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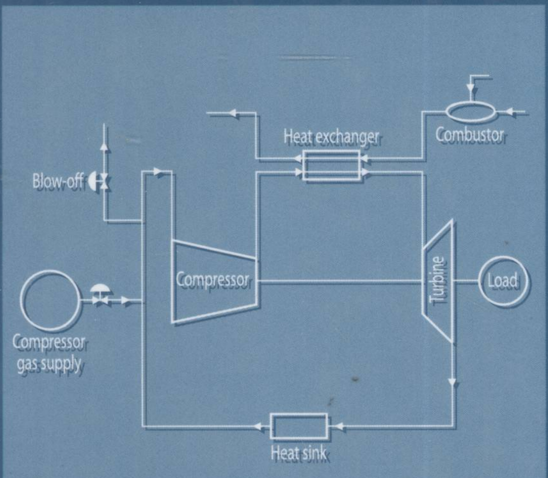
Industrial gas turbines

Performance and operability

A. M. Y. Razak



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Industrial gas turbines

Foreword

Improving gas turbine performance involves the bringing together and optimisation of the disciplines and skills required to achieve an operationally competitive gas turbine engine. Certainly, the design and performance of individual engine components, such as the compressors, combustors and turbine, could alone present an engineer with a worthwhile career. It is, however, the overall performance of the gas turbine that the customer actually purchases. The optimisation process involves many uncertainties and a proper understanding of these, together with the established facts and the method of handling this information, is required to permit manufacturers to develop their engines successfully and allow operators to operate the machines to their best advantage. This is particularly true in the de-regulated market in which many operate today and which others will be joining in the near future.

Although there are many very remarkable books on industrial gas turbine performance and engineering, this book offers something different through a combined approach to the theory of gas turbines, their performance, and the use of gas turbine simulators. Simulators form an analysis method which can be used to bring together the many disciplines involved and which provides a way of assessing the impact of uncertainties. The combination of the book with the example simulators provides an added dimension to the product and this seems to conform to what many educational and training experts in this field have been demanding for some time. The book/simulator combination provides a useful reference text for students and practising engineers in both gas turbine manufacturing and operations.

The book initially covers the theory of gas turbine performance from a design and off-design point of view, including transient analysis, and gives much detail on these two very important aspects of engine performance. The latter part of the book revisits the earlier chapters, using the simulators to highlight in detail the issues facing industrial gas turbines in the real world. The simulators are effectively virtual engines with respect to performance, deterioration, emissions, control, and life usage. There is also a useful life cycle calculation module. This provides a clear view of the operability of the gas turbine under different conditions.

The book includes numerous simulation exercises. These exercises are not restrictively academic but include much of the author's experience, gained from an operator's viewpoint. Unlike numerical exercises, which give a somewhat narrow understanding of the problem, simulation exercises provide a holistic view of performance, which students, manufacturers and operators will find invaluable.

Robin Elder, BSc, PhD, C Eng, FIMechE
Director, PCA Engineers Limited

Preface

The use of industrial gas turbines is widespread in many industries that require power. The power is used to generate electricity or drive equipment such as pumps and process compressors. Gas turbines are also used extensively in naval propulsion and in this case are often referred to as naval gas turbines. In any of these applications, the performance of the gas turbines is the end product that strongly influences the profitability of the business that employs them. Industrial gas turbines often have to operate for prolonged periods at conditions that do not correspond to their design conditions. Therefore, understanding the performance of gas turbines at such operating conditions is particularly important, especially in a deregulated market.

Other factors in addition to the performance of gas turbines affect their operability. These factors include emissions, deterioration, life usage and controls. For example, legislation may result in emissions being too high and the means to control them could affect the engine performance and thus revenue. Gas turbine performance deterioration is inevitable. This could be due to compressor fouling, which can be easily rectified by compressor washing, or to more serious damage to compressors or turbines. Therefore, an understanding of performance deterioration is now paramount. Various engine operating limits are imposed by manufacturers and correspond to the exhaust gas turbine limit, speed and power. These are necessary to achieve suitable engine life, namely turbine creep life. It is the responsibility of the engine control system to ensure that such operating limits are not exceeded. Furthermore, it is also the job of the control system to ensure that any engine load changes occur safely.

Improving the understanding of the above issues has provided the impetus to write this book. The book begins with a brief revision of engineering thermodynamics before considering the design point performance of gas turbines, including both simple and complex cycles. The performance of gas turbine components (compressors, combustors and turbines) is also discussed. Means to improve dry low-emission combustion systems are included. The prediction and modelling of the off-design performance of gas turbines is discussed, including the modelling of complex cycles which employ intercooling, reheat and regeneration. The impact and detection of performance deterioration and the importance of such detection and rectification are also discussed. Control system performance, including the prediction of the transient performance of gas turbines, is considered. Furthermore, the application of control systems to improve the performance of dry low-emission combustion systems by the use of variable geometry components is discussed.

The CD accompanying the book contains two gas turbine simulators, which correspond to single-shaft and two-shaft engines. These two engine configurations cover the vast majority of industrial gas turbines operating in the field. Much of the text describing the performance and operability of industrial gas turbines can be illustrated and enlivened by the use of these gas turbine simulators. The simulators are used extensively in Parts II and III to:

(1) simulate the effects of ambient temperature, pressure and humidity on performance, turbine creep life and emissions, including the impact of inlet and exhaust losses;
(2) simulate the effects of engine deterioration on performance, creep life and emissions;
(3) simulate the impact of power augmentation and enhancement using turbine inlet cooling, peak rating, water injection and optimisation on performance, creep life and emissions;
(4) simulate control system performance on engine operability including proportional off-set, integral wind-up and engine trips;
(5) simulate the effect of a change in fuel type (e.g. natural gas or diesel) on performance and emissions.

There are nearly 50 simulation exercises included using each simulator. Exercises using simulators give a holistic view of engine performance and operability which numerical exercises fail to achieve. Nevertheless, numerical exercises are essential to augment the understanding of engine performance and some worked examples are given.

The simulators include other useful features and can show:

(1) impact on life cycle costs, revenue and profitability (including the impact of emissions taxes such as CO_2 and NO_x on life cycle costs and, thus, profitability);
(2) output from the turbine inlet cooling simulation which can be used to evaluate the suitability of turbine inlet cooling for any gas turbine for a particular site;
(3) trends for many engine parameters, including key parameters such as EGT and speeds that protect the engine from damage;
(4) compressor characteristics and the operating point during engine transients;
(5) bar charts;
(6) simulated data that can be exported to other computer packages (e.g. Microsoft Excel spreadsheets).

Acknowledgements

Much of this work would have been impossible without the support, help and suggestions from friends and colleagues. In particular, I wish to thank Dr John Greenbank and John Layton for their expert proofreading, which has improved the quality of the text and presentation of the book. Also, my friend and mentor Professor Robin Elder, who is wholly responsible for first introducing me to serious engineering computing, for his encouragement and support throughout the writing and preparation of this book. Also, I thank Woodhead Publishing for its patience during the preparation of the manuscript, particularly Sheril Leich for her thorough checking of the manuscript and suggestions.

I also wish to remember J. R. (Jimmy) Palmer of Cranfield Institute of Technology (now Cranfield University) who, in his day, was considered one of the authorities on gas turbine performance. I am privileged to have known him.

Note about the CD-ROM accompanying this book

As stated in the Preface, this CD-ROM includes software simulating the operation of a single-shaft gas turbine and a two-shaft gas turbine. The simulators are built on the engine modelling concepts discussed in the book and should be used to repeat the simulation discussion in Parts II and III and to perform the exercises in Chapter 21.

- **Minimum system requirements**

This CD-ROM is intended for use with Windows-compatible computers. You will require an internet connection for registration (see below).

Please note that, as part of the registration process, you will need to make a note of the **Disk ID Number**. This can be found **on the front of the plastic wallet containing the CD-ROM**. We suggest you make a **note of this number now**. You need take no further steps in the registration process until you install the CD-ROM.

- **Software requirements**

Adobe® Reader®

- **Installation instructions**

Insert the CD-ROM into the CD-ROM drive. The CD-ROM should auto-run. If the CD-ROM does not auto-run, open Microsoft Internet Explorer® on your computer and open the file *index.html*. If you continue to experience difficulties, please contact Gas Path Analysis Ltd for help (e-mail: support@gpal.co.uk)

- **Registration process**

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Abbreviations and notation

C	thermal capacity ratio
CO	carbon monoxide
CO_2	carbon dioxide
c_p	specific heat at constant pressure
c_v	specific heat at constant volume
DLE	dry low emission
EGT	exhaust gas temperature
GG	gas generator
H	enthalpy
HP	high pressure
ICRHR	intercooled, reheat and regenerative cycle
IP	intermediate pressure
ISO	International Standards Organisation
J	Joules
K	Kelvin
kg	kilogram
LP	low pressure
LPM	lean premixed
m	mass flow rate
MCFC	molten carbonate fuel cell
MEA	methanol amine
MW	MegaWatt or molecular weight
NGV	nozzle guide vane
NO_x	oxides of nitrogen
NTU	number of transfer units
P	pressure
PID	Proportional, Integral and Derivative
pr	pressure ratio
Q	heat input
R	gas constant
RQL	Rich-burn, Quick-quench, Lean-burn
s	second

S	entropy
SCR	selective catalytic reduction
SOFC	solid oxide fuel cells
SOT	stator outlet temperature
T	temperature
TET	turbine entry temperature
UHC	unburnt hydrocarbons
VIGV	variable inlet guide vane
VSV	variable stator vane
W	work output
x	number of carbon atoms
y	number of hydrogen atoms
Z	compressibility factor
γ	ratio of specific heats
ε	effectiveness of heat exchanger
η	efficiency
ϕ	relative humidity
ω	specific or absolute humidity

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