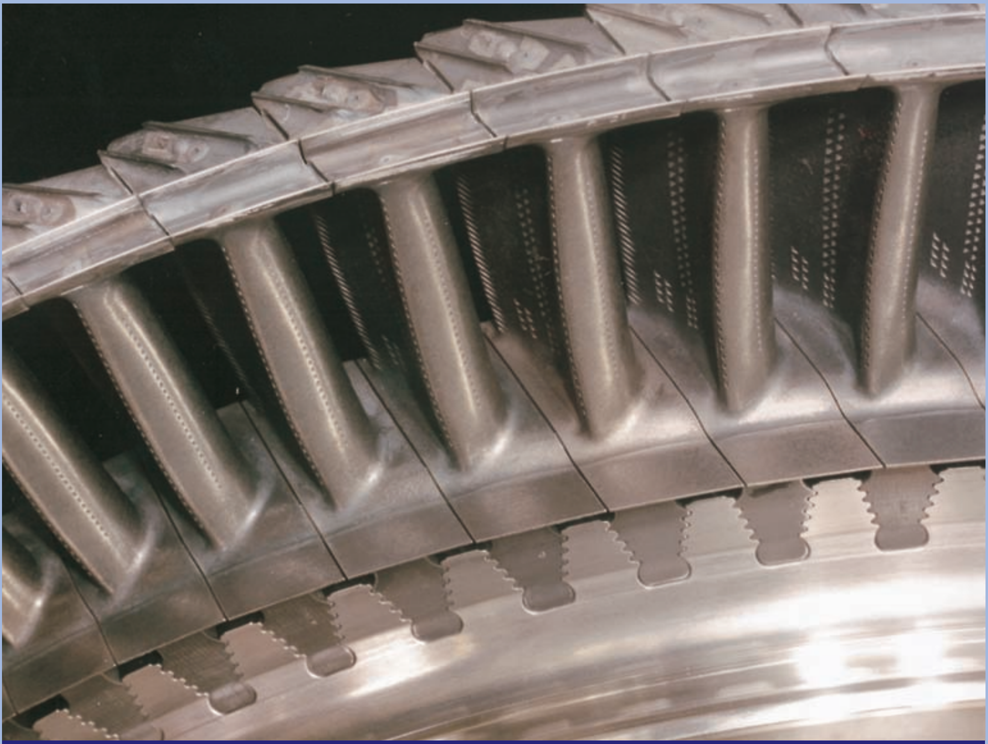
Gas Turbine Theory



SEVENTH EDITION

H.I.H. Saravanamuttoo
G.F.C. Rogers • H. Cohen
P.V. Straznicky • A.C. Nix

Pearson

7TH EDITION

GAS TURBINE THEORY

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Pearson Education Limited
Edinburgh Gate
Harlow CM20 2JE
United Kingdom
Tel: +44 (0)1279 623623
Web: www.pearson.com/uk

Published under the Longman imprint 1951, 1972, 1987, 1996
Fifth edition published under the Prentice Hall imprint 2001
Sixth edition published 2009 (print and electronic)
Seventh edition published 2017 (print and electronic)

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ISBN: 9781-292-09309-3 (print)
9781-292-09313-0 (PDF)
9781-292-13448-2 (ePub)

British Library Cataloguing-in-Publication Data
A catalogue record for the print edition is available from the British Library

Library of Congress Cataloging-in-Publication Data
Names: Saravanamuttoo, H. I. H., author. | Rogers, G. F. C. (Gordon Frederick Crichton), author. | Cohen, Henry, 1921 September 29- author.
Title: Gas turbine theory / HIH Saravanamuttoo, professor emeritus, Department of Mechanical and Aerospace Engineering, Carleton University, GFC Rogers, Lately professor emeritus, University of Bristol, H Cohen, Lately fellow, Queens' College, Cambridge, PV Straznicky, professor emeritus, Department of Mechanical and Aerospace Engineering, Carleton University, AC Nix, assistant professor, Department of Mechanical and Aerospace Engineering, West Virginia University.
Description: Seventh edition. | Harlow, England ; New York : Pearson, 2017. | Includes bibliographical references and index.
Identifiers: LCCN 2017010103| ISBN 9781292093093 (Print) | ISBN 9781292093130 (PDF) | ISBN 9781292134482 (ePub)
Subjects: LCSH: Gas-turbines.
Classification: LCC TJ778 .S24 2017 | DDC 621.43/3--dc23
LC record available at https://lccn.loc.gov/2017010103

10 9 8 7 6 5 4 3 2 1
21 20 19 18 17

Print edition typeset in 10/12pt Times LT Pro by SPi Global
Printed and bound in China

NOTE THAT ANY PAGE CROSS REFERENCES REFER TO THE PRINT EDITION

Contents

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Foreword

My introduction to gas turbines and to *Gas Turbine Theory* occurred almost 40 years ago as an undergraduate engineering student at Carleton University, when I had the good fortune to have Herb Saravanamuttoo as a professor. Not only was he a great educator, his passion and enthusiasm for the subject of aircraft engines and their industrial applications was, for me and many others, infectious. I began my career at Pratt Whitney Canada, eventually returning to Ottawa to join Gastops and to undertake post-graduate studies under Herb's supervision. I have maintained a professional relationship and a personal friendship with Herb since that time, and both Gastops and I have benefitted considerably from our association with Herb and with Carleton University's Department of Mechanical and Aerospace Engineering. We have collaborated on research and development projects, shared our thoughts or opinions on the significance of new gas turbine technology developments and, most importantly, several former students of Herb and Paul Straznicky have become employees of Gastops and made important contributions to our company and its success in the field of engine health monitoring. We have more than twenty engineers working at Gastops today who have graduated from Carleton University. They came to us well trained in the fundamentals of gas turbine design for aviation and industrial applications. Almost all of them, like me, keep their copies of *Gas Turbine Theory* by their desks for reference to the history, theory and practical design considerations of the gas turbine engine.

For the student, *Gas Turbine Theory* presents a thorough and well-organized treatment of the thermodynamic and aerodynamic theory that underlies the basic design of gas turbine engines in their various shaft power and aircraft propulsion cycle configurations. For the more advanced student and practising engineer, the book goes beyond this basic theory to include a number of important practical design considerations such as mechanical design, off-design and transient performance prediction, and engine control principles. *Gas Turbine Theory* also traces and explains in a highly informative way the many advances and changes to gas turbine design that have occurred from its introduction in the 1940s as a power plant for military aircraft to its present-day use as a highly efficient and economical power plant for a wide range of marine, industrial and aircraft applications.

I highly recommend this book to any engineering student or practising engineer who wishes to become acquainted with the development of the gas turbine as prime mover, the thermodynamic and aerodynamic theory of its design, and important practical aspects of its design and operations that are continuously changing and improving to meet the challenges of new application requirements.

Dave Muir
CEO, Gastops Ltd

Preface to the seventh edition

Cohen and Rogers wrote the Preface of the First Edition in 1950, and in 291 considerably smaller pages laid the foundations of a book which has been in print for 66 years. They were joined by Saravanamuttoo for the Second Edition and he and Rogers wrote the Third Edition following the death of Cohen. After the retirement of Rogers, Saravanamuttoo continued with the Fourth and Fifth Editions, with the Fifth marking 50 years in print. Straznicky brought new blood to the Sixth Edition and he and Saravanamuttoo are delighted to be joined by Andrew Nix for this new edition.

This edition includes a significant updating of key material and new material on combustion, turbine cooling and mechanical design. Professor Nix is currently active in many aspects of gas turbine technology, primarily focusing on turbine hot section durability, heat transfer and cooling, combustion, advanced thermal barrier coatings and sensors. Professor Straznicky brings many years of experience as a design engineer, which greatly enhanced the previous edition.

At the start of his career Saravanamuttoo had the great good fortune to fall under the wing of Dick Quan at Orenda Engines in Canada, and DQ provided mentorship, guidance and technical leadership for many years. DQ's only failure was to teach Saravanamuttoo to keep a tidy desk, and when he received a major award from the ASME many years later he was delighted to receive an e-mail headed "Messy kid makes good," a succinct and accurate summation of a long career. Saravanamuttoo would again like to thank Randy Batten of Pratt and Whitney Canada and Greg Chapman of Honeywell Aerospace for their continued help. He would again like to thank his wife Helen for her support for more than 50 years.

Andrew Nix has spent his relatively young career in gas turbine development in industry, government and academic positions. He has worked in gas turbine cycle design as an engineer at Bechtel Power, as a turbine design and durability engineer with the Naval Air Systems Command (NAVAIR) Propulsion and Power Division and as a university researcher at West Virginia University and at Virginia Tech. He would like to thank administrators and colleagues at WVU for their support in this endeavour, and former graduate student Andrew Sisler and engineers at the Department of Energy (DOE) National Energy Technology Laboratory (NETL) for their assistance in preparation of new material in advanced pressure gain combustion. It is humbling to be invited to participate in the continuing success of this longstanding prestigious text.

February 2017

H.I.H.S
P.V.S
A.C.N

Preface to the sixth edition

The first edition of this book appeared 56 years ago and I was one of the earliest users as an undergraduate. It was, in fact, the only book I bought and little did I think that my involvement with it would last for my entire career and into retirement. I was very pleased when the publishers asked me to prepare a sixth edition. Sadly, my good friend and colleague Gordon Rogers died in 2004, leaving me as the last of the triumvirate.

The original concept of Cohen and Rogers was simply to present the basic theory of the gas turbine, then in its infancy. When I was invited to join the original authors in the second edition, I was actively involved in both aircraft and industrial gas turbine activities, and this resulted in the introduction of material on the design process, operations and applications. Over the years there has been a trend away from the basic theory and there have been frequent requests for more material on design. This new edition has been extended to include a complete chapter on the mechanical design of gas turbines. I am deeply indebted to my colleague Professor Paul Straznicky for writing this invaluable contribution; Paul has had many years' experience as a designer of high-performance rotating machinery and has done an excellent job of presenting a vast amount of material in a single chapter.

Since my graduation in 1955 I have seen the gas turbine grow in importance from an almost exclusively military jet engine to a versatile prime mover which has both revolutionized passenger transportation and become a major factor in electric power generation and pipeline pumping. The huge improvements in power and efficiency have resulted from continuous developments in aerodynamics, metallurgy and manufacturing but the basic theory has not changed. It is interesting to observe, however, that some of the early cycle developments, required when turbine temperatures and pressure ratios were very low by today's standards, are reappearing in the 21st century, including heat-exchange, intercooling and reheat.

Commercially available software is now readily available for highly accurate calculations and all major manufacturers have their own proprietary software. I have concentrated on providing an underlying basis of the fundamentals of cycle calculations without emphasis on absolute accuracy, which I firmly believe to be the correct approach for an introductory text. Students may find the program GASTURB by Dr Joachim Kurzke useful for in-depth studies; a basic version is downloadable at www.gasturb.de.

Over a long career I believe my most important contribution is the large number of engineers I have trained, and many of these have now risen to high levels in the gas turbine industry around the world. It is salutary to find my students retiring and some day I should follow their example. Particular thanks for help with this edition goes to Randy Batten (Pratt & Whitney Canada), Mark Baseley (Rolls-Royce) and Greg Chapman (Honeywell). For many years I have had a close association with GasTOPS, founded by Dr Bernard MacIsaac in 1979, and now run by Dave Muir, and I extend my sincere thanks to both for their help over the years.

Finally, sincere thanks to Jeanne Jones of GasTOPS for her cheerful work in typing the changes to the manuscript and to my wife Helen for her continued support and encouragement for nearly 50 years.

September 2007 H.I.H.S.

Preface to the fifth edition

This edition has been written to mark the 50th anniversary of the original publication of *Gas Turbine Theory* in 1951. The gas turbine was in its infancy when Cohen and Rogers laid the foundation of the basic theory of this new prime mover, including cycle design, aerodynamics and thermodynamics of the individual components and off-design performance. Fifty years later the layout of the book is essentially the same, but it has been greatly expanded to cover the continued development and widely increasing applications of the gas turbine.

In 1951 the gas turbine had a very limited role, primarily as a military jet engine with a 'big' engine having a thrust of about 15 kN. There were no civil aircraft applications and only a handful of experimental industrial engines had been built; these could not compete successfully against the established diesel engine and steam turbine. In the last 50 years the gas turbine has had an enormous impact, starting with the introduction of commercial jet transports in the early 1950s; this led directly to the demise of oceanic passenger liners and trans-continental trains in North America. The application of gas turbines has resulted in a revolutionary growth in the gas pipeline industry and, more recently, has had a similar impact on electric power generation. Industrial gas turbines are now approaching unit sizes of 300 MW and thermal efficiencies in excess of 40 per cent, while combined gas and steam cycles achieve efficiencies of close to 60 per cent. The beginning of the 21st century may see the widespread use of the microturbine in distributed power plants and also the combination of the gas turbine with fuel cells. The outstanding reliability of the gas turbine is clearly demonstrated by the large-scale use of twin-engined passenger aircraft on oceanic routes, with engines achieving as much as 40 000 hours without being removed from the wing.

In this edition the Introduction has been updated and expanded to deal with current new developments, the propulsion material has been extended considerably, a new section on performance deterioration has been added, and numerous minor improvements have been made. The aim of the book is unchanged, in that it gives a broad-based introduction to the key aspects of the gas turbine and its applications.

Today's vast body of knowledge on gas turbines makes it very difficult to keep abreast of developments on a wide front, and I am very grateful to the large number of gas turbine engineers who have provided me with information and help over the years. I have gained especially from my long association with the Advisory Group on Aeronautical Research and Development (AGARD) and the International Gas Turbine Institute of the American Society of Mechanical Engineers. The long-term financial support of the Natural Sciences and Engineering Research Council of Canada has been invaluable to my work.

As a boy growing up during Second World War, I was fascinated by aeroplanes, and the appearance of the jet engine was a particularly exciting development. 1951 was also the year I started university and, in my final year, I was introduced to gas turbines using the book universally known as Cohen and Rogers. In 1964, after a decade in the Canadian gas turbine industry, I joined Professor Rogers on the staff of the University of Bristol and we have worked together since then. My first contribution to *Gas Turbine Theory* was with the second edition published in 1972.

It is my belief that several generations of gas turbine engineers, including myself, owe a deep debt of gratitude to Henry Cohen and Gordon Rogers for their pioneering efforts in gas turbine education, and I am very glad to have been able to continue this work to complete the half century in print.

Finally, I should like to thank my wife, Helen, for her continued support and encouragement for more than 40 years.

September 2000 H.I.H.S.

A Solutions Manual for the problems in this book is available free of charge from the publishers to lecturers only.

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Preface to the fourth edition

It is exactly 40 years since I was introduced to the study of gas turbines, using a book simply referred to as Cohen and Rogers. After a decade in the gas turbine industry I had the good fortune to join Professor Rogers at the University of Bristol and was greatly honoured to be invited to join the original authors in the preparation of the second edition in 1971. Sadly, Dr Cohen died in 1987, but I am sure he would be delighted to know that the book he initiated in 1951 is still going strong. Professor Rogers, although retired, has remained fully active as a critic and has continued to keep his junior faculty member in line; his comments have been very helpful to me.

Since the third edition in 1987, the gas turbine has been found to be suitable for an increasing number of applications, and this is reflected in the new Introduction. Gas turbines are becoming widely used for base-load electricity generation, as part of combined-cycle plant, and combined cycles receive more attention in this edition. With the increased use of gas turbines, control of harmful emissions has become ever more important. The chapter on combustion has been enlarged to include a substantial discussion of the factors affecting emissions and descriptions of current methods of attacking the problem. A section on coal gasification has also been added. Finally, the opportunity has been taken to make many small but significant improvements and additions to the text and examples.

As in the third edition, no attempt has been made to introduce computational methods for aerodynamic design of turbomachinery and the treatment is restricted to the fundamentals; those wishing to specialize must refer to the current, rapidly changing, literature. Readers wishing access to a suite of performance programs suitable for use on a Personal Computer will find the commercially available program GASTURB by Dr Joachim Kurzke very useful; this deals with both design and off-design calculations. The way to obtain this program is described in the rubric of Appendix B.

I would like to express my deepest gratitude to Gordon Rogers, who introduced me to a university career and for over 30 years has been boss, mentor, colleague and friend. Together with Henry Cohen, his early work led me to a career in gas turbines and it has been a great privilege to work with him over the years.

Thanks are once again due to the Natural Sciences and Engineering Research Council of Canada for financial support of my work for many years. Finally, sincere thanks to Lois Whillans for her patience and good humour in preparing the manuscript.

September 1995 H.I.H.S.

Preface to the third edition

The continued use of this book since the appearance of the first edition in 1951 suggests that the objectives of the original authors were sound. To the great regret of Professors Rogers and Saravanamuttoo, Dr Cohen was unable to join them in the preparation of this new edition. They would like to express their appreciation of his earlier contribution, however, and in particular for initiating the book in the first place.

Since the second edition was published in 1972 considerable advances have been made and the gas turbine has become well established in a variety of applications. This has required considerable updating, particularly of the Introduction. Sub-sections have been added to the chapter on shaft power cycles to include combined gas and steam cycles, cogeneration schemes and closed cycles, and many minor modifications have been made throughout the book to take account of recent developments. The chapter on axial flow compressors has been rewritten and enlarged, and describes in detail the design of a compressor to meet a particular aerodynamic specification which matches the worked example on turbine design. A section on radial flow turbines has been added to the turbine chapter.

In keeping with the introductory nature of the book, and to avoid losing sight of physical principles, no attempt has been made to introduce modern computational methods for predicting the flow in turbomachinery. Appropriate references to such matters have been added, however, to encourage the student to pursue these more advanced topics.

As a result of many requests from overseas readers, Professor Saravanamuttoo has agreed to produce a manual of solutions to the problems in Appendix B. The manual can be purchased by writing to: The Bookstore, Carleton University, Ottawa, Ontario K1S 5B6, Canada.

Finally, this edition would not have been possible without the generous support of Professor Saravanamuttoo's research by the Natural Sciences and Engineering Research Council of Canada. He would particularly like to express his thanks to Dr Bernard MacIsaac of GasTOPS and the many engineers from Pratt and Whitney Canada, Rolls-Royce, and the Royal Navy with whom he has collaborated for many years.

March 1986

G.F.C.R.
H.I.H.S.

Preface to the second edition

At the suggestion of the publishers the authors agreed to produce a new edition of *Gas Turbine Theory* in SI units. The continued use of the first edition encouraged the authors to believe that the general plan and scope of the book was basically correct for an introduction to the subject, and the object of the book remains as stated in the original Preface. So much development has taken place during the intervening 21 years, however, that the book has had to be rewritten completely, and even some changes in the general plan have been required. For example, because gas dynamics now forms part of most undergraduate courses in fluid mechanics a chapter devoted to this is out of place. Instead, the authors have provided a summary of the relevant aspects in an Appendix. Other changes of plan include the extension of the section on aircraft propulsion to a complete chapter, and the addition of a chapter on the prediction of performance of more complex jet engines and transient behaviour. Needless to say the nomenclature has been changed throughout to conform with international standards and current usage.

The original authors are glad to be joined by Dr Saravanamuttoo in the authorship of the new edition. He is actively engaged on aspects of the gas turbine with which they were not familiar and his contribution has been substantial. They are glad too that the publisher decided to use a wider page so that the third author's name could be added without abbreviation. Dr Saravanamuttoo in his turn would like to acknowledge his debt to the many members of staff of Rolls-Royce, the National Gas Turbine Establishment and Orenda Engines with whom he has been associated in the course of his work. The authors' sincere appreciation goes to Miss G. M. Davis for her expert typing of the manuscript.

October 1971

H.C.
G.F.C.R.
H.I.H.S.

Preface to the first edition

This book is confined to a presentation of the thermodynamic and aerodynamic theory forming the basis of gas turbine design, avoiding as far as possible the many controversial topics associated with this new form of prime-mover. While it is perhaps too early in the development of the gas turbine to say with complete assurance what are the basic principles involved, it is thought that some attempt must now be made if only to fill the gap between the necessarily scanty outline of a lecture course and the many articles which appear in the technical journals. Such articles are usually written by specialists for specialists and presuppose a general knowledge of the subject. Since this book is primarily intended for students, for the sake of clarity some parts of the work have been given a simpler treatment than the latest refinements of method would permit. Care has been taken to ensure that no fundamental principle has been misrepresented by this approach.

Practising engineers who have been engaged on the design and development of other types of power plant, but who now find themselves called upon to undertake work on gas turbines, may also find this book helpful. Although they will probably concentrate their efforts on one particular component, it is always more satisfactory if one's specialized knowledge is buttressed by a general understanding of the theory underlying the design of the complete unit.

Practical aspects, such as control systems and mechanical design features, have not been described as they do not form part of the basic theory and are subject to continuous development. Methods of stressing the various components have also been omitted since the basic principles are considered to have been adequately treated elsewhere. For a similar reason, the theory of heat-exchangers has not been included. Although heat-exchangers will undoubtedly be widely used in gas turbine plant, it is felt that at their present stage of development the appropriate theory may well be drawn from standard works on heat transmission.

Owing to the rate at which articles and papers on this subject now appear, and since the authors have been concerned purely with an attempt to define the basic structure of gas turbine theory, a comprehensive bibliography has not been included. A few references have been selected, however, and are appended to appropriate chapters. These are given not only as suggestions for further reading, but also as acknowledgements of sources of information. Some problems, with answers, are given at the end of the book. In most cases these have been chosen to illustrate various points which have not appeared in the worked examples in the text. Acknowledgements are due to the Universities of Cambridge, Bristol and Durham for permission to use problems which have appeared in their examination papers.

The authors have obtained such knowledge as they possess from contact with the work of a large number of people. It would therefore be invidious to acknowledge their debt by mention of one or two names which the authors associate in their minds with particular aspects of the work. They would, however, like to express their gratitude in a corporate way to their former colleagues in the research teams of what were once the Turbine Division of the Royal Aircraft Establishment and Power Jets (R. & D.) Ltd, now the National Gas Turbine Establishment.

In conclusion, the authors will welcome any criticisms both of detail and of the general scheme of the book. Only from such criticism can they hope to discover whether the right approach has been adopted in teaching the fundamentals of this new subject.

April 1950

H.C.
G.F.C.R.

Publisher's Acknowledgements

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1

Introduction

The gas turbine is unquestionably one of the most important inventions of the 20th century, and it has changed our lives in many ways. Gas turbine development started just before the Second World War with electric power applications in mind, but these were not competitive with existing prime movers such as steam turbines and diesels. The first important application of the gas turbine was the development of the military jet engine towards the end of the Second World War, when it provided a step change in speed from the existing propeller-driven aircraft. These early engines were fuel inefficient, unreliable and extremely noisy, but in less than 20 years they had matured to become the standard form of propulsion for civil aircraft. By the early 1970s, continuous development led to the development of the high bypass ratio turbofan and the major improvement in fuel efficiency made the high-capacity wide-body airliner possible. The resulting gains in productivity and economics were remarkable and opened up air travel to the masses. A brief historical review of civil propulsion is given in Ref. (1), where it is shown that jet engine developments resulted in the rapid demise of ocean passenger liners and long-distance passenger trains in North America.

It took longer for the gas turbine to have a similar impact in non-aircraft markets. Early gas turbines for power generation applications were of low power and their thermal efficiency was too low to be competitive. By the early 21st century, however, gas turbines were capable of outputs up to 500 MW with thermal efficiencies of over 40 per cent and the gas turbine (frequently combined with the steam turbine) became widely used in power generation. Another major market, which emerged in the 1960s, was the transmission of natural gas over long distances in pipelines, where the gas turbines were fuelled by gas extracted from the pipeline.

In order to produce an expansion through a turbine a pressure ratio must be provided, and the first necessary step in the cycle of a gas turbine plant must therefore be compression of the working fluid. If after compression the working fluid were to be expanded directly in the turbine, and there were no losses in either component, the power developed by the turbine would just equal that absorbed by the compressor. Thus if the two were coupled together the combination would do no more than turn itself round. But the power developed by the turbine can be

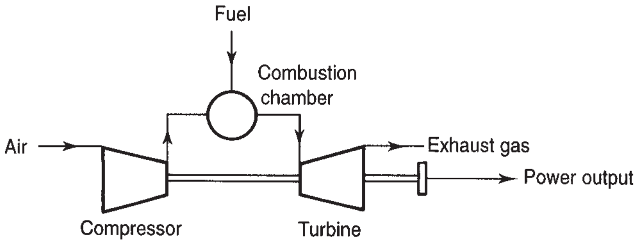

FIG. 1.1 Simple gas turbine system

increased by the addition of energy to raise the temperature of the working fluid prior to expansion. When the working fluid is air a very suitable means of doing this is by combustion of fuel in the air which has been compressed. Expansion of the hot working fluid then produces a greater power output from the turbine, so that it is able to provide a useful output in addition to driving the compressor. This represents the gas turbine or internal-combustion turbine in its simplest form. The three main components are a compressor, combustion chamber and turbine, connected together as shown diagrammatically in Fig. 1.1.

In practice, losses occur in both the compressor and turbine which increase the power absorbed by the compressor and decrease the power output of the turbine. It is therefore necessary to add energy to the working fluid, by supplying some fuel, before the turbine can produce sufficient power to drive the compressor. Further addition of fuel will result in useful power output, although for a given flow of air there is a limit to the rate at which fuel can be supplied and therefore to the net power output. The maximum fuel/air ratio that may be used is governed by the working temperature of the highly stressed turbine blades, which is limited by the creep strength of the turbine material and the working life required. Increasing the pressure ratio of the compressor increases the temperature at entry to the combustion chamber and hence reduces the fuel flow required to achieve the specified turbine inlet temperature.

Thus the three key factors affecting the performance of gas turbines are the compressor pressure ratio, the turbine inlet temperature and the component efficiencies. The higher they can be made, the better the overall performance of the plant.

It will be shown in Chapter 2 that the overall efficiency of the gas turbine cycle depends primarily upon the pressure ratio of the compressor. The difficulty of obtaining a sufficiently high pressure ratio with an adequate compressor efficiency was not resolved until the science of aerodynamics could be applied to the problem. The development of the gas turbine has gone hand in hand with the development of this science, and that of metallurgy, with the result that it is now possible to find advanced engines using pressure ratios of up to 60:1, component efficiencies of 85–90 per cent, and turbine inlet temperatures exceeding 1800 K.

In the earliest days of the gas turbine, two possible systems of combustion were proposed: one at constant pressure, the other at constant volume. Theoretically, the thermal efficiency of the constant volume cycle is higher than that of the constant pressure cycle, but the mechanical difficulties are very much greater. With heat addition at constant volume, valves are necessary to isolate the combustion chamber from the compressor and turbine. Combustion is therefore intermittent, which impairs the smooth running of the machine. It is difficult to design a turbine to operate efficiently under such conditions and, although several fairly successful attempts were made in Germany during the period 1908–1930 to construct gas turbines operating on this system, the development of the constant volume type has been discontinued. In the constant pressure gas turbine, combustion is a continuous process in which valves are unnecessary and it was soon accepted that the constant pressure cycle had the greater possibilities for future development. A key advantage of the constant pressure system was its ability to handle high mass flows, which in turn lead to high power.

It is important to realize that in the gas turbine the processes of compression, combustion and expansion do not occur in a single component as they do in a reciprocating engine. They occur in components which are separate in the sense that they can be designed, tested and developed individually, and these components can be linked together to form a gas turbine unit in a variety of ways. The possible number of components is not limited to the three already mentioned. Other compressors and turbines can be added, with intercoolers between the compressors, and reheat combustion chambers between the turbines. A heat-exchanger which uses some of the energy in the turbine exhaust gas to preheat the air entering the combustion chamber may also be introduced. These refinements may be used to increase the power output and efficiency of the plant at the expense of added complexity, weight and cost. The way in which these components are linked together affects not only the maximum overall thermal efficiency, but also the variation of efficiency with power output and of output torque with rotational speed. One arrangement may be suitable for driving an alternator under varying load at constant speed, while another may be more suitable for driving a ship's propeller where the power varies as the cube of the speed.

Apart from variations of the simple cycle obtained by the addition of these other components, consideration must be given to two systems distinguished by the use of *open* and *closed* cycles. In the almost universally used *open*-cycle gas turbine which has been considered up to this point, fresh atmospheric air is drawn into the circuit continuously and energy is added by the combustion of fuel in the working fluid itself. The products of combustion are expanded through the turbine and exhausted to the atmosphere. In the alternative, and rarely used, *closed* cycle shown in Fig. 1.2 the same working fluid, be it air or some other gas, is repeatedly circulated through the machine. Clearly, in this type of plant the fuel cannot be burnt in the working fluid and the necessary energy must be added in a heater or 'gas-boiler' in which the fuel is burnt in a separate air stream supplied by an auxiliary fan. The closed cycle is more akin to that of steam turbine plant in that the combustion gases do not themselves pass through the turbine. In the gas turbine the 'condenser' takes the form of a precooler for cooling of the gas before it

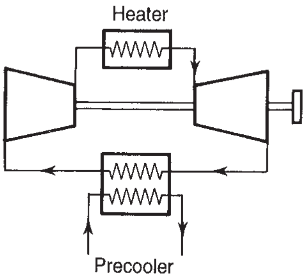

FIG. 1.2 Simple closed cycle

re-enters the compressor. Although little used, numerous advantages are claimed for the closed cycle and these will be put forward in section 1.3.

Finally, various *combined gas and steam cycles* are now widely used for electric power generation, with thermal efficiencies exceeding 60 per cent. The gas turbine exhaust, typically at a temperature of 500–600°C, is used to raise steam in a *waste heat boiler* (WHB) or *heat recovery steam generator* (HRSG); this steam is then used in a steam turbine which drives a generator. Figure 1.3 shows such a system, using a dual-pressure steam cycle. With increasing cycle temperatures the exhaust gas entering the HRSG is hot enough to permit the use of a triple-pressure steam cycle incorporating a stage of reheat, and this is becoming common in large base-load power stations. It should be noted that the turbine exhaust has unused oxygen content and it is possible to burn additional fuel in the boiler to raise steam output;

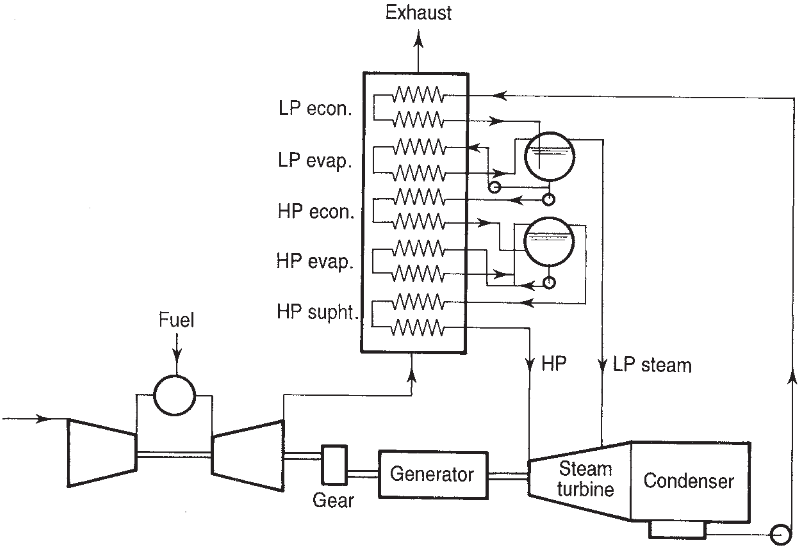

FIG. 1.3 Combined gas and steam cycle

this *supplementary firing* is most likely to be used with gas turbines operating at a relatively low exhaust gas temperature. The steam produced may be used in a process such as paper drying, brewing or building heating as well as producing electricity, and this is referred to as *cogeneration* or *combined heat and power* (CHP). Although the characteristic compactness of the gas turbine is sacrificed in *binary cycle* plant, the efficiency is so much higher than is obtainable with the simple cycle that such turbines are now widely used for large-scale electricity generating stations (see section 1.5).

The gas turbine has proved itself to be an extremely versatile prime mover and has been used for a wide variety of functions, ranging from electric power generation, mechanical drive systems and jet propulsion to the supply of process heat and compressed air, and the remainder of this Introduction is intended to emphasize the wide range of applications.† We commence, however, by discussing the various ways in which the components can be linked together to produce *shaft power.* Gas turbines for electric power generation, pump drives for gas or liquid pipelines and land and sea transport will be considered before turning our attention to aircraft propulsion.

1.1 Open-cycle single-shaft and twin-shaft arrangements

If the gas turbine is required to operate at a fixed rotational speed, as in electric power generation, the *single shaft* arrangement shown in Fig 1.1 is the most suitable. Variation of electrical load can be accommodated by a change of fuel flow while operating at constant speed. A heat-exchanger may be added as in Fig. 1.4 to improve the thermal efficiency, although for a given size of plant, the power output could be reduced by as much as 10 per cent owing to frictional pressure loss in the heat-exchanger. It will be shown in Chapter 2 that a heat-exchanger is essential for high efficiency when the cycle pressure ratio is low, but becomes less advantageous as the pressure ratio is increased; at high pressure ratios the turbine outlet temperature may be lower than the compressor delivery temperature and the

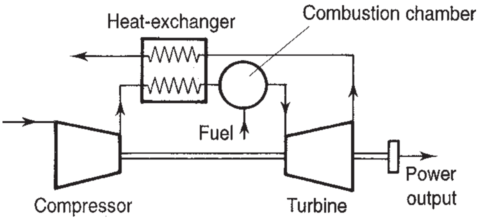

FIG. 1.4 Single-shaft open-cycle gas turbines with heat-exchanger

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†Some of the remarks about the ‘stability of operation’ and ‘part-load performance’ will be more fully understood when the rest of the book, and Chapter 9 in particular, have been studied. It is suggested therefore that the remainder of the Introduction be given a second reading at that stage.

heat-exchanger would then lower the cycle efficiency. As a result of continuous aerodynamic development and increasing turbine inlet temperatures, thermal efficiencies of over 40 per cent are achieved by simple cycle gas turbines and heat-exchangers are seldom used today. For many years, the heat-exchange cycle was not considered for new designs because high efficiency could be obtained either by the high pressure ratio simple cycle or the combined gas and steam cycle. In the 1990s, the Advanced Turbine Systems (ATS) program conducted in the USA focused attention on the use of heat-exchange for lower power units, resulting in the emergence of the 4 MW Solar Mercury (Fig. 2.14) with an efficiency of 39 per cent.

If the application involves a variable speed load, such as a pipeline compressor or marine propeller, the use of a mechanically independent (or *free*) *power turbine* is necessary. In this *twin- shaft* arrangement, Fig. 1.5, the high-pressure turbine drives the compressor and the combination acts as a gas generator for the low pressure power turbine. To drive a compressor, the turbine would be designed to run at the same speed as the compressor, making a gearbox unnecessary. The marine propeller, however, would run at a much lower speed and a reduction gearbox would be required. Twin-shaft engines may also be used to drive a generator, with the power turbine controlled to run at fixed speed; these would often be derived from jet engines with the exhaust gases expanded through a power turbine rather than the existing exhaust nozzle. The power turbine may be designed to run at the generator speed without a gearbox, as for the compressor drive (see Fig. 8.2). Shedding of electrical load can lead to the rapid over-speeding of the power turbine and the control system must be designed to prevent this. The twin-shaft engine has a significant advantage in ease of starting compared with a single-shaft engine, because the starter needs only to be sized to turn over the gas generator. The starter may be electric, a hydraulic motor, an expansion turbine operated from a supply of pipeline gas, or even a steam turbine or diesel engine.

Variation of power for both single-shaft and twin-shaft units is obtained by controlling the fuel flow supplied to the combustion chamber. Although they behave in rather different ways, as will be explained in Chapter 9, in both cases the cycle pressure ratio and turbine inlet temperature decrease as the power is reduced from the design value with the result that the thermal efficiency deteriorates considerably at part load. Gas turbines are not suitable for continued operation at low power and methods of alleviating this problem will be discussed later.

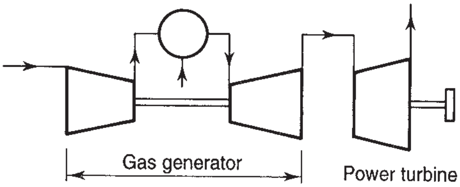

FIG. 1.5 Gas turbine with separate power turbine

The performance of a gas turbine may be significantly improved by reducing the work of compression and/or increasing the work of expansion. For any specified pressure ratio, the power required per unit quantity of working fluid is directly proportional to the inlet temperature. If the compression process is carried out in two or more stages with *intercooling,* the overall work of compression will be reduced. Similarly, the turbine output can be increased by dividing the expansion into two or more stages, and *reheating* the gas to the maximum permissible temperature between the stages. One possible arrangement of a plant incorporating intercooling, heat-exchange and reheat is shown in Fig. 1.6(a).

Complex cycles were used in the early days of gas turbines, when they were necessary to obtain a reasonable thermal efficiency at the low turbine inlet

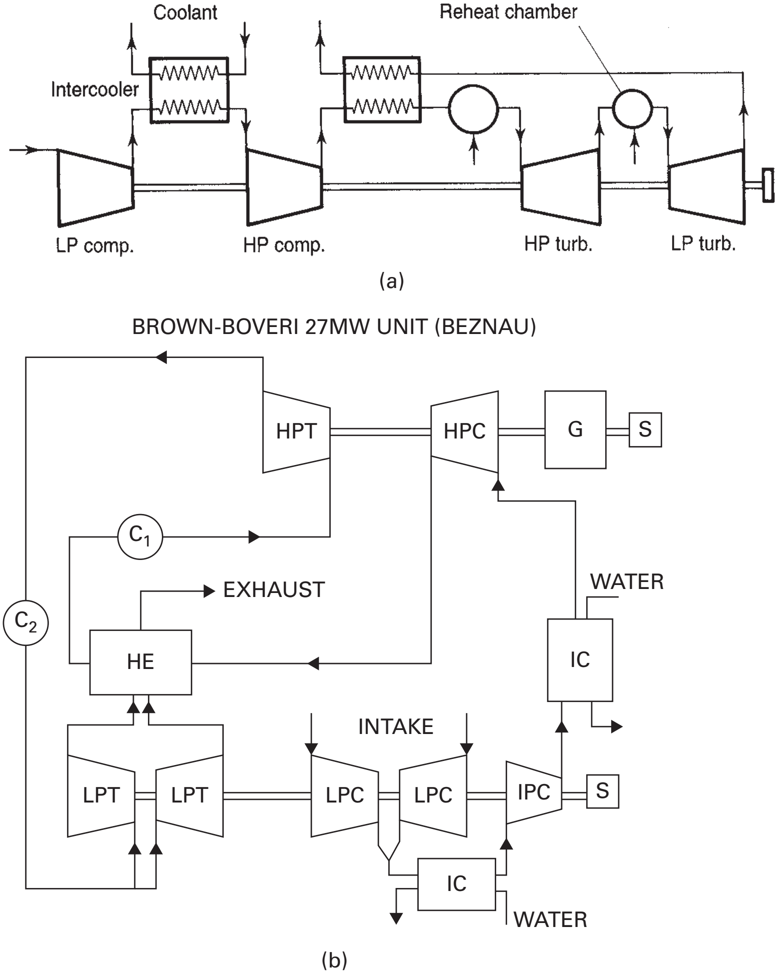

FIG. 1.6 Complex plant with intercooling, heat-exchange and reheat

temperatures and pressure ratios then possible. The arrangement of a 27 MW plant built by Brown Boveri in 1948 is shown in Fig. 1.6(b); this was the largest gas turbine built then. This required three compressors, two intercoolers, a heat-exchanger, two combustors and two turbines. It can also be seen that two separate shaft lines were used, each requiring its own starter. The maximum cycle temperature was around 900K and a thermal efficiency of 30 per cent was achieved. It can readily be seen that the inherent simplicity and compactness of the gas turbine have been lost. It is significant that gas turbines did not become widely used until higher turbine inlet temperatures and pressure ratios made the simple cycle economically viable.

The quest for high efficiency as gas turbines became more widely used in base-load applications led to a revival of interest in more complex cycles in the 1990s. ABB (later Alstom) reintroduced the reheat cycle, referred to as ‘sequential combustion’. This permitted the use of a very high pressure ratio, resulting in a thermal efficiency of around 36 per cent, with no intercooling or heat-exchange. A simple cycle with a very high pressure ratio would have an exhaust gas temperature of around 450°C, which would not be satisfactory for use in a combined cycle. The use of reheat, however, results in an exhaust gas temperature exceeding 600°C, permitting the use of a triple-pressure reheat steam cycle and a combined cycle efficiency of 60 per cent. Rolls-Royce developed the intercooled regenerative cycle (ICR) for naval propulsion, giving both high thermal efficiency at the design point and excellent part-load efficiency, a very important feature for warships which generally cruise for extended periods at much lower power levels than the design value (see Fig. 10.2). A key design requirement was that the ICR engine, despite its additional components, should fit into the same footprint as the current naval engines of similar power. GE reintroduced intercooling in the LMS100, a 100 MW unit for electric power application. The intercooled cycle gives an efficiency of 46 per cent, making the engine very attractive for peaking applications. The LMS100 combines the technology of both heavy-duty industrial engines and aircraft engines, using a twin-spool arrangement with free power turbine as described in the next section.

1.2 Multi-spool arrangements

To obtain a high thermal efficiency without using a heat-exchanger, a high pressure ratio is essential. The nature of the compression process, however, limits the pressure ratio which can be achieved.

Non-positive displacement compressors are always used in gas turbines because of the high air mass flow rates involved. At full power the density at the rear end of the compressor is much higher than at the inlet, and the dimensions of the compressor at exit are determined on the basis of the flow and density. When operated at rotational speeds well below the design value, however, the gas density at exit is much too low, resulting in excessive velocities and breakdown of the flow. This unstable region, which is manifested by violent aerodynamic vibration and reversal of the flow, is most likely to be encountered at low power or during start-up; this can result in either severe overheating in the turbine or a flame-out.

In the early days of gas turbines it was found that the problem was particularly severe if an attempt was made to obtain a pressure ratio of more than about 8:1 in a single axial flow compressor. One solution to this problem is to split the compressor into two or more sections. In this context we mean *mechanical* separation, permitting each section to run at different rotational speeds, unlike the intercooled compressor shown in Fig. 1.6. With mechanically independent compressors, each will require its own turbine and a suitable arrangement is shown in Fig. 1.7. The LP compressor is driven by the LP turbine, and the HP compressor is driven by the HP turbine (see also Figs 1.12(a) and 1.12(b)). Power may be taken from the LP shaft, as shown, or from a separate power turbine. The configuration shown in Fig. 1.7 is usually referred to as a *twin-spool* engine. It should be noted that although the spools are *mechanically* independent, their speeds are related *aerodynamically* and this will be further discussed in Chapter 10. Figure 1.16 shows a *triple-spool* layout for an engine sold both as a high bypass ratio turbofan and an industrial shaft power unit.

The twin-spool layout was primarily developed for the aircraft engines discussed in section 1.4, but there are many examples of shaft power derivatives of these; most aero-derivative engines substituted a free power turbine in place of the propelling nozzle. Current examples include the Rolls-Royce RB-211 and the PW FT-8. The GE LM 6000, on the other hand, uses the configuration of Fig. 1.7 and the generator and LP compressor run at constant speed. In smaller engines the HP compressor is frequently of the centrifugal type, because at the high pressures and densities involved the volume flow rate is low and the blading required for an axial compressor would be too small for good efficiency. Twin-spool units were first introduced at a pressure ratio of about 10 and are suitable for cycle pressure ratios of at least 45:1. Triple-spool arrangements can also be used in large turbofan engines, where there is a requirement for both a very high pressure ratio and a low rotational speed for the large-diameter fan.

As an alternative to multiple spools, a high pressure ratio can be safely employed with a single compressor if several stages of *variable stator blades* are used. GE pioneered this approach, which is now widely used by other companies; a pressure ratio of 35:1 on a single shaft is utilized in the Alstom reheat gas turbine. It is frequently necessary to use *blow-off* valves at intermediate locations in the compressor to handle the serious flow mismatch occurring during start-up; as

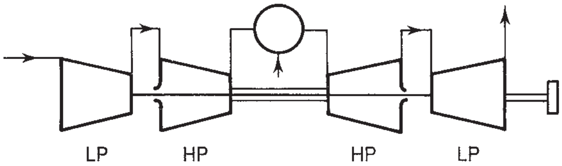

FIG. 1.7 Twin-spool engine