

Fluid Mechanics and Its Applications

Erik Dick

Fundamentals of Turbomachines

 Springer

Erik Dick

Fundamentals of Turbomachines

 Springer

Erik Dick
Department of Flow, Heat and Combustion
Mechanics
Ghent University
Gent
Belgium

ISSN 0926-5112 ISSN 2215-0056 (electronic)
Fluid Mechanics and Its Applications
ISBN 978-94-017-9626-2 ISBN 978-94-017-9627-9 (eBook)
DOI 10.1007/978-94-017-9627-9

Library of Congress Control Number: 2014954750

Springer Dordrecht Heidelberg New York London
© Springer Science+Business Media Dordrecht 2015

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

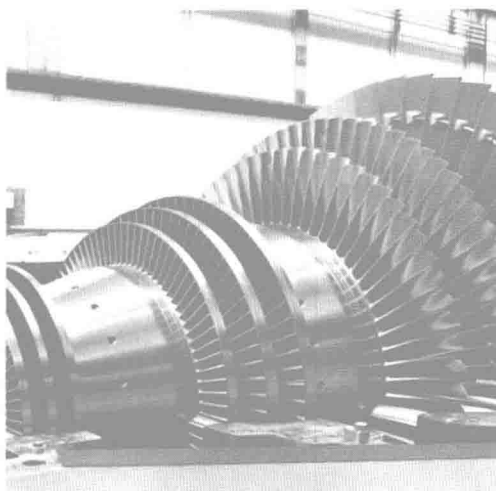
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface



This book is the English language version of a course on turbomachines, taught in Dutch by the author at Ghent University from 1992 to 2013. It was composed at the occasion of the change to English as teaching language in master programmes in engineering, starting with the academic year 2013–2014. Meanwhile, the text was adapted to include some modern evolutions in the field of turbomachinery, however avoiding advanced topics, since the objective of the book is to teach fundamentals of turbomachines.

In the first chapter, the basic equations of fluid mechanics and thermodynamics are derived from first principles, formulated for application to turbomachines. With this chapter, the necessary prior knowledge for the study of turbomachines is refreshed. The prior knowledge needed is basic fluid mechanics and basic technical thermodynamics. For fluid mechanics, this comprises topics such as mechanical properties of fluids, fluid statics, equations of flow in integral and differential form, dimensional analysis and internal laminar and turbulent flow of constant density

fluids. For technical thermodynamics, the supposed prior knowledge encompasses thermal properties of fluids, first law and second law of thermodynamics, basic heat engine cycles, gas mixtures, combustion and detailed analysis of steam cycles.

The course on turbomachines is taught at Ghent University in two parts. Chapters 1–10 form a first part, taught to all master students in electromechanical engineering. This part requires basic knowledge of flow past profiles, boundary layer flow and high speed flow of compressible fluids, which are topics often covered in an advanced fluid mechanics course. The necessary fundamentals of these topics are explained in the beginning of Chap. 2 and in Chap. 4. The second part is Chaps. 11–15, taught to students with specialisation in mechanical energy engineering. This part requires somewhat more advanced knowledge of fluid mechanics. Relevant topics are transition, turbulence and heat transfer in boundary layer flows and shock and expansion phenomena in high speed flows of compressible fluids. However, care has been taken not to rely too much on prior knowledge of these topics.

The objective of the book is, as already said, study of the fundamentals of turbomachines. The approach is analysis of all kinds of turbomachines with the same theoretical framework. Basic equations are formulated for a general equation of state of a fluid. Specification of constant density or ideal gas is only done when analysing particular machines. The building up of theory is mixed in the sense that first derivations are general, but that elaboration of the theoretical concepts is done on a particular machine, however taking into account the possibility for reuse on other machines or generalisation from constant density formulation to variable density formulation. The analysis starts with radial and axial fans, because these machines are the simplest ones. The next machines are steam turbines. The order of treating the different types of turbomachines is governed by the possibility of gradually building up the theoretical concepts. For each of the machine types, a balance is sought between fundamental understanding and acquiring knowledge of practical aspects. The main concern is always fundamental understanding and bringing the reader to independent reasoning. The point of view taken by the author is that readers should be able to understand what they see when a turbomachine is opened. They should also be able to make a reasoned choice of a turbomachine for a specific application and understand its operation. Design is not a primary objective. Design requires a more specialised study, although basic design of the simplest turbomachines such as a centrifugal fan, an axial steam turbine or a centrifugal pump is possible with the topics covered in the book.

Ghent, September 2014

Erik Dick

Acknowledgements

The following companies kindly provided figures.

For fans: ebm-papst; Fläkt Woods; TLT-Turbo.

For pumps: ANDRITZ; Flygt (a Xylem company); Grundfos; Johnson Pump (SPX Flow Technology); Klaus Union; Sulzer; Sundyne; Wilo.

For steam turbines: Alstom; MAN Diesel & Turbo; Siemens Energy.

For hydraulic turbines: ANDRITZ HYDRO.

For wind turbines: ENERCON; Vestas.

For power gas turbines: Mitsubishi-Hitachi Power Systems; Siemens Energy.

For aero gas turbines: GE Aviation; Rolls-Royce.

For radial compressors, radial turbines and turbochargers: ABB Turbo Systems; Dresser-Rand; KBB Kompressorenbau Bannewitz; MAN Diesel & Turbo.

The following publishers gave permission to reprint figures.

ASME; SAGE Publications; Springer Verlag; Vogel Buchverlag.

Author Biography



Erik Dick was born on December 10, 1950 in Torhout, Belgium. He obtained a M.Sc. in electromechanical engineering from Ghent University in 1973 and a Ph.D. in computational fluid dynamics in 1980. From 1973 he worked as researcher and became full professor of mechanical engineering at Ghent University in 1995, where he teaches turbomachines and computational fluid dynamics. His area of research is computational methods and turbulence and transition models for flow problems in mechanical engineering. He is author or co-author of about 125 papers in international scientific journals and about 250 papers at international conferences. He is the recipient of the 1990 Iwan Akerman award for fluid machinery of the Belgian National Science Foundation.

List of Symbols

a		acceleration	m/s^2
	or	axial interference factor	—
A		through-flow section area	m^2
b		rotor width in axial direction	m
	or	tangential interference factor	—
	or	bypass ratio	—
c		chord	m
	or	velocity of sound	m/s
c_a		axial chord	m
C_D		drag coefficient	—
c_f		friction coefficient	—
C_f		centrifugal force by rotor rotation	N/kg
C_{Fu}		tangential force coefficient	—
C_l		lift coefficient	—
C_M		Pfleiderer moment coefficient (3.30)	—
Co		Coriolis force by rotor rotation	N/kg
c_p		differential specific heat at constant pressure	J/kgK
C_p		pressure coefficient	—
	or	integral specific heat at constant pressure	J/kgK
C_p		power coefficient	—
C_T		thrust coefficient	—
Cu		centrifugal force by curvature	N/kg
d		diameter	m
D		drag per unit of span	N/m
DF		diffusion factor	—
D_{loc}		local diffusion factor	—
D_s		specific diameter (7.7)	—
e		internal energy per unit of mass	J/kg
E_k		kinetic energy per unit of mass	J/kg

E_m		mechanical energy per unit of mass	J/kg
E_p		pressure energy per unit of mass	J/kg
f		force per unit of mass	N/kg
	or	friction factor (2.30)	—
	or	fuel-air ratio	—
f_R		curvature factor (3.26)	—
g		gravitational force per unit of mass	N/kg
h		enthalpy	J/kg
	or	blade height or scroll height	m
H_m		manometric head	m
I		rothalpy	J/kg
k		equivalent sand-grain roughness	m
L		lift per unit of span	N/m
$\dot{m}$		mass flow rate	kg/s
M		rotor moment	Nm
M_d		disc or wheel friction moment	Nm
M_{shaft}		shaft moment	Nm
M_{st}		static moment of meridional section	m ³
$NPSH$		net positive suction head (8.5)	—
n		polytropic exponent	
$\bar{n}$		unit normal	—
p		pressure	Pa
P		power	W
Pf		Pfleiderer factor (3.23)	m ³
q		heat transferred per unit of mass	J/kg
	or	dynamic pressure	Pa
q_{irr}		heat by dissipation inside flow path	J/kg
q_{irr}^0		heat by dissipation outside flow path	J/kg
$\dot{Q}$		volume flow rate	m ³ /s
	or	heat transferred per unit of time	J/s=W
r		radius	m
	or	pressure ratio	—
R		kinematic degree of reaction	—
	or	radius of curvature	m
	or	gas constant	J/kgK
Re		Reynolds number	—
R_p		pressure degree of reaction (3.1)	—
R_s		isentropic degree of reaction (6.16)	—
s		entropy	J/kgK
	or	spacing of blades	m

S		surface area	m^2
t		time	s
	or	thickness of blades	m
T		temperature	K or °C
	or	thrust force	N
u		blade speed (radius x rotational speed)	m/s
U		gravitational potential energy	m/s
v_0		inflow velocity	m/s
v_e		energy reference velocity	m/s
w		flow velocity in relative frame	m/s
W		work per unit of time	J/s = W
x		coordinate along streamline	m
	or	coordinate in axial direction	m
y		coordinate perpendicular to streamline	m
	or	coordinate in circumferential direction	m
z		coordinate in vertical direction	m
	or	coordinate in radial direction	m
Z		number of blades	—
α		angle of absolute velocity w.r.t. meridional plane	°
β		angle of relative velocity w.r.t. meridional plane	°
Γ		circulation along a contour	m^2/s
δ		boundary layer thickness	m
ΔW		rotor work per unit of mass	J/kg
ε		Pfleiderer work reduction factor (3.23)	—
η_i		internal efficiency	—
η_m		mechanical efficiency	—
η_p		polytropic efficiency	—
	or	propulsive efficiency (12.7)	—
η_s		isentropic efficiency	—
η_{src}		isentropic re-expansion efficiency (11.7)	—
η_t		thermal efficiency (12.9)	—
η_{td}		thermodynamic efficiency (12.9)	—
η_{tt}		total-to-total isentropic efficiency	—
η_v		volumetric efficiency	—
η_x		infinitesimal efficiency	—
θ		angular coordinate	rad
	or	flow turning angle	rad
κ		heat transfer coefficient (11.18)	J/kJK
λ		speed ratio (u/v_0)	—

	or	coefficient in Pfleiderer factor Pf	—
μ		dynamic viscosity	Pas
ν		kinematic viscosity	Pas
ξ		pressure loss coefficient	—
ρ		density	kg/m ³
σ		solidity c/s	—
	or	Stodola slip factor (3.20)	—
	or	cavitation number(8.1)	—
σ_a		axial solidity c _a /s	—
σ_M		moment solidity (3.31)	—
τ		shear stress	N/m ²
	or	obstruction factor (Fig. 3.16)	—
ϕ		flow coefficient v_a / u or v_{2r} / u_2	—
Φ		flow factor (7.4)	—
ψ		work coefficient $\Delta W / u_2^2$	—
Ψ		head factor (7.5)	—
ψ_0		rotor total pressure coefficient	—
ψ_r		rotor static pressure coefficient	—
ω		rotor of relative velocity	m ² /s
	or	enthalpy loss coefficient	—
Ω		rotational speed	rad/s
Ω_s		specific speed (7.6)	—
Ω_{ss}		suction specific speed (8.14)	—

Subscripts

0		inlet of machine or installation	
	or	total state	
1		just upstream of rotor	
1b		just downstream of rotor inlet	
2		just downstream of rotor	
2b		just upstream of rotor outlet	
3		outlet of machine or installation	
∞		far away from object	
	or	with infinite number of blades	

	or	on infinitesimal flow path	
a		in axial direction	
c		compressor	
	or	critical or choking value	
d		discharge/delivery side	
def		deflection	
dyn		dynamic value	(12.6–12.7)
gas		gas value	(12.6–12.7)
id		ideal	
irr		due to irreversibility	
m		in meridional direction	
	or	mechanical or manometric or mean	
mean		mean value	
o		optimum	
p		pressure side	
prop		propulsive value	(12.6–12.7)
r		in radial direction or in relative frame	
	or	rotor or reversible	
s		suction side or stator	
	or	isentropic	
ss		isentropic for stator	
sr		isentropic for rotor	
sre		isentropic re-expansion value	
t		theoretical value	
	or	turbine	
T		tip value	
tt		total-to-total isentropic	
u		in circumferential direction	

Superscripts

*		design value
	or	choking value
—		average
→		vector quantity
b		blade value

Contents

1	Working Principles	1
1.1	Definition of a Turbomachine	1
1.2	Examples of Axial Turbomachines	2
1.2.1	Axial Hydraulic Turbine	2
1.2.2	Axial Pump	4
1.3	Mean Line Analysis	5
1.4	Basic Laws for Stationary Duct Parts	7
1.4.1	Conservation of Mass	7
1.4.2	Conservation of Momentum	7
1.4.3	Conservation of Energy	9
1.4.4	Forms of Energy: Mechanical Energy and Head	10
1.4.5	Energy Dissipation: Head Loss	12
1.5	Basic Laws for Rotating Duct Parts	14
1.5.1	Work and Energy Equations in a Rotating Frame with Constant Angular Velocity	14
1.5.2	Moment of Momentum in the Absolute Frame: Rotor Work	16
1.5.3	Moment of Momentum in the Relative Frame: Forces Intervening in the Rotor Work	21
1.5.4	Energy Component Changes Caused By the Rotor Work	23
1.5.5	Rotor Work in the Mean Line Representation of the Flow	24
1.6	Energy Analysis of Turbomachines	25
1.6.1	Mechanical Efficiency and Internal Efficiency	25
1.6.2	Energy Analysis of an Axial Hydraulic Turbine	26
1.6.3	Energy Analysis of an Axial Pump	30
1.7	Examples of Radial Turbomachines	33
1.8	Performance Characteristics	36
1.9	Exercises	40
	References	46
2	Basic Components	47
2.1	Aerofoils	47
2.1.1	Force Generation	47
2.1.2	Performance Parameters	49

2.1.3	Pressure Distribution	51
2.1.4	Boundary Layer Separation	52
2.1.5	Loss Mechanism Associated to Friction: Energy Dissipation	55
2.1.6	Profile Shapes	58
2.1.7	Blade Rows with Low Solidity	59
2.2	Linear Cascades	60
2.2.1	Relation with the Real Machine	60
2.2.2	Cascade Geometry	61
2.2.3	Flow in Lossless Cascades: Force Components	62
2.2.4	Significance of Circulation	65
2.2.5	Flow in Lossless Cascades: Work	67
2.2.6	Flow in Cascades with Loss: Force Components	68
2.2.7	Flow in Cascades with Loss: Energy Dissipation and Work by Drag Force	70
2.2.8	The Zweifel Tangential Force Coefficient	72
2.2.9	The Lieblein Diffusion Factor	74
2.2.10	Performance Parameters of Axial Cascades	75
2.3	Channels	75
2.3.1	Straight Channels	75
2.3.2	Bends	77
2.4	Diffusers	79
2.4.1	Dump Diffusers	79
2.4.2	Inlet Flow Distortion	79
2.4.3	Flow Separation	81
2.4.4	Flow Improvement	81
2.4.5	Representation of Diffuser Performance	82
2.4.6	Equivalent Opening Angle	84
2.4.7	Diffusion in a Bend	85
2.5	Exercises	87
	References	95
3	Fans	97
3.1	Fan Applications and Fan Types	97
3.1.1	Fan Applications	97
3.1.2	Large Radial Fans	98
3.1.3	Small Radial Fans	99
3.1.4	Large Axial Fans	99
3.1.5	Small Axial Fans	100
3.1.6	Cross-Flow Fans	100
3.2	Idealised Mean Line Analysis of a Radial Fan	101
3.2.1	Idealised Flow Concept: Infinite Number of Blades	101
3.2.2	Degree of Reaction	102
3.2.3	Relation Between Rotor Blade Shape and Perfor- mance Parameters	103
3.2.4	Performance Characteristics with Idealised Flow	105

3.3	Radial Fan Analysis for Lossless Two-Dimensional Flow with Finite Number of Rotor Blades	106
3.3.1	Relative Vortex in Blade Channels	106
3.3.2	Velocity Difference over a Rotating Blade	107
3.3.3	Slip: Reduction of Rotor Work	112
3.3.4	Number of Blades and Solidity: Pfleiderer Moment Coefficient	115
3.3.5	Number of Blades: Examples	118
3.4	Internal Losses with Radial Fans	120
3.4.1	Turning Loss at Rotor Entrance	120
3.4.2	Incidence Loss at Rotor Entrance	120
3.4.3	Displacement by Blade Thickness	122
3.4.4	Rotor Friction Loss and Rotor Diffusion Loss	123
3.4.5	Dump Diffusion Loss at Volute Entrance	123
3.4.6	Incidence Loss at Volute Entrance	125
3.4.7	Friction Loss Within the Volute	126
3.4.8	Diffusion at the Rotor Inlet	126
3.4.9	Flow separation at Rotor Inlet and Rotor Outlet	127
3.4.10	Applicability of the Loss Models	129
3.4.11	Optimisation of the Rotor Inlet of a Centrifugal Fan	129
3.4.12	Characteristics Taking Losses into Account	131
3.5	Overall Performance Evaluation	134
3.5.1	Mechanical Loss	134
3.5.2	Leakage Loss	135
3.5.3	Overall Efficiency with Power Receiving Machines	135
3.5.4	Overall Efficiency with Power Delivering Machines	136
3.6	Rotor Shape Choices with Radial Fans	136
3.7	Axial and Mixed-Flow Fans	140
3.7.1	Degree of Reaction with Axial Fans	140
3.7.2	Free Vortex and Non-Free Vortex Types	141
3.7.3	Axial Fan Characteristics; Adjustable Rotor Blades	143
3.7.4	Mixed-Flow Fans	144
3.8	Exercises	146
3.8.1	Centrifugal Pump (Idealised Flow)	146
3.8.2	Rotor of a Centrifugal Fan (Finite Number of Blades and Internal Losses)	146
3.8.3	Number of Blades of a Rotor of a Centrifugal Fan	147
3.8.4	Volute of a Centrifugal Fan	147
3.8.5	Leakage Flow Rate with Centrifugal Fan	147
3.8.6	Centrifugal Pump (Finite Number of Blades and Internal Losses)	148
3.8.7	Axial Fan (Idealised Flow): Analysis on Average Diameter	148
3.8.8	Axial Fan (Idealised Flow): Free Vortex and Non-Free Vortex	149

3.8.9	Inlet Guide Vane with a Centrifugal Fan	149
3.8.10	Change of Rotational Speed with Centrifugal and Axial Fans	149
3.8.11	Two-Stage Axial Fan	150
3.8.12	Axial Turbine	151
	References	151
4	Compressible Fluids	153
4.1	Basic Laws	153
4.2	Compressibility and Velocity of Sound	156
4.3	Compressibility Effect on the Velocity-Pressure Relation	158
4.4	Shape of a Nozzle	160
4.5	Nozzle with Initial Velocity	162
4.6	Nozzle with Losses: Infinitesimal Efficiency	163
4.7	Isentropic and Polytropic Efficiencies	167
4.8	Exercises	171
	References	174
5	Performance Measurement	175
5.1	Pressure Measurement	175
5.1.1	The Metal Manometer	175
5.1.2	The Pressure Transducer	175
5.1.3	The Digital Manometer	176
5.1.4	Calibration of Pressure Meters	177
5.2	Temperature Measurement	177
5.2.1	The Glass Thermometer	177
5.2.2	The Temperature Transducer	177
5.2.3	The Digital Thermometer	178
5.3	Flow Rate Measurement	178
5.3.1	Reservoir	178
5.3.2	Flow Over a Weir	178
5.3.3	Pressure Drop Devices	179
5.3.4	Industrial Mass Flow Rate Meters	180
5.3.5	Positioning of Flow Rate Meters in Ducts	180
5.4	Torque Measurement	181
5.4.1	Swinging Suspended Motor or Brake	181
5.4.2	Calibrated Motor	181
5.4.3	The Torque Transducer	181
5.5	Rotational Speed Measurement	182
5.5.1	Pulse Counters	182
5.5.2	The Speed Transducer	182
5.5.3	Electric Tachometer	182
5.6	Laboratory Test of a Pelton Turbine	182
5.6.1	Test Rig	182
5.6.2	Measurements	183

5.6.3	Measurement Procedure	183
5.6.4	Calculations	184
5.6.5	Measurement Example	184
5.7	Laboratory Test of a Centrifugal Fan	184
5.7.1	Test Rig	184
5.7.2	Measurements	187
5.7.3	Measurement Procedure	187
5.7.4	Calculations	188
5.7.5	Measurement Example	188
5.8	Laboratory Test of a Centrifugal Pump	189
5.8.1	Test Rig	189
5.8.2	Measurements	190
5.8.3	Measurement Procedure	190
5.8.4	Calculations	191
5.8.5	Measurement Example	192
6	Steam Turbines	193
6.1	Applications of Steam Turbines	193
6.2	Working Principles of Steam Turbines	195
6.3	The Steam Cycle	199
6.4	The Single Impulse Stage or Laval Stage	200
6.4.1	Velocity Triangles	200
6.4.2	Work and Energy Relations	201
6.4.3	Stage Efficiency Definitions	204
6.4.4	Blade Profile Shape	205
6.4.5	Loss Representation	208
6.4.6	Optimisation of Total-to-Static Efficiency	209
6.5	The Pressure-Compounded Impulse Turbine or Rateau Turbine	212
6.5.1	Principle	212
6.5.2	Efficiency	213
6.6	The Velocity-Compounded Impulse Turbine or Curtis Turbine	214
6.7	The Reaction Turbine	217
6.7.1	Degree of Reaction	217
6.7.2	Efficiency	218
6.7.3	Axial Inlet and Outlet	222
6.8	Steam Turbine Construction Forms	224
6.8.1	Large Steam Turbines for Power Stations	224
6.8.2	Industrial Steam Turbines	229
6.9	Blade Shaping	231
6.9.1	HP and IP Blades	231
6.9.2	LP Blades	233
6.10	Exercises	236
	References	246