshore industries has mushroomed in the past few years. It is to these users and manufacturers of gas turbines that this book is directed. The book will give the manufacturer a glimpse of some of the problems associated with his equipment in the field and help the user to achieve maximum performance efficiency and high availability of his gas turbines.

I have been involved in the research, design, operation, and maintenance of gas turbines since the early 1960s. I have also taught courses at the graduate and undergraduate level at the University of Oklahoma and Texas A&M University, and now, in general, to the industry. The enthusiasm of the students associated with these courses gave me the inspiration to undertake this endeavor. The many courses I have taught over the past 15 years have been an educational experience for me as well as for the students. The Texas A&M University Turbomachinery Symposium, which I had the privilege to organize and chair for seven years, is a great contributor to the operational and maintenance sections of this book. The discussions and consultations that resulted from my association with highly professional individuals have been a major contribution to both my personal and professional life as well as to this book.

In this book I have tried to assimilate the subject matter of various papers (and sometimes diverse views) into a comprehensive, unified treatment of gas turbines. Many illustrations, curves, and tables are employed to broaden the understanding of the descriptive text. Mathematical treatments are deliberately held to a minimum so that the reader can identify and resolve any problems before he is ready to execute a specific design. In addition, the references direct the reader to sources of information that will help him to investigate and solve his specific problems. It is hoped that this book will serve as a reference text after it has accomplished its primary objective of introducing the reader to the broad subject of gas turbines.

I wish to thank the many engineers whose published work and discussions have been a cornerstone to this work. I especially thank all my graduate students and former colleagues on the faculty of Texas A&M University without whose encouragement and help this book would not be possible. Special thanks go to the Advisory Committee of the Texas A&M University Turbomachinery Symposium

and Dr. C.M. Simmang, Chairman of the Texas A&M University Department of Mechanical Engineering, who were instrumental in the initiation of the manuscript, and to Janet Broussard for the initial typing of the manuscript. Acknowledgment is also gratefully made of the competent guidance of William Lowe and Scott Becken of Gulf Publishing Company. Their cooperation and patience facilitated the conversion of the raw manuscript to the finished book. Lastly, I wish to acknowledge and give special thanks to my wife, Zarine, for her readiness to help and her constant encouragement throughout this project.

I sincerely hope that this book will be as interesting to read as it was for me to write and that it will be a useful reference to the fast-growing field of turbomachinery.

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Foreword

The Alexandrian scientist Hero (circa 120 B.C.) would hardly recognize the modern gas turbine of today as the outgrowth of his aeolipile. His device produced no shaft work—it only whirled. In the centuries that followed, the principle of the aeolipile surfaced in the windmill (A.D. 900-1100) and again in the powered roasting spit (1600s). The first successful gas turbine is probably less than a century old.

Until recently, two principal obstacles confronted the design engineer in his quest for a highly efficient turbine: (1) the temperature of the gas at the nozzle entrance of the turbine section must be high, and (2) the compressor and the turbine sections must each operate at a high efficiency. Metallurgical developments are continually raising inlet temperatures, while a better understanding of aerodynamics is partly responsible for improving the efficiency of centrifugal and axial-flow compressors and radial-inflow and axial-flow turbines.

Today there are a host of other considerations and concerns which confront design and operating engineers of gas turbines. These include bearings, seals, fuels, lubrication, balancing, couplings, testing, and maintenance. *Gas Turbine Engineering Handbook* presents necessary data and helpful suggestions to assist engineers in their endeavors to obtain optimum performance for any gas turbine under all conditions.

Meherwan Boyce is no stranger to gas turbines. For more than a decade he has been highly active with the techniques of turbomachinery in industry, academics, research, and publications. The establishment of the annual Texas A&M University Turbomachinery Symposium can be numbered among his major contributions to the field of turbomachinery. Dr. Boyce subsequently directed the following seven prior to forming his own consulting and engineering company. The tenth symposium was held recently and attracted more than 1200 engineers representing many different countries.

This important new handbook comes to us from an experienced engineer at a most opportune time. Never has the cost of energy been greater, nor is there a promise that it has reached its price ceiling. Dr. Boyce is aware of these concerns, and through this handbook he has provided the guide and means for optimum use of each unit of energy supplied to a gas turbine. The handbook should find its place in all the reference libraries of those engineers and technicians who have even a small responsibility for design and operation of gas turbines.

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Part IV Auxiliary Components and Accessories

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Part I

Design: Theory and Practice

1

An Overview of Gas Turbines

The gas turbine is a power plant which produces a great amount of energy for its size and weight. The gas turbine has found increasing service in the past 15 years in the petrochemical industry and utilities throughout the world. Its compactness, low weight, and multiple fuel application make it a natural power plant for offshore platforms. Today there are gas turbines which run on natural gas, diesel fuel, naphtha, methane, crude, low-Btu gases, vaporized fuel oils, and even waste. Gas turbines in the petrochemical industry can be classified into four broad groups:

1. Industrial heavy-duty gas turbines
2. Aircraft-derivative gas turbines
3. Medium-range gas turbines
4. Small gas turbines

In the past the gas turbine was perceived as a relatively inefficient power source when compared to other power sources. Its efficiencies were as low as 15%. Despite these low efficiencies, its compactness and light weight make it attractive for certain applications. The limiting factor for most gas turbines has been the turbine inlet temperature. With new schemes of air cooling and breakthroughs in blade metallurgy, higher turbine temperatures have been achieved. Regeneration has been very useful in lowering the heat rate from 18,000-20,000 Btu/kWh to about 12,000 Btu/kWh. Further reduction using regenerators is limited by metallurgical problems. By combining the gas turbine cycle with a steam turbine cycle, heat rates of around 8000 Btu/kWh have been obtained.

Figure 1-1 shows a comparison of various heat rates in four different cycle types. It is obvious that as turbine temperature increases, heat rates become more attractive.

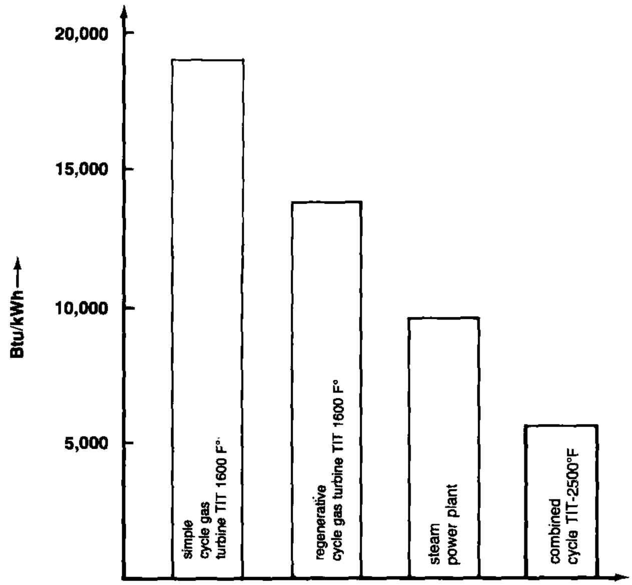

Figure 1-1. Comparison of heat rates for four cycle types.

Some factors one must consider in deciding what type of power plant is best suited for the needs at hand are capital cost, time from planning to completion, maintenance costs, and fuel costs. Table 1-1 shows the costs for various types of plants. The gas turbine has the lowest maintenance and capital cost. It also has the fastest completion time to full operation of any other plant. Its disadvantage is its high heat rate. The combination of plant cycles seems to be an attractive alternative.

The design of any gas turbine must meet essential criteria based on operational considerations. Chief among these criteria are:

1. High efficiency
2. High reliability and thus high availability
3. Ease of service
4. Ease of installation and commission
5. Conformance with environmental standards
6. Incorporation of auxiliary and control systems which have a high degree of reliability
7. Flexibility to meet various service and fuel needs

A look at each of these criteria will enable the user to get a better understanding of the requirements.

Table 1-1
Analysis of Various Types of Power Plants

Type of Power Plant	Capital Cost ($/kW)	Heat Rate (Btu/kW hr)	Maint. (Mils/kWh)	Fuel Cost ($/10⁶ Btu)	Cost M/Btu: Annual Zero Operation	Cost M/Btu: $kW 6760 h/yr	Time From Planning To Comp.	Growth Potential	Air/Water
Simple cycle gas turb. (2000°F)	170	10,500	15	3.12	31	324	1-2 yrs	To 2,800°F	NO_x/0.0
Comb. cycle gas turb. (2000°F)	270	8,500	1.6	3.12		276	1-2 yrs	To 2800°F	NO_x/0.4
Std. steam	600	9,400	25	1.1	110	224	6-8 yrs	None	NO_x/1.0
Comb. cycle synthetic fuel (2200°F)	290	7,300	14	3.12	54	266	4-5 yrs	To 2,800°F	NO_x/0.4
Comb. cycle gasifier (2200°F)	540	8,100	30	1.1	102	204	4¼-5 yrs	To 2,800°F	Best/0.5
Comb. cycle fluid bed coal gasification (1700°F)	515	9,100	25/30	1.1	96	204	4¼-5 yrs	Steam addition	Better/0.70
Closed cycle (1700°F) nuclear	900	7,040 Helium topping cycle Ammonia bottoming cycle	25/30	1.1			5-6 yrs	To 1900°F	Better/0.7

The two factors which most affect high turbine efficiencies are temperature and pressure ratios. The effect of temperature is very predominant—for every 100°F increase in temperature, the work output increases approximately 10% and gives about a 1½% increase in efficiency. Higher turbine inlet temperatures improve efficiencies on the simple-cycle gas turbine. Another way to achieve higher efficiencies is with regenerators. Figure 1-2 shows a simple-cycle gas turbine performance map as a function of pressure ratio and turbine inlet temperature. Figure 1-3 shows the effects of pressure ratio and temperatures on efficiencies and work for a regenerative cycle. The effect of pressure ratio for this cycle is opposite to that experienced in the simple cycle. Regenerators can increase efficiency as much as 15-20% at today's operating temperatures. The optimum pressure ratios are about 7:1 for a regenerative system compared to 18:1 for the simple-cycle at today's higher turbine inlet temperatures that approach 2000°F.

To achieve a high reliability factor, the designer must keep in mind many factors. Some of the more important considerations which govern the design are blade and shaft stresses, blade loadings, material integrity, auxiliary systems, and control systems. The high temperatures required for high efficiencies have a disastrous effect on turbine blade life. Proper cooling must be provided to achieve blade metal temperatures of about 1000-1250°F. Thus, the right type of cooling systems with proper blade coatings and materials are needed to ensure the high reliability of a turbine.

Serviceability is an important part of any design, since fast turnabounds result in high availability to a turbine and reduce costs. Service can be accomplished by providing proper checks such as exhaust temperature monitoring, shaft vibration monitoring, and surge monitoring. Also, the designer should incorporate borescope ports for fast visual checks of hot parts in the system. Split casings for fast disassembly, field balancing ports for easy access to the balance planes, and combustor cans which can be easily disassembled without removing the entire hot section are some of the many ways that afford ease of service.

Ease of installation and commissioning is another reason for gas turbine use. A gas turbine unit can be tested and repackaged at the factory. Use of a unit should be carefully planned so as to cause as few start cycles as possible. Frequent startups and shutdowns at commissioning greatly reduce the life of a unit.

Environmental considerations are critical in the design of any system. The system's impact on the environment must be within legal limits and thus must be addressed by the designer carefully. Combustors are the most critical component, and great care must be taken to design them to provide low smoke and low NO_x output. Wet combustors could become prevalent if new

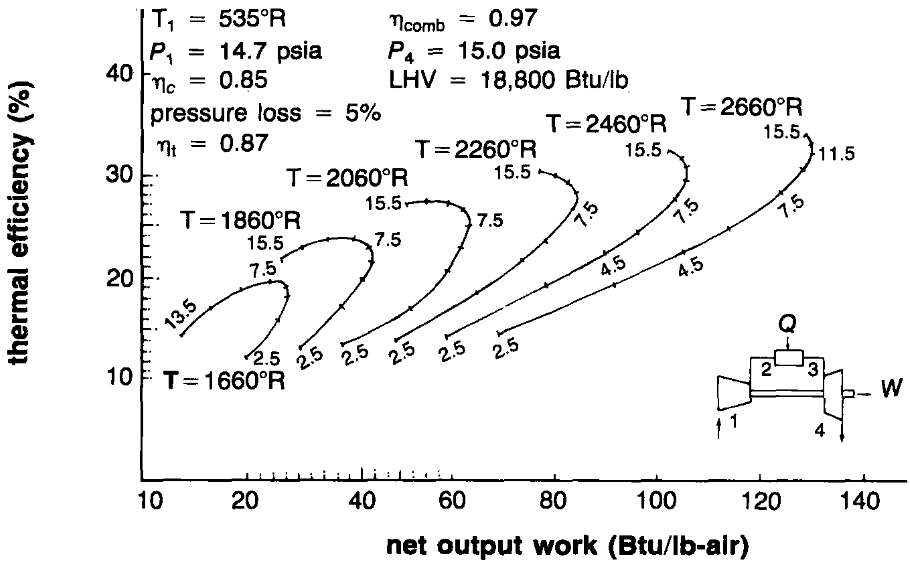

Figure 1-2. Performance map of a simple cycle.

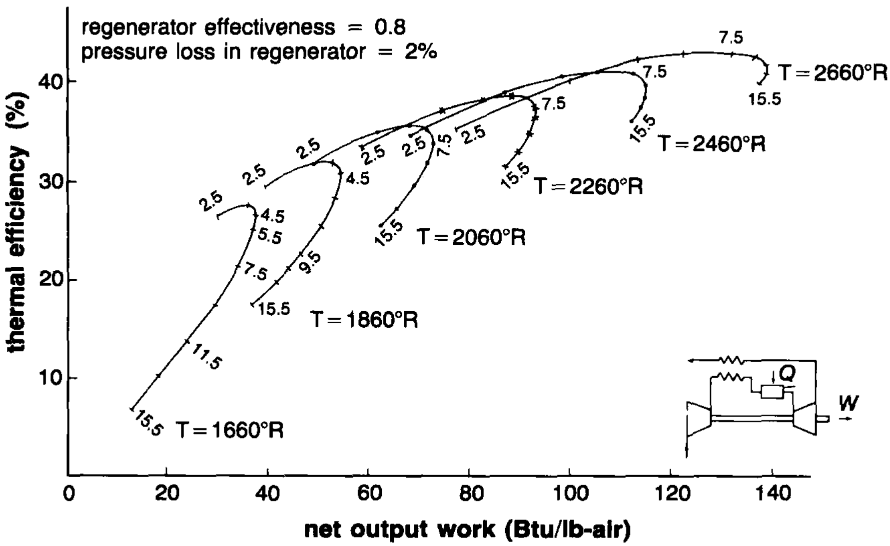

Figure 1-3. Performance map of a regenerative cycle.

environmental proposals concerning NO_x emissions are made into law. Noise is another important factor which must be controlled. Air noise can be reduced by lowering the inlet velocities and providing proper inlet silencers. Considerable work by NASA on compressor casings has greatly reduced noise.

Auxiliary systems and control systems must be designed carefully, since they are often responsible for the downtime in many units. Lubrication systems, one of the critical auxiliary systems, must be designed with a backup system and should be as close to failure-proof as possible. Control systems must provide acceleration time cards for startups as well as cntrol various antisurge valves. At operating speeds they must regulate fuel supply and monitor vibrations, temperatures, and pressures through the engine.

Flexibility of service and fuels are criteria which enhance a turbine system, but they are not necessary for every application. The energy shortage makes both these criteria important: flexibility of service enables the unit to perform closer to its operating point and thus operate at higher efficiencies. This flexibility may entail a two-shaft design incorporating a power turbine, which is separate and not connected to the gasifier unit. Multiple fuel applications are now in greater demand, especially where various fuels may be in shortage at different times of the year.

The previous criteria are some of the many that designers must meet to design successful units.

Industrial Heavy-Duty Gas Turbines

These gas turbines were designed shortly after World War II and introduced to the market in the early 1950s. The early heavy-duty gas turbine design was largely an extension of steam turbine design. Restrictions of weight and space were not important factors for these ground-based units, and so the design characteristics included heavy-wall casings split on horizontal centerlines, sleeve bearings, large-diameter combustors, thick airfoil sections for blades and stators, and large frontal areas. The overall pressure ratio of these units varied from 5:1 for the earlier units to 15:1 for the units in present-day service. Turbine inlet temperatures have been increased and run as high as 1950°F on some of these units. Projected temperatures approach 3000°F and, if achieved, would make the gas turbine a very efficient unit. The High-Temperature Turbine Technology Program sponsored by the U.S. Department of Energy has these high temperatures as one of its goals.

The industrial heavy-duty gas turbines most widely used employ axial-flow compressors and turbines. In most U.S. designs combustors are can-annular combustors, as seen in Figures 1-4a and 1-4b. Single-stage side combustors, as seen in Figure 1-5, are used in European designs. The combustor cans used in these units have heavy walls and are very durable. The liners are designed

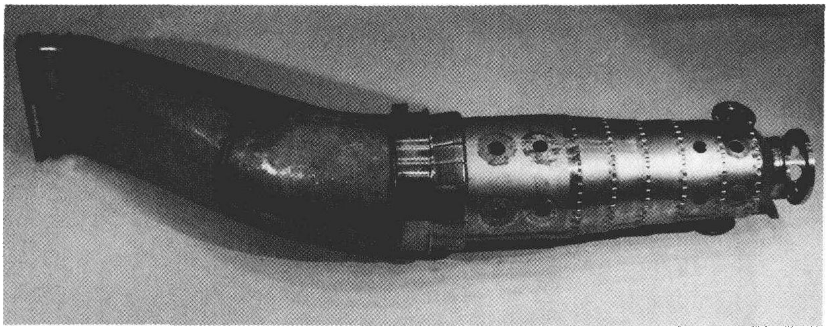

Figure 1-4a. Can-annular combustor with transition piece. (©Rolls- Royce Limited.)

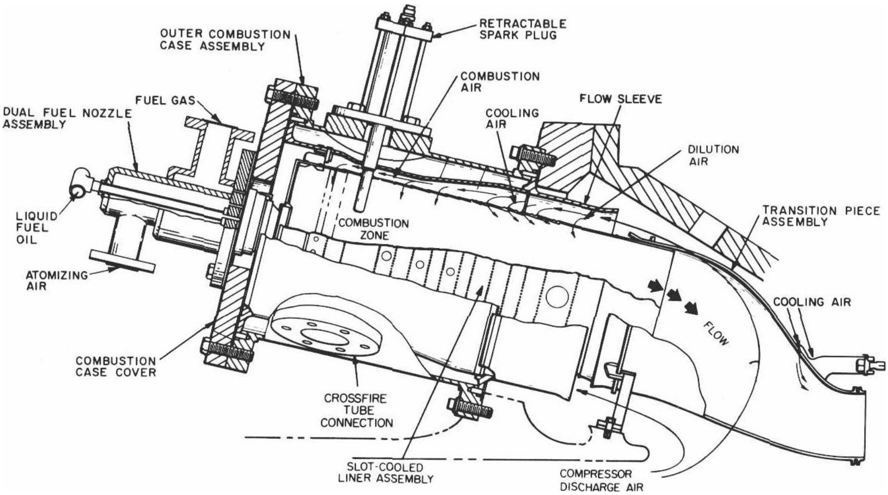

Figure 1-4b. A typical can-annular combustor. (Courtesy General Electric Company.)

specifically to produce low smoke and low NO_x emissions. Many of these units have dual fuel flexibility.

The large frontal areas of these units reduce the inlet velocities, thus reducing air noise. The pressure rise in each compressor stage is reduced, creating a large, stable operating zone.

The auxiliary modules used on most of these units have gone through considerable hours of testing and are heavy-duty pumps and motors. The control system uses heavy-duty governors. Electronic governors are being introduced in some of the newer models.

The advantages of the heavy-duty gas turbines are their long life, high availability, and slightly higher overall efficiencies. The noise level from this