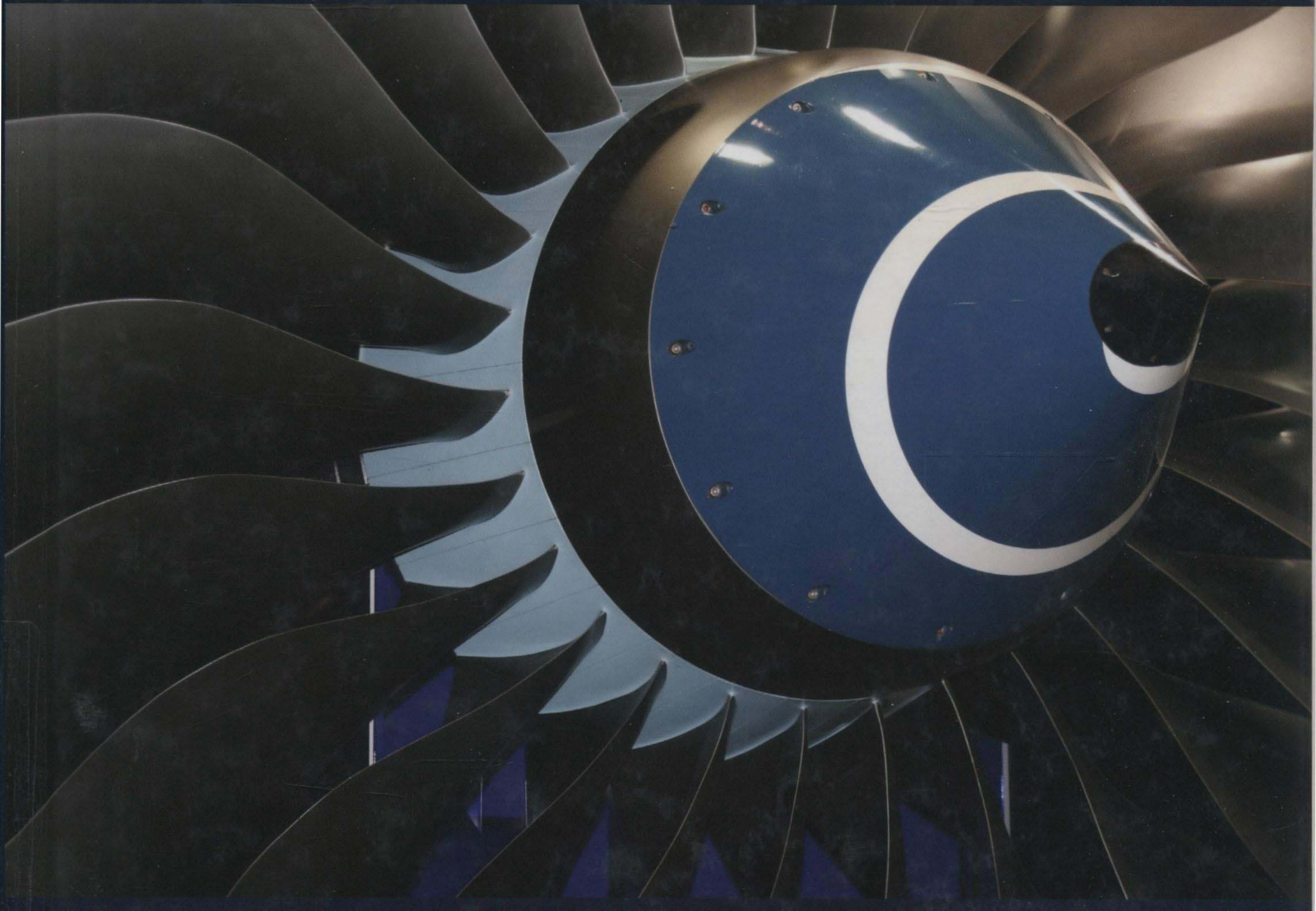
Fluid Mechanics and Thermodynamics of Turbomachinery



S. L. DIXON AND C. A. HALL

SEVENTH EDITION

Fluid Mechanics and Thermodynamics of Turbomachinery

Seventh Edition

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Seventh Edition

Dedication

In memory of Avril (22 years) and baby Paul.

Preface to the Seventh Edition

This book was originally conceived as a text for students in their final year reading for an honors degree in engineering that included turbomachinery as a main subject. It was also found to be a useful support for students embarking on postgraduate 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 specialized mathematical methods is kept to a minimum.

Compared to the sixth edition, this new edition has had a large number of changes made in terms of presentation of ideas, new material, and additional examples. 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. In addition, the properties of working fluids other than perfect gases are covered and a steam chart is included in the appendices. 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 characteristics. Additional types of turbomachine are considered and examples of high-speed characteristics are presented. 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. Also, in this chapter the basics of cavitation are examined for pumps and hydraulic turbines.

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 was completely reorganized in the previous edition. In this edition, further emphasis is given to compressible flow and on understanding the physics that constrain the design of turbomachine blades and determine cascade performance. In addition, a completely new section on computational methods for cascade design and analysis has been added, which presents the details of different numerical approaches and their capabilities.

Chapters 4 and 5 cover axial turbines and axial compressors, respectively. In Chapter 4, new material has been added to give better coverage of steam turbines. Sections explaining the numerous sources of loss within a turbine have been added and the relationships between loss and efficiency are further detailed. The examples and end-of-chapter problems have also been updated. Within this chapter, 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. Several new figures, examples, and end-of-chapter problems have been added. There is new coverage of compressor loss sources and, in particular, shock wave losses within high-speed rotors are explored in detail. New material on off-design operation and stage matching in multistage compressors has been added, which enables the performance of large compressors to be quantified.

Several new examples and end-of-chapter problems have also been added that reflect the new material on design, off-design operation, and compressible flow analysis of high-speed compressors.

Chapter 6 covers three-dimensional effects in axial turbomachinery and it possibly has the most new features relative to the sixth edition. There are extensive new sections on three-dimensional flows, three-dimensional design features, and three-dimensional computational methods. The section on through-flow methods has also been reworked and updated. Numerous explanatory figures have been added and there are new worked examples on vortex design and additional end-of-chapter problems.

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. In this edition, the range of coverage of the wind itself has been increased in terms of probability theory. This allows for a better understanding of how much energy a given size of wind turbine can capture from a normally gusting wind. Instantaneous measurements of wind speeds made with anemometers are used to determine average velocities and the average wind power. 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 make of them—answers are provided in Appendix F!

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S. Larry Dixon

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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 and my son Sebastian.

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
CF	capacity factor $(=\overline{P}_W/P_R)$
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	internal diameter of pipe
D	drag force, diameter
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	number of stages, polytropic index
o	throat width
P	power

P_R	rated power of wind turbine
$\overline{P}_W$	average wind turbine power
p	pressure
p_a	atmospheric pressure
p_v	vapor pressure
q	quality of steam
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	dryness fraction, wetness fraction
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
Ω_S	specific speed
Ω_{SP}	power specific speed
Ω_{SS}	suction specific speed
ω	vorticity

Subscripts

0	stagnation property
b	blade
c	compressor, centrifugal, critical
cr	critical value
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

$\mathbf{v}$	velocity
x, y, z	Cartesian coordinate components
θ	tangential

Superscripts

$\cdot$	time rate of change
$-$	average
$'$	blade angle (as distinct from flow angle)
$*$	nominal condition, throat condition
$\wedge$	nondimensionalized quantity

Contents