SOLVED PRACTICAL PROBLEMS IN FLUID MECHANICS

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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

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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.

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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.

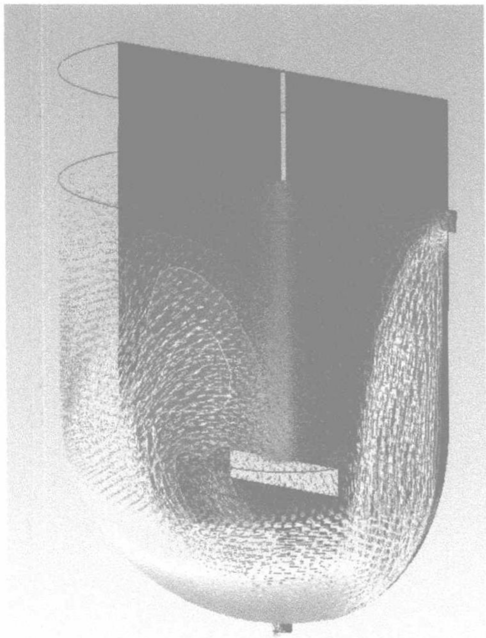
It is recognised that students develop and use a variety of study methods that are dependent on their own personal needs, circumstances, and available resources. For many, a quicker and deeper understanding of the concepts and principles is achieved when a problem is provided with an accompanying solution. 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
a	Coefficient	(—)
a	Lapse rate	$° km^{-1}$
B	Bingham number	(—)
b	Exponent	(—)
C	Concentration	$kmol\ m^{-3}$
C_d	Coefficient of discharge	(—)
C_H	Head coefficient	(—)
C_Q	Capacity coefficient	(—)
c	Exponent	(—)
D	Impeller diameter	m
d	Diameter	m
d_c	Critical particle diameter	m
d_e	Equivalent hydraulic diameter	m
d_p	Particle diameter	m
E_o	Eötvös number	(—)
e	Voidage	(—)
F	Force	N
f	Friction factor	(—)
Fr	Froude number	(—)
G	Mass flux	$kgm^{-2}s^{-1}$
g	Gravitational acceleration	ms^{-2}
H	Depth	m
H_p	Head required for pumping	m
i	Gradient of slope	$m\ m^{-1}$
j	Superficial velocity	ms^{-1}
K	Coefficient	(—)
L	Length	m
M_o	Morton number	(—)
M_w	Molecular weight	(—)
$\dot{m}$	Mass flow rate	kgs^{-1}
m_p	Mass of particle	kg
N	Impeller diameter	m
N	Rotational speed	$rev\ s^{-1}$
N_p	Power number	(—)
N_s	Specific speed	$m^{3/4}s^{-3/2}$
P	Wetted perimeter	m
P_o	Power number	(—)
p	Pressure	Nm^{-2}
Δp	Pressure difference	Nm^{-2}
$\dot{Q}$	Volumetric flow rate	m^3s^{-1}
R	Radius	m
R	University gas constant	$kJkmol^{-1}K$
r	Radius	m
r_H	Hydraulic radius	m
Re	Reynolds number	(—)
Re_B	Bingham Reynolds number	(—)
S	Slip ratio	(—)
S_n	Suction specific speed	(—)
s	Specific area	m^2m^{-3}
T	Temperature	K
T	Torque	Nm
t	Thickness	m
t	Time	s
U	Fluid velocity	ms^{-1}
V	Volume	m^3
W	Width	m
X	Multiplier	(—)
x	Horizontal distance	m
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	(—)

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