FUNDAMENTALS OF FLUID MECHANICS

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SECOND EDITION

Second Edition

Fundamentals of Fluid Mechanics

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TABLE 1.5 Approximate Physical Properties of Some Common Liquids (BG Units)

Liquid	Temperature (°F)	Density, ρ (slugs/ft^3)	Specific Weight, γ (lb/ft^3)	Dynamic Viscosity, μ (lb·s/ft^2)	Kinematic Viscosity, ν (ft^2/s)	Surface Tension,[a] σ (lb/ft)	Vapor Pressure, p_v [lb/in.^{2} (abs)]	Bulk Modulus,[b] E_v (lb/in.^{2})
Carbon tetrachloride	68	3.09	99.5	2.00 E − 5	6.47 E − 6	1.84 E − 3	1.9 E + 0	1.91 E + 5
Ethyl alcohol	68	1.53	49.3	2.49 E − 5	1.63 E − 5	1.56 E − 3	8.5 E − 1	1.54 E + 5
Gasoline[c]	60	1.32	42.5	6.5 E − 6	4.9 E − 6	1.5 E − 3	8.0 E + 0	1.9 E + 5
Glycerin	68	2.44	78.6	3.13 E − 2	1.28 E − 2	4.34 E − 3	2.0 E − 6	6.56 E + 5
Mercury	68	26.3	847	3.28 E − 5	1.25 E − 6	3.19 E − 2	2.3 E − 5	4.14 E + 6
SAE 30 oil[c]	60	1.77	57.0	8.0 E − 3	4.5 E − 3	2.5 E − 3	—	2.2 E + 5
Seawater	60	1.99	64.0	2.51 E − 5	1.26 E − 5	5.03 E − 3	2.56 E − 1	3.39 E + 5
Water	60	1.94	62.4	2.34 E − 5	1.21 E − 5	5.03 E − 3	2.56 E − 1	3.12 E + 5

[a] In contact with air.

[b] Isentropic bulk modulus calculated from speed of sound.

[c] Typical values. Properties of petroleum products vary.

TABLE 1.6 Approximate Physical Properties of Some Common Liquids (SI Units)

Liquid	Temperature (°C)	Density, ρ (kg/m^3)	Specific Weight, γ (kN/m^3)	Dynamic Viscosity, μ (N·s/m^2)	Kinematic Viscosity, ν (m^2/s)	Surface Tension,[a] σ (N/m)	Vapor Pressure, p_v [N/m^2 (abs)]	Bulk Modulus,[b] E_v (N/m^2)
Carbon tetrachloride	20	1,590	15.6	9.58 E − 4	6.03 E − 7	2.69 E − 2	1.3 E + 4	1.31 E + 9
Ethyl alcohol	20	789	7.74	1.19 E − 3	1.51 E − 6	2.28 E − 2	5.9 E + 3	1.06 E + 9
Gasoline[c]	15.6	680	6.67	3.1 E − 4	4.6 E − 7	2.2 E − 2	5.5 E + 4	1.3 E + 9
Glycerin	20	1,260	12.4	1.50 E + 0	1.19 E − 3	6.33 E − 2	1.4 E − 2	4.52 E + 9
Mercury	20	13,600	133	1.57 E − 3	1.15 E − 7	4.66 E − 1	1.6 E − 1	2.85 E + 10
SAE 30 oil[c]	15.6	912	8.95	3.8 E − 1	4.2 E − 4	3.6 E − 2	—	1.5 E + 9
Seawater	15.6	1,030	10.1	1.20 E − 3	1.17 E − 6	7.34 E − 2	1.77 E + 3	2.34 E + 9
Water	15.6	999	9.80	1.12 E − 3	1.12 E − 6	7.34 E − 2	1.77 E + 3	2.15 E + 9

[a] In contact with air.

[b] Isentropic bulk modulus calculated from speed of sound.

[c] Typical values. Properties of petroleum products vary.

TABLE 1.7 Approximate Physical Properties of Some Common Gases at Standard Atmospheric Pressure (BG Units)

Gas	Temperature (°F)	Density, ρ (slugs/ft³)	Specific Weight, γ (lb/ft³)	Dynamic Viscosity, μ (lb·s/ft²)	Kinematic Viscosity, ν (ft²/s)	Gas Constant,[a] R (ft·lb/slug·°R)	Specific Heat Ratio,[b] k
Air (standard)	59	2.38 E − 3	7.65 E − 2	3.74 E − 7	1.57 E − 4	1.716 E + 3	1.40
Carbon dioxide	68	3.55 E − 3	1.14 E − 1	3.07 E − 7	8.65 E − 5	1.130 E + 3	1.30
Helium	68	3.23 E − 4	1.04 E − 2	4.09 E − 7	1.27 E − 4	1.242 E + 4	1.66
Hydrogen	68	1.63 E − 4	5.25 E − 3	1.85 E − 7	1.13 E − 4	2.466 E + 4	1.41
Methane (natural gas)	68	1.29 E − 3	4.15 E − 2	2.29 E − 7	1.78 E − 4	3.099 E + 3	1.31
Nitrogen	68	2.26 E − 3	7.28 E − 2	3.68 E − 7	1.63 E − 4	1.775 E + 3	1.40
Oxygen	68	2.58 E − 3	8.31 E − 2	4.25 E − 7	1.65 E − 4	1.554 E + 3	1.40

[a] Values of the gas constant are independent of temperature.

[b] Values of the specific heat ratio depend only slightly on temperature.

TABLE 1.8 Approximate Physical Properties of Some Common Gases at Standard Atmospheric Pressure (SI Units)

Gas	Temperature (°C)	Density, ρ (kg/m³)	Specific Weight, γ (N/m³)	Dynamic Viscosity, μ (N·s/m²)	Kinematic Viscosity, ν (m²/s)	Gas Constant,[a] R (J/kg·K)	Specific Heat Ratio,[b] k
Air (standard)	15	1.23 E + 0	1.20 E + 1	1.79 E − 5	1.46 E − 5	2.869 E + 2	1.40
Carbon dioxide	20	1.83 E + 0	1.80 E + 1	1.47 E − 5	8.03 E − 6	1.889 E + 2	1.30
Helium	20	1.66 E − 1	1.63 E + 0	1.94 E − 5	1.15 E − 4	2.077 E + 3	1.66
Hydrogen	20	8.38 E − 2	8.22 E − 1	8.84 E − 6	1.05 E − 4	4.124 E + 3	1.41
Methane (natural gas)	20	6.67 E − 1	6.54 E + 0	1.10 E − 5	1.65 E − 5	5.183 E + 2	1.31
Nitrogen	20	1.16 E + 0	1.14 E + 1	1.76 E − 5	1.52 E − 5	2.968 E + 2	1.40
Oxygen	20	1.33 E + 0	1.30 E + 1	2.04 E − 5	1.53 E − 5	2.598 E + 2	1.40

[a] Values of the gas constant are independent of temperature.

[b] Values of the specific heat ratio depend only slightly on temperature.

Fundamentals of Fluid Mechanics

To Erik and all others who possess the curiosity, patience, and desire to learn

About the Authors

Bruce R. Munson, Professor of Engineering Mechanics at Iowa State University since 1974, received his B.S. and M.S. degrees from Purdue University and his Ph.D. degree from the Aerospace Engineering and Mechanics Department of the University of Minnesota in 1970.

From 1970 to 1974, Dr. Munson was on the mechanical engineering faculty of Duke University. From 1964 to 1966, he worked as an engineer in the jet engine fuel control department of Bendix Aerospace Corporation, South Bend, Indiana.

Dr. Munson's main professional activity has been in the area of fluid mechanics education and research. He has been responsible for the development of many fluid mechanics courses for studies in civil engineering, mechanical engineering, engineering science, and agricultural engineering and is the recipient of an Iowa State University Superior Engineering Teacher Award.

He has authored and coauthored many theoretical and experimental technical papers on hydrodynamic stability, low Reynolds number flow, secondary flow, and the applications of viscous incompressible flow. He is a member of The American Society of Mechanical Engineers, The American Physical Society, and The American Society for Engineering Education.

Donald F. Young, Anson Marston Distinguished Professor in Engineering, is a faculty member in the Department of Aerospace Engineering and Engineering Mechanics at Iowa State University. Dr. Young received his B.S. degree in mechanical engineering, his M.S. and Ph.D. degrees in theoretical and applied mechanics from Iowa State, and has taught both undergraduate and graduate courses in fluid mechanics for many years. In addition to being named a Distinguished Professor in the College of Engineering, Dr. Young has also received the Standard Oil Foundation Outstanding Teacher Award and the Iowa State University Alumni Association Faculty Citation. He has been engaged in fluid mechanics research for more than 35 years, with special interests in similitude and modeling and the interdisciplinary field of biomedical fluid mechanics. Dr. Young has contributed to many technical publications and is the author or coauthor of two textbooks on applied mechanics. He is a Fellow of The American Society of Mechanical Engineers.

Theodore H. Okiishi, Professor and Chair of Mechanical Engineering at Iowa State University, has taught fluid mechanics courses there since 1967. He received his undergraduate and graduate degrees at Iowa State.

From 1965 to 1967, Dr. Okiishi served as a U.S. Army officer with duty assignments at the National Aeronautics and Space Administration Lewis Research Center, Cleveland, Ohio, where he participated in rocket nozzle heat transfer research, and at the Combined Intelligence Center, Saigon, Republic of South Vietnam, where he studied seasonal river flooding problems.

Professor Okiishi is active in research on turbomachinery fluid dynamics. He and his graduate students and other colleagues have written a number of journal articles based on their studies. Some of these projects have involved significant collaboration with government and industrial laboratory researchers with one technical paper winning the ASME Melville Medal.

Dr. Okiishi has received several awards for teaching. He has developed undergraduate and graduate courses in classical fluid dynamics as well as the fluid dynamics of turbomachines.

He is a licensed professional engineer. His technical society activities include having been chair of the board of directors of The American Society of Mechanical Engineers (ASME) International Gas Turbine Institute. He is a fellow member of the ASME and the technical editor of the *Journal of Turbomachinery.*

Preface

This book is intended for junior and senior engineering students who are interested in learning some fundamental aspects of fluid mechanics. This area of mechanics is mature, and a complete coverage of all aspects of it obviously cannot be accomplished in a single volume. We developed this text to be used as a first course. The principles considered are classical and have been well-established for many years. However, fluid mechanics education has improved with experience in the classroom, and we have brought to bear in this book our own ideas about the teaching of this interesting and important subject. This second edition has been prepared after several years of experience by the authors using the first edition for an introductory course in fluid mechanics. Based on this experience, along with suggestions from reviewers, colleagues, and students, we have made a number of changes in this new edition. Many of these changes are minor and have been made to simply clarify and expand certain ideas and concepts. Major changes include the addition of a new chapter on turbomachines and the addition of many new problems.

One of our aims is to represent fluid mechanics as it really is—an exciting and useful discipline. To this end, we include analyses of numerous everyday examples of fluid-flow phenomena to which students and faculty can easily relate. In the second edition 170 examples are presented that provide detailed solutions to a variety of problems. Also, a generous set of homework problems in each chapter stresses the practical application of principles. Those problems that can be worked best with a programmable calculator or a computer, about 10% of the problems, are so identified. Also included in most chapters of the second edition are several open-ended problems. These problems require critical thinking in that in order to work them one must make various assumptions and provide the necessary data. Students are thus required to make reasonable estimates or to obtain additional information outside the classroom. These open-ended problems are clearly identified. Another new feature is the inclusion of extended, laboratory-type problems in most chapters. Actual experimental data are included in these problems, and the student is asked to perform a detailed analysis of the problem similar to that required for a typical laboratory. It is believed that this type of problem will be particularly useful for fluid mechanics courses that do not have a laboratory as a part of the course. These laboratory-type problems are located at the end of the problems section in most chapters and can be easily recognized. The examples and homework problems illustrate the considerable versatility of fluid mechanical analyses.

Our message to students is that fluid motion is consistent with well-established physical laws. The mathematical statements, or equations that represent these laws and thus describe fluid behavior, form the basis for problem solving. In some instances, the solution of these fundamental equations results in the answers sought. Often, however, experimental data-based correlations and dimensional analysis are required in addition to basic equations for solution closure.

Since this is an introductory text, we have designed the presentation of material to allow for the gradual development of student confidence in fluid mechanics problem solving. Each important concept or notion is considered in terms of simple and easy-to-understand circumstances before more complicated features are introduced.

In this second edition two systems of units continue to be used throughout the text: the British Gravitational System (pounds, slugs, feet, and seconds), and the International System of Units (newtons, kilograms, meters, and seconds). Both systems are widely used, and we believe that students need to be knowledgeable and comfortable with both systems. Approximately one-half of the examples and homework problems use the British System; the other half is based on the International System.

In the first four chapters, the student is made aware of some fundamental aspects of fluid motion, including important fluid properties, regimes of flow, pressure variations in fluids at rest and in motion, fluid kinematics, and methods of flow description and analysis. Some new material on non-Newtonian fluids has been added in Chapter 1. The Bernoulli equation is introduced in Chapter 3 to draw attention, early on, to some of the interesting effects of fluid motion on the distribution of pressure in a flow field. We believe that this timely consideration of elementary fluid dynamics will increase student enthusiasm for the more complicated material that follows. In Chapter 4, we convey the essential elements of kinematics, including Eulerian and Lagrangian mathematical descriptions of flow phenomena, and indicate the vital relationship between the two views. For teachers who wish to consider kinematics in detail before the material on elementary fluid mechanics, Chapters 3 and 4 can be interchanged without loss of continuity.

Chapters 5, 6, and 7 expand on the basic analysis methods generally used to solve or to begin solving fluid mechanics problems. Emphasis is placed on understanding how flow phenomena are described mathematically and on when and how to use infinitesimal and finite control volumes. Owing to the importance of numerical techniques in fluid mechanics, we have included additional introductory material on this subject in Chapter 6. Some simple examples have been added so that students can gain some insight into this approach to the solution of problems. The effects of fluid friction on pressure and velocity distributions are also considered in some detail. A formal course in thermodynamics is not required to understand the various portions of the text that consider some elementary aspects of the thermodynamics of fluid flow. Experiments or tests must be relied on when mathematical analysis alone is inadequate to solve a problem. Chapter 7 features the advantages of using dimensional analysis and similitude for organizing test data and for planning experiments and the basic techniques involved.

Chapters 8 to 11 offer students opportunities for the further application of the principles learned early in the text. Also, where appropriate, additional important notions such as boundary layers, transition from laminar to turbulent flow, and flow separation are introduced. Practical concerns such as pipe flow, open-channel flow, flow measurement, drag and lift, and the effects of compressibility are discussed. In Chapter 11 a new section on two-dimensional compressible flow has been included.

A major new feature of the second edition is the addition of Chapter 12—Turbomachines. This new chapter, in keeping with the general philosophy of the rest of the book, places emphasis on the fluid mechanics fundamentals associated with turbomachines, particularly pumps and turbines.

There are two important supplements that are available to professors who adopt this book for classroom use. The first is an Instructor's Manual containing complete, detailed solutions to all the problems in the text and selected enlarged figures suitable for making transparency masters. The second is software that consists of programs that provide the solutions to all the computer-designated problems in the book. Both supplements may be obtained directly from the publishers.

Students who study this text and who solve a representative set of the exercises provided should acquire a useful knowledge of the fundamentals of fluid mechanics. Faculty who use this text are provided with numerous topics to select from in order to meet the objectives of their own courses. More material is included than can be reasonably covered in one term. All are reminded of the fine collection of supplementary material. Where appropriate, we have cited throughout the text the articles and books that are available for enrichment.

We express our thanks to the many colleagues who have helped in the development of this text. We are indebted to the following reviewers of the second edition for their comments and suggestions:

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Working with students over the years has taught us much about fluid mechanics education. We have tried in earnest to draw from this experience for the benefit of users of this book. Obviously we are still learning, and we welcome any suggestions and comments from you.

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