

SOLVED
PRACTICAL
PROBLEMS IN
**FLUID
MECHANICS**

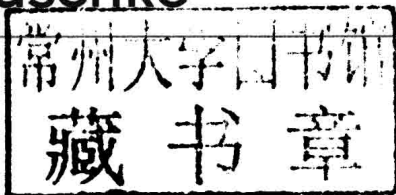
Carl J. Schaschke



CRC Press
Taylor & Francis Group

SOLVED PRACTICAL PROBLEMS IN FLUID MECHANICS

Carl J. Schaschke



CRC Press

Taylor & Francis Group

Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an Informa business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

© 2016 by Taylor & Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works

Printed on acid-free paper
Version Date: 20150723

International Standard Book Number-13: 978-1-4822-4298-0 (Hardback)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Library of Congress Cataloging-in-Publication Data

Schaschke, Carl, author.
Solved practical problems in fluid mechanics / Carl J. Schaschke.
pages cm
Includes bibliographical references and index.
ISBN 978-1-4822-4298-0 (hardcover : acid-free paper) 1. Fluid mechanics--Problems, exercises, etc. I. Title.

TA357.3.S323 2015
620.1'06--dc23

2015025709

Visit the Taylor & Francis Web site at
<http://www.taylorandfrancis.com>

and the CRC Press Web site at
<http://www.crcpress.com>

Printed and bound by CPI Group (UK) Ltd, Croydon, CR0 4YY

**SOLVED
PRACTICAL
PROBLEMS IN
FLUID
MECHANICS**

Preface

The study of fluid mechanics forms an essential part of all engineering degree courses worldwide. While there have been many changes in education over the years, the teaching of mathematics and physical sciences remains critical to ensure that the next generation of engineers is fully equipped with all the necessary tools for professional practice. Providing undergraduates with solved problems has proved to be a successful and effective part of the learning process to demonstrate the complexities of the discipline.

This book is a comprehensive collection of problems with accompanying solutions in fluid mechanics which demonstrate the application of fluid flow principles in a range of commonly used engineering applications. It is a compilation of problems presented in a form that has a consistent nomenclature recognisable to all students of engineering. Aimed primarily at undergraduate students in the early stages of their academic formation, this book is also aimed at academic tutors as well as practitioners who may encounter challenging problems in fluid mechanics perhaps for the first time. Recognising that many students learn most effectively by the use of solved problems, the book will also be useful in the preparation of exams.

Each problem begins with a statement. The solution that follows does not present mathematical derivations but instead presents a solution from an easily recognisable starting point. Both problem and solution are therefore presented to enable the reader to follow each step in the analysis in a way that could be realistically achieved in a tutorial situation. The nomenclature is designed to be familiar to all engineers.

A number of the problems have been provided by academics who are directly involved in teaching fluid mechanics, and by industrialists. The problems selected are illustrative of key concepts and the significance of their solutions. They are tailored in such a way that the identity of a particular university or company and the nature of its business is avoided.

The problems include two-phase and multi-component flow, viscometry and the use of rheometers, non-Newtonian fluids, as well as new and novel applications of classical fluid flow principles. Each problem has been prepared using the SI system of units throughout, but it is recognised that non-SI units are still widely used in many industries. Reference is made to commonly encountered units and conversions presented, where appropriate.

In the preparation of this book, I am indebted to the many people who have assisted by providing solved problems. In particular, I would like to express my sincere appreciation to Dr. Isobel Fletcher (University of Strathclyde, Glasgow, Scotland), Andrew Bell (University of Strathclyde), Andrew McGuire (University of Cambridge, United Kingdom), Dr. Ian Wilson (University of Cambridge, United Kingdom), Dr. Andy Durrant

(University of the West of Scotland, Paisley). My thanks to the editorial staff of Taylor & Francis/CRC Press, Dr. Gangadeep Singh, Hayley Ruggieri, and Linda Leggio. Finally, this book could not have been produced without the support of my wife, Melodie, and my daughters, Emily and Rebecca.

The text has been carefully checked. Any errors, omissions, misprints, or obscurities are entirely my own. I would be grateful to receive suggestions for improvements.

Carl Schaschke
Abertay University
Dundee, Scotland

Author

Carl Schaschke, Ph.D., is a chemical engineer and is head of the School of Science, Engineering, and Technology at Abertay University (Dundee, Scotland), having previously served as head of the Department of Chemical and Process Engineering at the University of Strathclyde (Glasgow, Scotland) for 8 years. Prior to pursuing a Ph.D. in chemical engineering, he worked in the nuclear reprocessing industry at Sellafield (Cumbria, United Kingdom). He is a full professor and teaches fluid mechanics to undergraduates, and his research interests are in the thermophysical measurement of substances under extreme pressure. He serves as a UK representative of the European Federation of Chemical Engineering Working Party on High Pressure Technology. Dr. Schaschke has published several books including the *Dictionary of Chemical Engineering* (Oxford University Press, 2014). He is a fellow of the Institution of Chemical Engineers. He is married with two daughters, Emily and Rebecca.

Introduction

Fluid mechanics concerns the behaviour of fluids when subjected to changes in pressure; the effects of frictional resistance; the flow through pipes, ducts, and restrictions; and the production of power. The study of the behaviour of fluids forms an integral part of the education of an engineer for which a sound understanding of fluids is critical for the cost-effective design and efficient operation of machines and processes, and which also includes the development and testing of theories devised to explain various phenomena.

Generally well known for the large number of concepts required to solve even the simplest of problems, it is essential for the engineer to possess a sound grasp of the many concepts encountered in fluid mechanics to attempt to solve even the most seemingly straightforward of problems. A full and lucid grasp of the basics is therefore essential if such concepts are to be applied correctly and meaningfully. It is also worth remembering, however, that the solutions are only as valid as the mathematical models and the experimental data used to describe fluid flow phenomena. There can be no substitute for an all around understanding and appreciation of the underlying concepts and the ability to solve or check problems from first principles.

For many students or those new to the subject, there is often difficulty in identifying the necessary and relevant information to solve problems. Students may also be hesitant in applying theories covered in their studies, resulting from either an incomplete understanding of the principles or due to a lack of confidence as the result of unfamiliarity with the subject matter. While some concepts are straightforward, unexpected difficulties can be encountered when seemingly similar or related simple problems require the evaluation of a different but associated variable. Although the solution may involve the same starting point, the route through to the final answer may be quite different. Finding a clear path to solving a particular problem may therefore not always be straightforward. There is a propensity that the student may dwell unnecessarily on a mathematical quirk as the direct result of the application of an incorrect or inappropriate formula that is entirely due to the manner in which the problem had been incorrectly approached and which is irrelevant to the subject.

It is recognised that students develop and use a variety of study methods that are dependent on their own personal needs, circumstances, and available resources. For many, a quicker and deeper understanding of the concepts and principles is achieved when a problem is provided with an accompanying solution. The use of problems with solutions is an established and widely used approach to self-study. By providing a clear and logical approach from a distinct starting point through defined steps, together with the relevant mathematical formulae and manipulation, the student is able to

gain an appreciation of both the depth and complexity involved in reaching a practical solution.

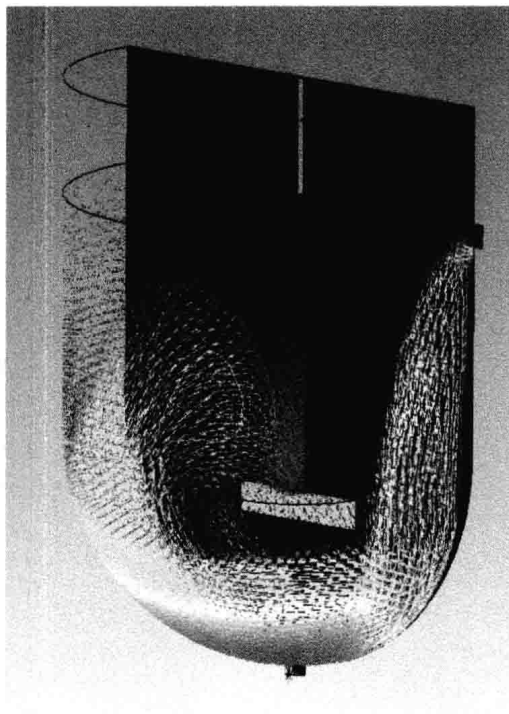
While applications require the straightforward application of the many fundamental principles of fluid mechanics that were founded in the 17th and 18th centuries by scientists such as Bernoulli, Newton, and Euler, many of today's fluid mechanics problems are complex, nonlinear, three-dimensional, and transient. High-speed and powerful computers are increasingly used to solve complex problems, particularly in computational fluid dynamics (CFD). Problems involving multi-phase flow can require involved procedures that are based on underlying concepts but require the use of empirical correlations based on experimental evidence. The combined flow of water and air along a horizontal pipe, for example, is complicated by the relative amounts of each phase, their relative velocities, and their different properties of density and viscosity, as well as interfacial surface tension between the two.

There has been long history of developments in the understanding of multi-phase processing. From the flow pattern maps and empirical correlations of Baker in the 1950s to today's highly sophisticated approaches of computational fluid dynamics requiring considerable computing power, the most valuable references for today's applications in texts and journals span the best part of half a century. The reference list provided at the end of this book is intended to enable the reader to delve more deeply and to review critically and compare models, form considered judgments, and distinguish between postulated models in terms of their merit.

This book is intended principally to support understanding in fluid mechanics. It is intended to be of assistance in solving related problems that may be encountered in a wide range of applications. Through the use of defined problems, the book is designed to enable the student to become familiar with, and to grasp firmly, important concepts and principles in fluid mechanics. Simple mathematical approaches have therefore been employed, although it is assumed that the reader has a prior knowledge of basic engineering concepts. Readers should be able to recognise similarities with their own problems and by following the provided solution, be able to reach their own solutions. The book, however, is not intended to be a complete and authoritative course or substitute to full texts on the subject. This book is therefore aimed at engineers who already have an understanding of fluid flow phenomena gained elsewhere. It requires the knowledge and application of fundamental engineering concepts such as dimensionless numbers and a fluency in basic mathematical skills such as differential calculus and associated application of boundary condition for solutions.

Each of the nine chapters has been prepared specifically to enable the reader to develop a sufficient knowledge and understanding of the fundamentals encountered in engineering, and to gain confidence in their application. The book is therefore intended to enable the reader to have an appreciation and understanding of fluids. Each problem has been selected

and developed specifically to make as clear as possible, and without ambiguity or oversimplification, the important concepts used in this field of study. The book is therefore intended for the reader to draw on his or her own practical experience and to develop a critical and constructive approach to tackling problems.



Nomenclature

Roman

A	Flow area	m^2	\dot{m}	Mass flow rate	$kg s^{-1}$
a	Coefficient	(—)	m_p	Mass of particle	kg
a	Lapse rate	$^{\circ} km^{-1}$	N	Impeller diameter	m
B	Bingham number	(—)	N	Rotational speed	rev s^{-1}
b	Exponent	(—)	N_p	Power number	(—)
C	Concentration	$kmol m^{-3}$	N_s	Specific speed	$m^{3/4} s^{-3/2}$
C_d	Coefficient of discharge	(—)	P	Wetted perimeter	m
C_H	Head coefficient	(—)	P_o	Power number	(—)
C_Q	Capacity coefficient	(—)	p	Pressure	Nm^{-2}
c	Exponent	(—)	Δp	Pressure difference	Nm^{-2}
D	Impeller diameter	m	\dot{Q}	Volumetric flow rate	$m^3 s^{-1}$
d	Diameter	m	R	Radius	m
d_c	Critical particle diameter	m	R	University gas constant	$kJ kmol^{-1} K$
d_e	Equivalent hydraulic diameter	m	r	Radius	m
d_p	Particle diameter	m	r_H	Hydraulic radius	m
E_o	Eötvös number	(—)	Re	Reynolds number	(—)
e	Voidage	(—)	Re_B	Bingham Reynolds number	(—)
F	Force	N	S	Slip ratio	(—)
f	Friction factor	(—)	S_n	Suction specific speed	(—)
Fr	Froude number	(—)	s	Specific area	$m^2 m^{-3}$
G	Mass flux	$kg m^{-2} s^{-1}$	T	Temperature	K
g	Gravitational acceleration	ms^{-2}	T	Torque	Nm
H	Depth	m	t	Thickness	m
H_p	Head required for pumping	m	t	Time	s
i	Gradient of slope	$m m^{-1}$	U	Fluid velocity	ms^{-1}
j	Superficial velocity	ms^{-1}	V	Volume	m^3
K	Coefficient	(—)	W	Width	m
L	Length	m	X	Multiplier	(—)
M_o	Morton number	(—)	x	Horizontal distance	m
M_w	Molecular weight	(—)	x	Mass quality	(—)
			y	Vertical distance	m
			Z	Compressibility	(—)
			z	Elevation	m

Greek

α	Gas void fraction	(—)
β	Coefficient	(—)
δ	Film thickness	m
ε	Surface roughness	m
η	Pump efficiency	(—)
θ	Angle of inclination	°
λ	Friction factor	(—)
λ_L	Liquid hold-up	(—)
μ	Viscosity	Nsm ⁻²
π	Pi	3.14 159
ρ	Density	kgm ⁻³
ρ_p	Particle density	kgm ⁻³
τ	Shear stress	Nm ⁻²
τ_w	Wall shear stress	Nm ⁻²
φ	Sphericity or shape factor	(—)
Φ	Two-phase multiplier	(—)

Contents

Preface.....	xi
Author.....	xiii
Introduction.....	xv
Nomenclature.....	xix
1. Fluid Statics	1
Introduction.....	1
Problem 1.1: Fluid Statics	2
Solution.....	2
Problem 1.2: Falkirk Wheel.....	4
Solution.....	4
Problem 1.3: Gauge Pressure.....	6
Solution.....	7
Problem 1.4: Air Pressure with Altitude.....	8
Solution.....	8
Problem 1.5: Pascal's Paradox.....	10
Solution.....	10
Problem 1.6: Fish Ladder.....	12
Solution.....	12
Problem 1.7: Vessel Sizing and Testing	14
Solution.....	14
Problem 1.8: Air-Lift.....	15
Solution.....	16
Problem 1.9: Liquid-Liquid Separator	18
Solution.....	19
Further Problems	19
2. Flow Measurement.....	25
Introduction.....	25
Problem 2.1: Venturi Meter Calibration.....	28
Solution.....	28
Problem 2.2: Orifice Plate Meter	30
Solution.....	31
Problem 2.3: Evaluation of the Coefficient of Discharge.....	33
Solution.....	34
Problem 2.4: Pitot Tube Traverse.....	35
Solution.....	35
Problem 2.5: Venturi Flume.....	37
Solution.....	37

Problem 2.6: Flowmeter Calibration by Dilution Method	38
Solution.....	38
Further Problems	40
3. Freely Discharging Flow	43
Introduction	43
Problem 3.1: Discharge through an Orifice	44
Solution.....	44
Problem 3.2: Reservoir Inflow	46
Solution.....	46
Problem 3.3: Laminar Flow	48
Solution.....	48
Problem 3.4: Tank Drainage	49
Solution.....	49
Problem 3.5: Tank Drainage through a Connecting Pipe	51
Solution.....	51
Problem 3.6: Drainage between Tanks.....	53
Solution.....	53
Problem 3.7: Tank Containment.....	55
Solution.....	55
Problem 3.8: Siphon	57
Solution.....	57
Problem 3.9: Water Clock	59
Solution.....	59
Problem 3.10: Force on a Nozzle	61
Solution.....	61
Further Problems	63
4. Fluid Friction	65
Introduction	65
Problem 4.1: Connected Reservoir Flow	66
Solution.....	67
Problem 4.2: Laminar Flow	68
Solution.....	69
Problem 4.3: Tapered Pipe Section	70
Solution.....	70
Problem 4.4: Ventilation Duct.....	71
Solution.....	72
Problem 4.5: Flow in Noncircular Ducts	72
Solution.....	73
Problem 4.6: Valve Test.....	75
Solution.....	75
Problem 4.7: Flow of a Thick Fluid	78
Solution.....	78