

Herbert Oertel
Editor

Prandtl's Essentials of Fluid Mechanics

Second Edition

With Contributions by M. Böhle, D. Etling, U. Müller,
K.R.S. Sreenivasan, U. Riedel, and J. Warnatz

Translated by Katherine Mayes

With 530 Illustrations



Springer

Herbert Oertel
Institut für Strömungslehre
Universität Karlsruhe
Kaiserstr. 12
Karlsruhe D-76131
Germany
oertel@isl.mach.uni-karlsruhe.de

Ludwig Prandtl, em. Prof. Dr. Dr.-Ing. e.h.mult., Universität Göttingen, Dir. MPI für Strömungsforschung, † 1953.

Editors:

S.S. Antman
Department of Mathematics
and
Institute for Physical Science
and Technology
University of Maryland
College Park, MD 20742-4015
USA
ssa@math.umd.edu

J.E. Marsden
Control and Dynamical
Systems, 107-81
California Institute of
Technology
Pasadena, CA 91125
USA
marsden@cds.caltech.edu

L. Sirovich
Division of Applied
Mathematics
Brown University
Providence, RI 02912
USA
chico@camelot.mssm.edu

Mathematics Subject Classification (2000): 76A02, 76-99

Library of Congress Cataloging-in-Publication Data
Oertel, Herbert.

Prandtl's essentials of fluid mechanics / Herbert Oertel
p. cm.

Includes bibliographical references and index.
ISBN 0-387-40437-6 (alk. paper)

I. Fluid mechanics. I. Title.

TA357.O33 2003

620.1'06—dc22

2003059136

ISBN 0-387-40437-6

Printed on acid-free paper.

Originally published in the German language by Vieweg Verlag/GWV Fachverlage GmbH, D-65189 Wiesbaden, Germany, as "Herbert Oertel (Hsrg.): Führer durch die Strömungslehre. 10. Auflage (10th Edition)" © Friedr. Vieweg & Sohn Verlagsgesellschaft mbH, Braunschweig/Wiesbaden, 2001.

© 2004 Springer-Verlag New York, Inc.

All rights reserved. This work may not be translated or copied in whole or in part without the written permission of the publisher (Springer-Verlag New York, Inc., 175 Fifth Avenue, New York, NY 10010, USA), except for brief excerpts in connection with reviews or scholarly analysis. Use in connection with any form of information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed is forbidden.

The use in this publication of trade names, trademarks, service marks, and similar terms, even if they are not identified as such, is not to be taken as an expression of opinion as to whether or not they are subject to proprietary rights.

Printed in the United States of America. (EB)

9 8 7 6 5 4 3 2 1

SPIN 10939734

Springer-Verlag is a part of *Springer Science+Business Media*

springeronline.com

Contents

Preface	V
1. Introduction	1
2. Properties of Liquids and Gases	17
2.1 Properties of Liquids	17
2.2 State of Stress	18
2.3 Liquid Pressure	21
2.4 Properties of Gases	26
2.5 Gas Pressure	29
2.6 Interaction Between Gas Pressure and Liquid Pressure	32
2.7 Equilibrium in Other Force Fields	35
2.8 Surface Stress (Capillarity)	39
2.9 Problems	42
3. Kinematics of Fluid Flow	47
3.1 Methods of Representation	47
3.2 Acceleration of a Flow	51
3.3 Topology of a Flow	52
3.4 Problems	59
4. Dynamics of Fluid Flow	63
4.1 Dynamics of Inviscid Liquids	63
4.1.1 Continuity and the Bernoulli Equation	63
4.1.2 Consequences of the Bernoulli Equation	67
4.1.3 Pressure Measurement	75
4.1.4 Interfaces and Formation of Vortices	77
4.1.5 Potential Flow	80
4.1.6 Wing Lift and the Magnus Effect	93
4.1.7 Balance of Momentum for Steady Flows	95
4.1.8 Waves on a Free Liquid Surface	103
4.1.9 Problems	113
4.2 Dynamics of Viscous Liquids	118
4.2.1 Viscosity (Inner Friction), the Navier–Stokes Equation	118

4.2.2	Mechanical Similarity, Reynolds Number	122
4.2.3	Laminar Boundary Layers	123
4.2.4	Onset of Turbulence	126
4.2.5	Fully Developed Turbulence	136
4.2.6	Flow Separation and Vortex Formation	144
4.2.7	Secondary Flows	151
4.2.8	Flows with Prevailing Viscosity	153
4.2.9	Flows Through Pipes and Channels	160
4.2.10	Drag of Bodies in Liquids	165
4.2.11	Flows in Non-Newtonian Media	175
4.2.12	Problems	180
4.3	Dynamics of Gases	186
4.3.1	Pressure Propagation, Velocity of Sound	186
4.3.2	Steady Compressible Flows	190
4.3.3	Conservation of Energy	195
4.3.4	Theory of Normal Shock Waves	196
4.3.5	Flows past Corners, Free Jets	200
4.3.6	Flows with Small Perturbations	203
4.3.7	Flows past Airfoils	207
4.3.8	Problems	213
5.	Fundamental Equations of Fluid Mechanics	217
5.1	Continuity Equation	217
5.2	Navier–Stokes Equations	218
5.2.1	Laminar Flows	218
5.2.2	Reynolds Equations for Turbulent Flows	225
5.3	Energy Equation	230
5.3.1	Laminar Flows	230
5.3.2	Turbulent Flows	234
5.4	Fundamental Equations as Conservation Laws	236
5.4.1	Hierarchy of Fundamental Equations	236
5.4.2	Navier–Stokes Equations	237
5.4.3	Derived Model Equations	240
5.4.4	Reynolds Equations for Turbulent Flows	247
5.4.5	Multiphase Flows	248
5.4.6	Reactive Flows	251
5.5	Differential Equations of Perturbations	253
5.6	Problems	258
6.	Aerodynamics	265
6.1	Fundamentals of Aerodynamics	265
6.1.1	Bird Flight and Technical Imitations	266
6.1.2	Airfoils and Wings	268
6.1.3	Airfoil and Wing Theory	276
6.1.4	Aerodynamic Facilities	290

6.2	Transonic Aerodynamics	292
6.2.1	Swept Wings	294
6.2.2	Shock–Boundary–Layer Interaction	297
6.2.3	Flow Separation	304
6.3	Supersonic Aerodynamics	306
6.3.1	Delta Wings	307
6.4	Problems	314
7.	Turbulent Flows	319
7.1	Fundamentals of Turbulent Flows	319
7.2	Onset of Turbulence	320
7.2.1	Linear Stability	321
7.2.2	Nonlinear Stability	323
7.2.3	Nonnormal Stability	324
7.3	Developed Turbulence	326
7.3.1	The Notion of a Mixing Length	326
7.3.2	Turbulent Mixing	328
7.3.3	Energy Relations in Turbulent Flows	329
7.4	Classes of Turbulent Flows	331
7.4.1	Free Turbulence	331
7.4.2	Flow Along a Boundary	334
7.4.3	Rotating and Stratified Flows, Flows with Curvature Effects	337
7.4.4	Turbulence in Tunnels	340
7.4.5	Two-Dimensional Turbulence	344
7.5	New Developments in Turbulence	348
7.5.1	Lagrangian Investigations of Turbulence	353
7.5.2	Field-Theoretic Methods	354
7.5.3	Outlook	354
8.	Fluid-Mechanical Instabilities	357
8.1	Fundamentals of Fluid-Mechanical Instabilities	357
8.1.1	Examples of Fluid-Mechanical Instabilities	357
8.1.2	Definition of Stability	363
8.1.3	Local Perturbations	366
8.2	Stratification Instabilities	367
8.2.1	Rayleigh–Bénard Convection	367
8.2.2	Marangoni Convection	379
8.2.3	Diffusion Convection	382
8.3	Hydrodynamic Instabilities	388
8.3.1	Taylor Instability	388
8.3.2	Görtler Instability	393
8.4	Shear-Flow Instabilities	395
8.4.1	Boundary-Layer Flows	396
8.4.2	Tollmien–Schlichting and Cross-Flow Instabilities	403

8.4.3	Kelvin–Helmholtz Instability	419
8.4.4	Wake Flows	422
9.	Convective Heat and Mass Transfer	427
9.1	Fundamentals of Heat and Mass Transfer	427
9.1.1	Free and Forced Convection	427
9.1.2	Heat Conduction and Convection	429
9.1.3	Diffusion and Convection	430
9.2	Free Convection	431
9.2.1	Convection at a Vertical Plate	431
9.2.2	Convection at a Horizontal Cylinder	437
9.3	Forced Convection	438
9.3.1	Pipe Flows	438
9.3.2	Boundary-Layer Flows	442
9.3.3	Bodies in Flows	449
9.4	Heat and Mass Exchange	449
9.4.1	Mass Exchange at the Flat Plate	450
10.	Multiphase Flows	453
10.1	Fundamentals of Multiphase Flows	453
10.1.1	Definitions	454
10.1.2	Flow Patterns	457
10.1.3	Flow Pattern Maps	457
10.2	Flow Models	460
10.2.1	The One-Dimensional Two-Fluid Model	461
10.2.2	Mixing Models	464
10.2.3	The Drift–Flow Model	466
10.2.4	Bubbles and Drops	468
10.2.5	Spray Flows	471
10.3	Pressure Loss and Volume Fraction in Hydraulic Components	474
10.3.1	Friction Loss in Horizontal Straight Pipes	475
10.3.2	Acceleration Losses	479
10.4	Propagation Velocity of Density Waves and Critical Mass Fluxes	483
10.4.1	Density Waves	483
10.4.2	Critical Mass Fluxes	486
10.4.3	Cavitation	493
10.5	Instabilities in Two-Phase Flows	497
11.	Reactive Flows	503
11.1	Fundamentals of Reactive Flows	503
11.1.1	Rate Laws and Reaction Orders	503
11.1.2	Relation Between Forward and Reverse Reactions	504
11.1.3	Elementary Reactions and Reaction Molecularity	505
11.1.4	Temperature Dependence of Rate Coefficients	508

11.1.5	Pressure Dependence of Rate Coefficients	510
11.1.6	Characteristics of Reaction Mechanisms	512
11.2	Laminar Reactive Flows	517
11.2.1	Structure of Premixed Flames	517
11.2.2	Flame Velocity of Premixed Flames	520
11.2.3	Sensitivity Analysis	521
11.2.4	Nonpremixed Counterflow Flames	523
11.2.5	Nonpremixed Jet Flames	525
11.2.6	Nonpremixed Flames with Fast Chemistry	526
11.2.7	Exhaust Gas Cleaning with Plasma Sources	527
11.2.8	Flows in Etching Reactors	530
11.2.9	Heterogeneous Catalysis	531
11.3	Turbulent Reactive Flows	532
11.3.1	Overview and Concepts	532
11.3.2	Direct Numerical Simulation	533
11.3.3	Turbulence Models	535
11.3.4	Mean Reaction Rates	536
11.3.5	Eddy-Break-Up Models	542
11.3.6	Large-Eddy Simulation (LES)	542
11.3.7	Turbulent Nonpremixed Flames	543
11.3.8	Turbulent Premixed Flames	554
11.4	Hypersonic Flows	560
11.4.1	Physical-Chemical Phenomena in Reentry Flight	560
11.4.2	Chemical Nonequilibrium	561
11.4.3	Thermal Nonequilibrium	564
11.4.4	Surface Reactions on Reentry Vehicles	567
12.	Flows in the Atmosphere and in the Ocean	571
12.1	Fundamentals of Flows in the Atmosphere and in the Ocean	571
12.1.1	Introduction	571
12.1.2	Fundamental Equations in Rotating Systems	571
12.1.3	Geostrophic Flow	574
12.1.4	Vorticity	576
12.1.5	Ekman Layer	579
12.1.6	Prandtl Layer	582
12.2	Flows in the Atmosphere	584
12.2.1	Thermal Wind Systems	584
12.2.2	Thermal Convection	588
12.2.3	Gravity Waves	590
12.2.4	Vortices	592
12.2.5	Global Atmospheric Circulation	598
12.3	Flows in the Ocean	600
12.3.1	Wind-Driven Flows	601
12.3.2	Water Waves	603
12.4	Application to Atmospheric and Oceanic Flows	606

12.4.1	Weather Forecast	606
12.4.2	Greenhouse Effect and Climate Prediction	608
12.4.3	Ozone Hole	612
13.	Biofluid Mechanics of Blood Circulation	615
13.1	Fundamentals of Biofluid Mechanics	615
13.1.1	Respiratory System	618
13.1.2	Blood Circulation	620
13.1.3	Rheology of the Blood	625
13.2	Flow in the Heart	626
13.2.1	Physiology and Anatomy of the Heart	627
13.2.2	Structure of the Heart	630
13.2.3	Excitation Physiology of the Heart	634
13.2.4	Flow in the Heart	637
13.2.5	Cardiac Valves	642
13.3	Flow in Blood Vessels	645
13.3.1	Unsteady Pipe Flow	649
13.3.2	Unsteady Arterial Flow	650
13.3.3	Arterial Branches	653
14.	Thermal Turbomachinery	655
14.1	Fundamentals of Thermal Turbomachinery	655
14.2	Axial Compressor	659
14.2.1	Flow Coefficient, Pressure Coefficient, and Degree of Reaction	659
14.2.2	Method of Design	663
14.2.3	Subsonic Compressor	666
14.2.4	Transonic Compressor	668
14.3	Centrifugal Compressor	672
14.3.1	Flow Physics of the Centrifugal Compressor	672
14.3.2	Flow Coefficient, Pressure Coefficient, and Efficiency . .	676
14.3.3	Slip Factor	678
14.4	Combustion Chamber	679
14.4.1	Flow with Heat Transfer	679
14.4.2	Geometry of the Combustion Chamber	681
14.5	Turbine	682
14.5.1	Basics	682
14.5.2	Efficiency, Flow Coefficient, Work Coefficient, and Degree of Reaction	683
14.5.3	Impulse and Reaction Stage	684
	Selected Bibliography	687
	Index	715