Radial Flow Turbocompressors

An introduction to the theory and engineering practice that underpins the component design and analysis of radial flow turbocompressors. Drawing upon an extensive theoretical background and years of practical experience, the authors provide the following:

- Descriptions of applications, concepts, component design, analysis tools, performance maps, flow stability and structural integrity, with numerous illustrative examples
- Wide coverage of all types of radial compressor over a range of applications unified by the consistent use of dimensional analysis
- The methods needed to analyse the performance, flow and mechanical integrity that underpin the design of efficient centrifugal compressors with good flow range and stability
- Explanation of the design of all radial compressor components, including inlet guide vanes, impellers, diffusers, volutes, return channels, deswirl vanes and side-streams

This volume is suitable as a reference for advanced students of turbomachinery, and a perfect tool for practising mechanical and aerospace engineers already within the field as well as those just entering it.

Michael Casey is a director of PCA Engineers Limited, and was previously a Professor of Thermal Turbomachinery at the University of Stuttgart.

Chris Robinson is managing director at PCA Engineers Limited and a specialist in the aeromechanical design of centrifugal compressors.

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Design, Analysis, and Applications

MICHAEL CASEY
PCA Engineers Limited

CHRIS ROBINSON
PCA Engineers Limited

CAMBRIDGE
UNIVERSITY PRESS

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University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India

79 Anson Road, #06–04/06, Singapore 079906

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning, and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781108416672
DOI: 10.1017/9781108241663

First published 2021

Printed in the United Kingdom by TJ Books Limited, Padstow Cornwall

A catalogue record for this publication is available from the British Library.

Library of Congress Cataloging-in-Publication Data
Names: Casey, Michael, 1948- author. | Robinson, Chris, 1959- author.
Title: Radial flow turbocompressors : design, analysis, and applications / Michael Casey, PCA Engineers Limited, Chris Robinson, PCA Engineers Limited.
Description: Cambridge, United Kingdom ; New York, NY, USA : Cambridge University Press, 2021. | Includes bibliographical references and index.
Identifiers: LCCN 2020046835 (print) | LCCN 2020046836 (ebook) | ISBN 9781108416672 (hardback) | ISBN 9781108241663 (epub)
Subjects: LCSH: Centrifugal compressors.
Classification: LCC TJ990 .C366 2021 (print) | LCC TJ990 (ebook) | DDC 621.5/1–dc23
LC record available at https://lccn.loc.gov/2020046835
LC ebook record available at https://lccn.loc.gov/2020046836

ISBN 978-1-108-41667-2 Hardback

The first author gratefully dedicates his part in this book to his parents, Jean and Eric Casey, who made it all possible by their struggles and sacrifices in the hard times of the 1950s and 1960s and for their endearing love and encouragement over the whole of their lives.

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Cambridge University Press
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Credits

Unless otherwise stated, the simulations presented in the book have been obtained with ANSYS CFX and ANSYS mechanical software.

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Introduction

This book is about the engineering science that is most useful for the design and analysis of radial turbocompressors over a wide range of applications. The aim is to provide the most relevant information for designers, especially the pragmatic approaches that the authors find are quickest and the most effective. The book concentrates on one-dimensional (1D) and two-dimensional (2D) analyses of the fluid dynamic, thermodynamic and mechanical phenomena. These analyses provide rigorous, common-sense ways of looking at the problems and are usually the most insightful way to an engineering solution that is suitable for design purposes. These methods are also the most amenable and doable for engineers who study them. The 1D and 2D analyses often provide a good grounding for understanding the results arising from detailed analysis with three-dimensional (3D) simulations.

During their careers, the authors have been faced with many difficult questions with regard to radial compressors, and this book documents some of the approaches and shortcuts in the wide literature on this subject that they have found to be the most useful. The book provides a coherent description of the most useful theory and the necessary pragmatic experience associated with it in the design environment. It is hoped that the book provides a suitable introduction to engineers entering this field, enabling them to get up to speed when starting from scratch, and gives useful guidance for advanced students of turbomachinery. It should also act as a practical detailed reference for practitioners, specialists and academics working in this area, helping them to see the clusters in the forest rather than individual trees. For additional guidance, each chapter includes a brief list of the important learning objectives related to its content and gives extensive references for further study.

In Chapter 1, the basic definition of a turbomachine is considered together with a classification and history of different turbomachines. Different applications of radial flow turbocompressors are then outlined to show their wide range of aerodynamic duty. They are used in many different industries due to their inherent robustness, good efficiency and broad operating range. Meeting environmental goals with reduced carbon and other greenhouse gas emissions is likely to lead to more applications of radial compressors in the future. The focus of Chapters 2–9 is to take all readers to the same level of understanding in the essential principles and concepts of aerothermodynamics relevant to compressors before details of the design and performance of radial compressors are examined in the subsequent chapters. The background knowledge in these early chapters is also relevant for most other turbomachines, but is presented in a way that draws out specific information and useful insights relevant to radial compressors. Much of the content of these first chapters derives from lecture courses on fluid dynamics, gas dynamics and thermodynamics.

Chapter 2 considers energy transfer in radial compressors, both from the kinematic point of view through the velocity triangles and from the statements of the first and second laws of thermodynamics. Here some emphasis is placed on the definition and physics of the aerodynamic work, also known as the polytropic head, in isentropic, polytropic and isothermal compression processes. The importance of the centrifugal effect and the relevance of the degree of reaction are particularly emphasised. This is followed by Chapter 3 introducing different equations of state that can be used to model the gas behaviour for the many radial compressor applications where the gas deviates from ideal gas behaviour. Chapter 4 covers some thorny and oft-neglected concepts related to the definition of efficiency in compressors taking into account the dissipation losses, the aerodynamic work and the change in kinetic energy across a component. Chapters 3 and 4 might be omitted on a first reading of the book.

Chapters 5–9 provide fundamentals of the basic fluid dynamic theory needed to understand the complex flow in radial turbocompressors. Chapter 5 provides a physical description of the fluid dynamics of diffusing flow in curved blades and flow channels and how this is affected by the duty of the compressor. Chapter 6 provides an overview of gas dynamics for compressible flow including the important features of the shock system at the inlet to the blade rows in a transonic impeller. Chapter 7 highlights the important fluid dynamic principles of the flows around aerofoils, cascades of blades and the aerodynamic loading limits involved in the diffusing flow in radial compressor flow channels both in impellers and vaned diffusers. Chapter 8 introduces the nondimensional similarity parameters that are of most use in the analysis of turbocompressors and provides a description of their relevance and application. A consistent use of these dimensionless parameters is used throughout the book to categorise the different aspects and link the technology in different compressor applications. The effect of compressibility is considered from the concept of thermodynamic similarity leading to the definition of the tip-speed Mach number, based on the ratio of the inlet speed of sound and the mechanical blade speed at the impeller outlet. Chapter 9 discusses two other non-dimensional parameters known as the specific speed and specific diameter, together with their presentation in a Cordier diagram. The awkwardness of these dimensionless parameters is described in Chapter 9, where reasons for scepticism with regard to their use for radial compressors is explained. Despite its popularity in many radial compressor publications, the specific speed is otherwise hardly mentioned in the book.

These earlier chapters are a compendium of fundamental knowledge and concepts that are referred to in the subsequent chapters, which then examine details of the design, development, performance and testing of radial turbocompressors. Chapters 10–20 are derived from the lecture course on axial and radial compressors given by the first author at the Institute of Thermal Turbomachinery and Machinery Laboratory (ITSM) in Stuttgart University and from training material used by PCA Engineers Limited. Chapter 10 begins this process with a one-dimensional description of the losses and the prediction of the performance levels of radial compressors. The relevance of the duty required in terms of the important nondimensional parameters, the flow coefficient and the tip-speed Mach number in determining the level of the efficiency that can be expected is highlighted. Elementary considerations which determine the size and rotational speed of a compressor for a given duty are also described.

The background to the design of different components is covered in in the next three chapters. In Chapter 11, the design of the impeller inlet to achieve the most compact stage is emphasised. The crucial importance of the work coefficient in determining the steepness of the impeller characteristic is explained. The impeller and the diffuser are coupled together by the impeller outlet flow and its velocity triangle and a little-known diagram, first used by Mehldahl (1941), is presented in different forms to elucidate the matching of these components at different flow rates and for different styles of design. In Chapter 12, the pressure recovery of a vaneless diffuser and of various forms of vaned diffuser is described. The performance of the different zones of vaned diffuser is linked to the performance of planar diffusers. Chapter 13 considers other stator components, including the inlet nozzle and inlet guide vanes upstream of the impeller, and the different possible downstream components, including crossover channels, return channels, deswirl vanes, volutes, sidestream inlets and the rotor-stator cavities, and their influence on axial thrust.

The aerodynamic design tools that the authors have found to be most useful in practical applications are described in Chapter 14 (geometry definition), Chapter 15 (throughflow methods) and Chapter 16 (computational fluid dynamics). The first author was involved in the development of geometry definition methods and throughflow methods for radial machines in the early 1980s. The second author has spent most of his career using these methods. Both authors were separately involved in some of the first applications of computational fluid dynamics (CFD) methods in industry in the 1980s and early 1990s. Some of the teething difficulties of CFD technology during its development from infancy to maturity over the last 40 years left a lasting impression and has certainly coloured our reflection of this important technology.

The critical difference between compressors and turbines is that compressors are subject to rotating stall and to surge, which limit the safe operating range of the machines. The critical issue is the onset of instabilities in the flow and how to avoid them. Despite the advances in numerical methods, the stable operating range remains one of the least well-predicted aspects of performance. The current understanding of the unstable nature of the flow in compressors at low flow near the surge line is reviewed in Chapter 17 together with different control strategies to increase the operating range. Performance maps from surge to choke in single-stage and multistage compressors are described in Chapter 18, and their use in the matching of components in different compressor applications is described.

Chapter 19 offers an introduction to the key aspects of structural integrity and rotor dynamics. The objective here is to introduce the important mechanical concepts so that an aerodynamic designer is aware of the issues and can take advantage of the many specialist works in this field. Chapter 20 closes the book by providing some details of the typical design and development processes up to and including compressor testing.

An extensive list of references is provided to demonstrate that our views are well supported by the evidence in the technical literature. This is barely the tip of the iceberg of the relevant papers that are available on the subject, and these in turn give copious leads to other sources of useful information. The list includes most of our own technical publications, not that these have any special modicum of merit compared to other publications, but because these are the ones with which we are most familiar and are our personal anchor to the technology. Like all engineer scientists we are pleased with our contribution to design methods which were not there until we personally developed them.

Communication with the authors with regard to any aspects of the book can be made via the following website: www.pcaeng.co.uk.

Preface

This book is our homage to radial flow turbocompressors. These have not only presented us with many challenging engineering design problems but also provided us with a rewarding subject of academic study. They have also given us many friends, a network of great like-minded colleagues the world over and the major part of our income over many years.

The risk of writing a preface is that it can have the unwanted effect that some readers may read the preface and leave the rest of the book untouched. While working together as engineers on axial compressors, the authors experienced this effect with several doctoral and master theses. In many of these, the preface was invariably compelling reading, occasionally more immediately memorable than the theses themselves. So here we give our greetings to all those who, like us, prefer to start a book with the preface.

There is no single correct way to structure a book on radial turbocompressors, and our approach is outlined in the Introduction. The content is guided by our experience and knowledge of the subject. It gives a glimpse of the theoretical concepts in the order they are needed, much like an introductory lecture course, and provides references to more detailed coverage. As the story develops, important things get emphasised by appearing in many different chapters, often in different guises and usually increasing in complexity. The book is based on part of an introductory lecture course on axial and radial compressors given by the first author to master students in the University of Stuttgart. The content of the lecture course has been greatly expanded and tempered by practical experience both authors have gained in consultancy and design work for many compressor industries. It has been helped by notes made by the first author with regard to technical issues throughout his career, either jotted on paper or annotated on to copies of important technical papers. Without these, the book would have been a great deal poorer, as memories of the initial difficulty in understanding a new concept when it is still on the learning curve fade quickly when the concept has finally been grasped. The second author has been more than happy to let the first author lead the way in describing the theory, feeling himself to be more suited to describing the pragmatism in application.

The purpose of this book is to set out the basic principles and rules associated with the design of radial flow turbocompressors across a range of applications. Primarily the book is concerned with the aerodynamic design, but this cannot be divorced from the mechanical aspects, and so these are touched upon but are not gone into so deeply.

The book is written from the point of view of the designer and tries to cover most of the points that need to be considered in order to produce a successful radial flow turbocompressor. The emphasis is on understanding the theory behind the design process and on minimising the reliance on empirical rules. However, because of the complexity of the flow patterns, a lot of empiricism and some conjecture still remains.

This is a book the authors wished they had had when they first started work on centrifugals. We hope that it gives guidance to newcomers on their own road of discovery with this technology and conveys something of our own pleasure and excitement of working in this field. It is also intended to provide fresh insights for experienced engineers and specialists already in this field; we hope to incite reflection on the basic engineering science and the value and enduring contribution of 1D and 2D methods, often as a means of understanding modern 3D simulations.

Acknowledgements

Many individuals have helped in the writing of this book, and it is a pleasure to acknowledge this. Foremost among these are Hamid Hazby, Daniel Rusch, Paul Galpin and Maxine Backus. Dr Hazby provided the initial formulation of the content on transonic impeller design and was kind enough to review some of the early drafts of other chapters, making several useful contributions. Dr Rusch of ABB Turbocharging read several chapters and was always willing to help by explaining his own understanding of many issues. Paul Galpin provided a short description about modern CFD codes, which is the basis of some of Chapter 16 . Maxine Backus read and corrected the use of English in all the chapters in draft form and made the book better with her concise improvements to the style.

Closer to home within PCA Engineers Limited, we are grateful to all of our colleagues and partners who have supported our activity on this book. Specific thanks go to Peter Came, who provided the solid foundation for the evolution of compressor design at PCA. John Calvert kindly reviewed some of the content and made useful suggestions. Ian Woods, Mark Dempsey and Colin McFarlane helped with the technical content on mechanical integrity and rotor dynamics. Simon Welburn and Rob O'Donoghue did excellent work on many of the figures.

The first author would like to thank many graduate and postgraduate students in Stuttgart University who attended or helped with the lecture course on *Turboverdichter* (turbocompressors in German), which provided the initial structure for this book, Casey (2008).

For the stimulating discussions on many issues, feedback on different chapters, supply of offprints of technical papers, provision of initial versions of illustrations and technical data, provision of some excellent summaries of technical issues and help in various other ways, we are grateful to the following persons: Nicola Aldi of the University of Ferrara, Claudine Bargetzi of MAN Energy Solutions, Urs Baumann of MAN Energy Solutions, Yves Bidaut of MAN Energy Solutions, John Bolger of Rolls-Royce Ltd., Colin Casey, Professor Nick Cumpsty of Imperial College, Peter Dalbert, Fabian Dietmann, Ivor Day of Cambridge University, Professor Günther Dibelius of RWTH Aachen University (deceased), Markus Diehl, Professor John Denton formerly of Cambridge University, Professor Erik Dick of Ghent University, Fabian Dietmann of Celeroton AG, Dietrich Eckardt, Professor Phillip Epple of Friedrich Alexander University, John Fabian, Paul Galpin of ISIMQ, Daniel Grates of RWTH Aachen University, Professor Ed Greitzer of Massachusett Institute of

Technology (MIT) Gas Turbine Laboratory, Professor Georg Gyarmathy of the ETH Zürich (deceased), Tom Heuer of BorgWarner, Werner Jahnen of SWS Tech AG, Tony Jones of Pratt and Whitney, Professor Nicole Key and Fangyuan Lou of Purdue University, Franz Marty (deceased), Professor Rob Miller of Cambridge University, Professor Beat Ribi of FNHW, Colin Rodgers, Professor Isabelle Trébinjac of the École Centrale de Lyon, Professor Markus Schatz of Helmut Schmidt University, Georg Scheurerer of ISIMQ, Joachim Schmid of Delta JS AG, Christoph Schreiber, Om Sharma of United Technologies, Professor Zoltan Spakovsky of MIT Gas Turbine Laboratory, Professor Stephen Spence of Trinity College in Dublin, Bobby Sirakov of Garret Motion Inc., Professor Xinqian Zheng of Tsinghua University in Peking, Christof Zwyssig of Celeroton AG, and others who have helped but may have inadvertently been forgotten in this list.

For their patience and forbearance in guiding us through the production of the book, we would also like to thank all the team at Cambridge University Press.

We would also like to acknowledge the enormous debt we both owe to many engineers and teachers who, even when being unaware of exactly how they were helping us, encouraged us to find our own way and own solutions throughout our careers. The book is written partly in thanks to the many engineers, researchers and companies who have a similar interest in this technology and have shared their enthusiasm by publishing a wealth of technical literature describing the essential engineering science that explains the performance of radial flow turbocompressors. Hopefully the book does justice to their work.

For those parts of the book which are still unclear, and for any muddles in the text and blunders in the equations, the authors are directly responsible.

Conventions and Nomenclature

Conventions

1. Unless otherwise stated, all units in all equations are SI units.
2. It has not been possible to avoid the use of the same symbol for several different quantities. This is usually made clear by the context.
3. Parameter values and quantities used only very locally in the text are defined where they are used and are not all listed here.
4. Several slightly different conventions have been used for station locations. The normal notation uses locations with numerical values increasing from 1, 2 and 3 and so on through a compressor stage, as shown in Figure 10.6. In different situations, 1 and 2 can also indicate the inlet and exit of a stage or the inlet and outlet of a component. Subscript 2 is most often used to denote the impeller outlet. In some situations, *i* is used to denote the inlet and *o* is used to denote the outlet.
5. The subscripts *h* and *c* are used to denote the hub and the casing contour coordinates, and the subscript *m* is used for the arithmetic mean and *rms* for the root mean square.
6. All angles are given in degrees. The blade angles are defined relative to the meridional flow direction. A positive value indicates flow angles that are in the direction of rotation and negative values are against the direction of rotation, as shown in Figure 2.4. With this convention, the typical inlet and outlet angle of an impeller blade has a negative value. In such a situation, the statement that the backsweep or the inlet angle increases usually implies a more negative value.

Nomenclature

Letters

a	Speed of sound
$a_1, a_2, \ldots$	Polynomial coefficients in equation for specific heat
$a, b, c, d, \ldots$	Coefficients in equations
$A, B, C, D, \ldots$	Coefficients in equations
A	Area
b	Flow channel width
B	Bernstein polynomial

B	(1) Blockage
	(2) Greitzer B parameter
BL	Blade loading parameter
c	(1) Absolute velocity
	(2) Damping coefficient
c_u, c_r, c_z, c_m	Absolute velocity components
c_d	Dissipation coefficient
c_f	Skin friction coefficient
c_p	Specific heat at constant pressure
c_v	Specific heat at constant volume
C	Coefficient in Mallen and Saville method
C_D	Drag coefficient
C_L	Lift coefficient
C_M	Moment coefficient
C_p	Pressure coefficient
D	(1) Diameter
	(2) Drag
D_h	Hydraulic diameter
D_s	Specific diameter
DF	Diffusion factor
DH	The De Haller number
e	Eccentricity
E	(1) Energy
	(2) Young's modulus
f_D	Darcy friction factor
f_s	Schultz correction factor
F	Force component
g	(1) Staggered spacing
	(2) Acceleration due to gravity
h	(1) Specific enthalpy
	(2) Height
h_t	Specific total enthalpy
H	Boundary layer shape factor
i	Incidence angle
I	(1) Specific rothalpy
	(2) Moment of inertia
j_{12}	Specific dissipation losses
k, l, m, n	Coefficients in equations
k	(1) Blockage factor
	(2) Bending stiffness
k_c	The Casey coefficient for heat transfer to a compressor
K	Coefficient
KE	Kinetic energy

L	(1) Length
	(2) Lift
m	(1) Distance along the meridional direction
	(2) Mass
	(3) Exponent in gas dynamics equations
m'	Distance along the normalised meridional direction
$\dot{m}$	Mass flow rate
M	(1) Mach number
	(2) Torsional moment on a shaft
M_{u2}	Impeller tip-speed Mach number
M_w	Molecular weight
MR	Mach number ratio
n	(1) Rotational speed in rps
	(2) Polytropic exponent
	(3) Normal vector to a surface
	(4) Distance in the normal direction
	(5) Coefficient in Haaland equation
N	(1) Rotational speed in rpm
	(2) Amount of a constituent expressed in moles
$NPSH$	Net positive suction head
o	Throat width
p	(1) Pressure
	(2) s-shaped logistic function
p^*	Rotary stagnation pressure
P	(1) Power
	(2) Parameter value
PIF	Power input factor
P_h	Preheat factor
PE	Potential energy
q	Distance along a quasiorthogonal
q_{12}	Specific heat input
Q	Heat input
r	Radius
r, z, θ	Coordinates in cylindrical coordinate system
r_k	Kinematic degree of reaction
R	Specific gas constant
R_m	Universal gas constant
Ra	Centre-line average roughness
Re	Reynolds number
RF	Relaxation factor
s	(1) Specific entropy
	(2) Distance along a streamline or a blade
	(3) Spacing

S	(1) Entropy
	(2) Source terms in Chapter 16
St	Strouhal number
t	(1) Time
	(2) Blade thickness
T	Absolute temperature
$Trim$	Square of the impeller casing diameter ratio
u	(1) Blade speed
	(2) Specific internal energy
	(3) Fluid velocity in Chapter 16
U	Internal energy
v	Specific volume
V	(1) Volume
	(2) Velocity in Chapter 16
$\dot{V}$	Volume flow rate
w	Relative velocity
w_{s12}	Specific shaft work
w_{v12}	Specific displacement work
W	(1) Width of flow channel in diffusers
	(2) Work input
x	Mole fraction
x, y, z	Coordinates in Cartesian coordinate system
r, θ, z	Coordinates in cylindrical coordinate system
y_{12}	Specific aerodynamic work
y^+	Normalised distance from the wall in a boundary layer
Y	Stagnation pressure loss coefficient
Z	(1) Altitude above a datum level
	(2) Gas compressibility factor
	(3) Blade number

Symbols

α	Absolute flow angle
$\Delta\alpha$	Flow turning angle of a cascade
α'	Absolute blade angle
α, β	Reynolds-independent and Reynolds-dependent losses
β	(1) Relative flow angle
	(2) Reduced frequency
	(3) Core rotation factor in swirling flow
β'	Relative blade angle
γ	(1) Ratio of specific heats (and isentropic exponent of an ideal gas)
	(2) Blade lean angle and rake angle
δ	(1) Boundary layer thickness
	(2) Deviation angle

	(3) Shock wave deflection angle
	(4) Logarithmic decrement
δ^*	Boundary layer displacement thickness
δ, ε	Coefficients in real gas equations
Δ	Difference or change in a parameter, such as Δh_t
ε	(1) Tip clearance gap
	(2) Kinetic energy thickness of a boundary layer
	(3) Turbine expansion ratio
	(4) Shock wave angle
	(5) Inclination angle of meridional flow to axial direction
	(6) Diffusion coefficient
ζ	(1) Energy or enthalpy loss coefficient
	(2) Damping ratio
ζ_q	Heat transfer in a diabatic compression as a fraction of the aerodynamic work
η	Efficiency
θ	(1) Boundary layer momentum thickness
	(2) Circumferential coordinate
	(3) Planar diffuser divergence half-angle
	(4) Camber line slope angle
κ	Isentropic exponent
ω_s	Specific speed
Ω_s	Secondary circulation
λ	(1) Work coefficient
	(2) Fluid conductivity in Chapter 16
μ	Dynamic viscosity
ν	(1) Kinematic viscosity
	(2) Inlet dimeter to outlet diameter ratio
	(3) Poisson's ratio
ξ	(1) Kinetic energy loss coefficient
	(2) Ratio of local kinetic energy to the shaft work
π	Pressure ratio
ρ	Density
σ	(1) Solidity
	(2) Stress
	(3) Slip velocity ratio
τ	Shear stress
υ	Polytropic ratio
Φ	Mass-flow function
ϕ	(1) Flow coefficient
	(2) Phase angle
ϕ_{t1}	Global inlet flow coefficient
χ	Entropy loss coefficient

χ_d	Nondimensional slope of work characteristic at design point
ψ	(1) Pressure rise coefficient
	(2) Slope angle of a quasiorthogonal to the meridional direction
ω	(1) Rotational speed in radians per second
	(2) Pressure loss coefficient

Subscripts

0	At zero Mach number
1, 2, 3	(1) Station numbers
	(2) Component numbers
1	Inlet
2	Outlet
∞	Far upstream
a	Annular
act	Actual
b	Burst
btob	Blade-to-blade
c	(1) Compressor
	(2) Curvature
	(3) At critical conditions
	(4) Vortex centre
	(5) Relating to the camber line
	(6) Absolute velocity
ch	Choke
corr	Corrected
d	(1) Disturbance
	(2) Discharge
	(3) Design
dep	Departure function value
diff	Diffuser
ds	Deswirl
DF	Disc friction
e	(1) Value at the edge of a boundary layer
	(2) Engine
eff	Effective
eq	Equivalent
exit	Exit
Euler	From the Euler equation
f	(1) Friction
	(2) Fuel
htoc	Hub to casing
GT	Gas turbine
i, *j*	Station location

i	Isothermal
id	Ideal
igv	Inlet guide vanes
imp	Impeller
irr	Irreversible
j	Jet
l	Lower
le	Leading edge
lam	Laminar
leak	Leakage
m	(1) Meridional
	(2) Mechanical
max	Maximum value
min	Minimum value
n	(1) Normal to meridional direction
	(2) Natural
o	Outlet
opt	Optimum value
p	(1) Polytropic
	(2) at peak efficiency
ps	Pressure surface
q	Along the quasiorthogonal
r	(1) Rotor
	(2) Reduced
rc	Return channel
rec	Recirculation
ref	Reference
rev	Reversible
rp	At rated point
RS	Rotating stall
s	(1) Stator
	(2) Isentropic
	(3) Sand
	(4) Shroud
shutoff	Shutoff value at zero flow
ss	Suction surface
SW	Swept
t	Total conditions
te	Trailing edge
th	Throat
turb	(1) Turbulent
	(2) Turbine
TC	Turbocharger

u	(1) In the circumferential direction
	(2) Virtual station in Figure 2.18
	(3) Upper
	(3) Ultimate
v	Vapour pressure
vd	Vaned diffuser
vld	Vaneless diffuser
vol	Volumetric
w	(1) Wheel
	(2) Wake
	(3) relative velocity
θ	Circumferential direction

Superscripts

0	Inlet
*	Critical conditions at a throat
′	related to blade value
c	Compressor
comp	Compressible
d	Design
ss	Static-static
stall	At stall
t	turbine
ts	Total–static
tt	Total–total