Fluid Mechanics and Thermodynamics of Turbomachinery

Fluid Mechanics and Thermodynamics of Turbomachinery

Sixth Edition

S. L. Dixon, B. Eng., Ph.D.
Honorary Senior Fellow, Department of Engineering,
University of Liverpool, UK

C. A. Hall, Ph.D.
University Lecturer in Turbomachinery,
University of Cambridge, UK

ELSEVIER

AMSTERDAM • BOSTON • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO
Butterworth-Heinemann is an imprint of Elsevier

Butterworth-Heinemann is an imprint of Elsevier
30 Corporate Drive, Suite 400, Burlington, MA 01803, USA
The Boulevard, Langford Lane, Kidlington, Oxford, OX5 1GB, UK

First published by Pergamon Press Ltd. 1966
Second edition 1975
Third edition 1978
Reprinted 1979, 1982 (twice), 1984, 1986, 1989, 1992, 1995
Fourth edition 1998
Fifth edition 2005 (twice)
Sixth edition 2010

Library of Congress Cataloging-in-Publication Data

Dixon, S. L. (Sydney Lawrence)
Fluid mechanics and thermodynamics of turbomachinery/S.L. Dixon, C.A. Hall. – 6th ed.
p. cm.
Includes bibliographical references and index.
ISBN 978-1-85617-793-1 (alk. paper)
1. Turbomachines–Fluid dynamics. I. Hall, C. A. (Cesare A.) II. Title.
TJ267.D5 2010
621.406–dc22 2009048801

British Library Cataloguing-in-Publication Data

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

For information on all Butterworth–Heinemann publications visit our Web site at *www.elsevierdirect.com*

Typeset by: diacriTech, Chennai, India

Printed in the United States of America
10 11 12 13 14 10 9 8 7 6 5 4 3 2 1

Contents

Preface to the Sixth Edition

This book was originally conceived as a text for students in their final year reading for an honours degree in engineering that included turbomachinery as a main subject. It was also found to be a useful support for students embarking on post-graduate courses at masters level. The book was written for engineers rather than for mathematicians, although some knowledge of mathematics will prove most useful. Also, it is assumed from the start that readers will have completed preliminary courses in fluid mechanics. The stress is placed on the actual physics of the flows and the use of specialised mathematical methods is kept to a minimum.

Compared to the fifth edition this new edition has had a large number of changes made in style of presentation, new ideas and clarity of explanation. More emphasis is given to the effects of compressibility to match the advances made in the use of higher flow and blade speeds in turbomachinery. In Chapter 1, following the definition of a turbomachine, the fundamental laws of flow continuity, the energy and entropy equations are introduced as well as the all-important Euler work equation, which applies to all turbomachines. In Chapter 2 the main emphasis is given to the application of the "similarity laws," to dimensional analysis of all types of turbomachine and their performance characterisics. The important ideas of specific speed and specific diameter emerge from these concepts and their application is illustrated in the Cordier Diagram, which shows how to select the machine that will give the highest efficiency for a given duty. Did you realise that the *dental drill* is actually a turbomachine that fits in very well with these laws? Also, in this chapter the basics of cavitation within pumps and hydraulic turbines are examined.

The measurement and understanding of cascade aerodynamics is the basis of modern axial turbomachine design and analysis. In Chapter 3, the subject of cascade aerodynamics is presented in preparation for the following chapters on axial turbines and compressors. This chapter has been completely reorganised relative to the fifth edition. It starts by presenting the parameters that define the blade section geometry and performance of any axial turbomachine. The particular considerations for axial compressor blades are then presented followed by those for axial turbine blades. The emphasis is on understanding the flow features that constrain the design of turbomachine blades and the basic prediction of cascade performance. Transonic flow can dramatically modify the characteristics of a blade row and special attention is given to the effects of compressibility on cascade aerodynamics.

Chapters 4 and 5 cover axial turbines and axial compressors, respectively. In Chapter 4, new material has been developed to cover the preliminary design and analysis of single- and multi-stage axial turbines. The calculations needed to fix the size, the number of stages, the number of aerofoils in each blade row, and the velocity triangles are covered. The merits of different styles of turbine design are considered including the implications for mechanical design such as centrifugal stress levels and cooling in high speed and high temperature turbines. Through the use of some relatively simple correlations the trends in turbine efficiency with the main turbine parameters are presented. In Chapter 5, the analysis and preliminary design of all types of axial compressors are covered. This includes a new presentation of how measurements of cascade loss and turning can be translated into the performance of a compressor stage. Both incompressible and compressible cases are covered in the chapter and it is interesting to see how high speed compressors can achieve a pressure rise through quite a different flow process to that in a low speed machine. The huge importance of off-design performance is covered in some detail including how the designer can influence compressor operating range in the very early design stages. There is also a selection of new examples and problems involving the compressible flow analysis of high speed compressors.

Chapter 6 covers three-dimensional effects in axial turbomachinery. The aim of this chapter is to give the reader an understanding of spanwise flow variations and to present some of the main flow features that are not captured within mean-line analysis. It includes a brief introduction to the subject of computational fluid dynamics, which now plays a large part in turbomachinery design and analysis. Detailed coverage of computational methods is beyond the scope of this book. However, all the principles detailed in this book are equally applicable to numerical and experimental studies of turbomachines.

Radial turbomachinery remains hugely important for a vast number of applications, such as turbocharging for internal combustion engines, oil and gas transportation, and air liquefaction. As jet engine cores become more compact there is also the possibility of radial machines finding new uses within aerospace applications. The analysis and design principles for centrifugal compressors and radial inflow turbines are covered in Chapters 7 and 8. Improvements have been made relative to the fifth edition including new examples, corrections to the material, and reorganization of some sections.

Renewable energy topics were first added to the fourth edition of this book by way of the Wells turbine and a new chapter on hydraulic turbines. In the fifth edition a new chapter on wind turbines was added. Both of these chapters have been retained in this edition as the world remains increasingly concerned with the very major issues surrounding the use of various forms of energy. There is continuous pressure to obtain more power from renewable energy sources and hydroelectricity and wind power have a significant role to play. In this edition, hydraulic turbines are covered in Chapter 9, which includes coverage of the Wells turbine, a new section on tidal power generators, and several new example problems. Chapter 10 covers the essential fluid mechanics of wind turbines, together with numerous worked examples at various levels of difficulty. Important aspects concerning the criteria of blade selection and blade manufacture, control methods for regulating power output and rotor speed, and performance testing are touched upon. Also included are some very brief notes concerning public and environmental issues, which are becoming increasingly important as they, ultimately, can affect the development of wind turbines.

To develop the understanding of students as they progress through the book, the expounded theories are illustrated by a selection of worked examples. As well as these examples, each chapter contains problems for solution, some easy, some hard. See what you can make of them!

Acknowledgments

The authors are indebted to a large number of people in publishing, teaching, research, and manufacturing organisations for their help and support in the preparation of this volume. In particular thanks are given for the kind permission to use photographs and line diagrams appearing in this edition, as listed below:

ABB (Brown Boveri, Ltd)
American Wind Energy Association
Bergey Windpower Company
Elsevier Science
Hodder Education
Institution of Mechanical Engineers
Kvaener Energy, Norway
Marine Current Turbines Ltd., UK
National Aeronautics and Space Administration (NASA)
NREL
Rolls-Royce plc
The Royal Aeronautical Society and its Aeronautical Journal
Siemens (Steam Division)
Sirona Dental
Sulzer Hydro of Zurich
Sussex Steam Co., UK
U.S. Department of Energy
Voith Hydro Inc., Pennsylvania
The Whittle Laboratory, Cambridge, UK.

I would like to give my belated thanks to the late Professor W. J. Kearton of the University of Liverpool and his influential book *Steam Turbine Theory and Practice*, who spent a great deal of time and effort teaching us about engineering and instilled in me an increasing and life-long interest in turbomachinery. This would not have been possible without the University of Liverpool's award of the W. R. Pickup Foundation Scholarship supporting me as a university student, opening doors of opportunity that changed my life.

Also, I give my most grateful thanks to Professor (now Sir) John H. Horlock for nurturing my interest in the wealth of mysteries concerning the flows through compressors and turbine blades during his tenure of the Harrison Chair of Mechanical Engineering at the University of Liverpool. At an early stage of the sixth edition some deep and helpful discussions of possible additions to the new edition took place with Emeritus Professor John P. Gostelow (a former undergraduate student of mine). There are also many members of staff in the Department of Mechanical Engineering during my career who helped and instructed me for which I am grateful.

Last, but by no means least, to my wife Rosaleen, whose patient support enabled me to meet this new edition to be prepared.

S. Larry Dixon

I would like to thank the University of Cambridge, Department of Engineering, where I have been a student, researcher, and now lecturer. Many people there have contributed to my development as an academic and engineer. Of particular importance is Professor John Young who initiated my enthusiasm for thermofluids through his excellent teaching of the subject in college supervisions. I am also very grateful to Rolls-Royce plc, where I worked for several years. I learned a lot about compressor and turbine aerodynamics from my colleagues there and they continue to support me in my research activities.

As a lecturer in turbomachinery there is no better place to be based than the Whittle Laboratory. I would like to thank the members of the lab, past and present, for their support and all they have taught me. I would like to make a special mention of Dr. Tom Hynes, my Ph.D. supervisor, for encouraging my return to academia from industry and for handing over the teaching of a turbomachinery course to me when I started as a lecturer as this has helped me build up the knowledge needed for this book. Since starting as a lecturer, Dr. Rob Miller has been a great friend and colleague and I would like to thank him for the sound advice he has given on many technical, professional, and personal matters.

King's College, Cambridge, has provided me with accommodation and an environment where I have met many exceptional people. I would like to thank all the fantastic staff there who have given their help and support throughout the preparation of this book. During the spring of 2009 I spent a sabbatical in Spain, where I worked on parts of this book. I am very grateful to Professor Jose Salva and the Propulsion Group within La Universidad Politecnica de Madrid for their hospitality during this time.

Finally, special personal thanks go to my parents, Hazel and Alan for all they have done for me. I would like to dedicate my work on this book to my wife Gisella for her love and happiness.

Cesare A. Hall

List of Symbols

A	area
a	sonic velocity
$\overline{a}, a'$	axial-flow induction factor, tangential flow induction factor
b	axial chord length, passage width, maximum camber
C_c, C_f	chordwise and tangential force coefficients
C_L, C_D	lift and drag coefficients
C_p	specific heat at constant pressure, pressure coefficient, pressure rise coefficient
C_v	specific heat at constant volume
C_X, C_Y	axial and tangential force coefficients
c	absolute velocity
c_o	spouting velocity
D	drag force, diameter
DR_{eq}	equivalent diffusion ratio
D_h	hydraulic mean diameter
D_s	specific diameter
DF	diffusion factor
E, e	energy, specific energy
F	force, Prandtl correction factor
F_c	centrifugal force in blade
f	friction factor, frequency, acceleration
g	gravitational acceleration
H	blade height, head
H_E	effective head
H_f	head loss due to friction
H_G	gross head
H_S	net positive suction head (NPSH)
h	specific enthalpy
I	rothalpy
i	incidence angle
J	wind turbine tip–speed ratio
j	wind turbine local blade–speed ratio
K, k	constants
L	lift force, length of diffuser wall
l	blade chord length, pipe length
M	Mach number
m	mass, molecular mass
N	rotational speed, axial length of diffuser
N_S	specific speed (rev)
N_{SP}	power specific speed (rev)
N_{SS}	suction specific speed (rev)

n	number of stages, polytropic index
o	throat width
P	power
p	pressure
p_a	atmospheric pressure
p_v	vapour pressure
Q	heat transfer, volume flow rate
R	reaction, specific gas constant, diffuser radius, stream tube radius
Re	Reynolds number
R_H	reheat factor
R_o	universal gas constant
r	radius
S	entropy, power ratio
s	blade pitch, specific entropy
T	temperature
t	time, thickness
U	blade speed, internal energy
u	specific internal energy
V, v	volume, specific volume
W	work transfer, diffuser width
ΔW	specific work transfer
W_x	shaft work
w	relative velocity
X	axial force
x, y, z	Cartesian coordinate directions
Y	tangential force
Y_p	stagnation pressure loss coefficient
Z	number of blades, Zweifel blade loading coefficient

α	absolute flow angle
β	relative flow angle, pitch angle of blade
Γ	circulation
γ	ratio of specific heats
δ	deviation angle
ε	fluid deflection angle, cooling effectiveness, drag–lift ratio in wind turbines
ζ	enthalpy loss coefficient, incompressible stagnation pressure loss coefficient
η	efficiency
θ	blade camber angle, wake momentum thickness, diffuser half angle
κ	angle subtended by log spiral vane
λ	profile loss coefficient, blade loading coefficient, incidence factor
μ	dynamic viscosity
ν	kinematic viscosity, hub-tip ratio, velocity ratio
ξ	blade stagger angle

ρ	density
σ	slip factor, solidity, Thoma coefficient
σ_b	blade cavitation coefficient
σ_c	centrifugal stress
τ	torque
ϕ	flow coefficient, velocity ratio, wind turbine impingement angle
ψ	stage loading coefficient
Ω	speed of rotation (rad/s)
Ω_S	specific speed (rad)
Ω_{SP}	power specific speed (rad)
Ω_{SS}	suction specific speed (rad)
ω	vorticity

Subscripts

0	stagnation property
b	blade
c	compressor, centrifugal, critical
d	design
D	diffuser
e	exit
h	hydraulic, hub
i	inlet, impeller
id	ideal
m	mean, meridional, mechanical, material
max	maximum
min	minimum
N	nozzle
n	normal component
o	overall
opt	optimum
p	polytropic, pump, constant pressure
R	reversible process, rotor
r	radial
ref	reference value
rel	relative
s	isentropic, shroud, stall condition
ss	stage isentropic
t	turbine, tip, transverse
ts	total-to-static
tt	total-to-total
v	velocity
x, y, z	Cartesian coordinate components
θ	tangential

Superscript

.	time rate of change
-	average
′	blade angle (as distinct from flow angle)
*	nominal condition, throat condition
^	non-dimensionalised quantity