FUNDAMENTALS OF FLUID MECHANICS

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Bruce R. Munson, Professor of Engineering Science and 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 Engineering Science and 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 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 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.

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 being a member of the board of directors of The American Society of Mechanical Engineers (ASME) International Gas Turbine Institute and serving as an associate editor for gas turbines of the ASME *Journal of Turbomachinery* and the *Journal of Engineering for Gas Turbines and Power*.

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.

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. More than 160 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 best worked with a programmable calculator or a computer, about 10% of the problems, are so identified. 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.

Two systems of units are 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. 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. 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. The advantages of using dimensional analysis and similitude for organizing test data and for planning experiments and the basic techniques involved are featured in Chapter 7.

Chapters 8 to 11 offer students opportunities for the further application of the principles learned earlier 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.

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 to meet the objectives of their own courses. More material than can be reasonably covered in one term is included. 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 wish to express our thanks to the many colleagues who have helped in the development of this text. We are indebted to the following reviewers for their comments and suggestions: Willem F. Brutsaert, University of Maine; Robert R. Faddick, Colorado School of Mines; James A. Liburdy, Clemson University; Robert A. Medrow, University of Missouri-Rolla; Charles L. Merkle, Pennsylvania State University; Edgar A. O'Rear, University of Oklahoma; and Laura L. Pauley, Pennsylvania State University. We also appreciate the help provided by Dennis Cronin, Nickolaos Ster-

giopulos, and Mark Kroneman relative to the homework problems and solutions manual. We wish to express our gratitude to the many persons who supplied the photographs used throughout the text and to Milton Van Dyke for his help in this effort. We acknowledge the superb typing of the manuscript by Carolyn Taylor. Finally, we thank our families for their continued encouragement during the writing of this text.

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 thus welcome any suggestions and comments from you.

Bruce R. Munson
Donald F. Young
Theodore H. Okiishi

Publisher's Note. 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 solutions to all of the problems in the text and more than 90 transparency masters. The second is IBM-PC compatible software which consists of programs that allow students to solve the computer problems in the book. Both supplements may be obtained directly from the publisher.

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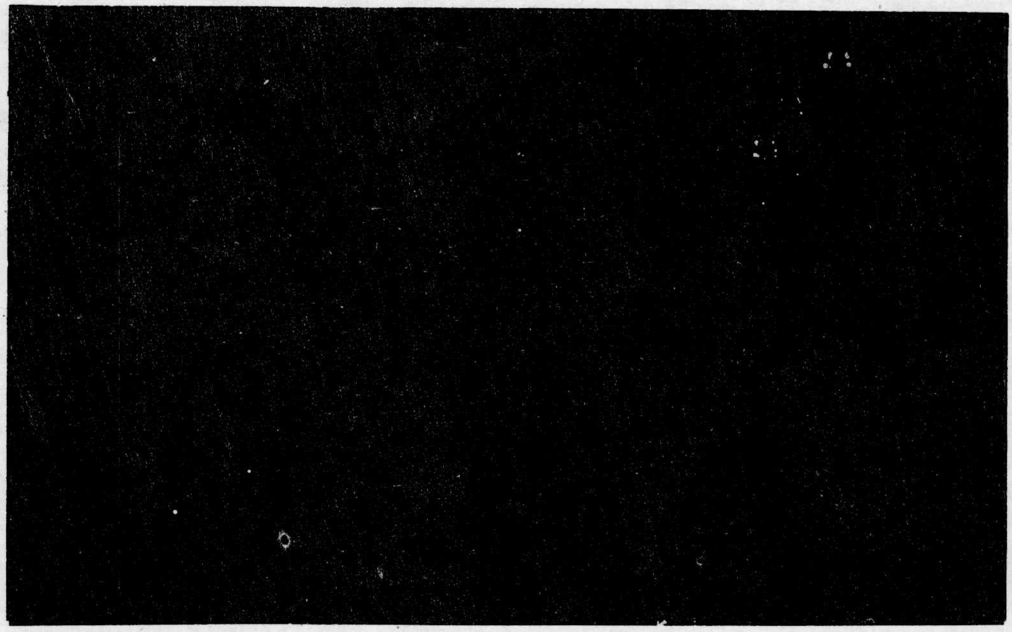

Liquid jet breakup: A jet of liquid breaks up into a series of drops because of surface tension effects. The number, size, and spacing of the drops is a function of various fluid properties including surface tension, density, and viscosity. (Water in air.) (Photograph courtesy of G. J. Jameson.)

ONE

INTRODUCTION

Fluid mechanics is that discipline within the broad field of applied mechanics concerned with the behavior of liquids and gases at rest or in motion. This field of mechanics obviously encompasses a vast array of problems that may vary from the study of blood flow in the capillaries (which are only a few microns in diameter) to the flow of crude oil across Alaska through an 800-mile-long 4-ft-diameter pipe. Fluid mechanics principles are needed to explain why airplanes are made streamlined with smooth surfaces for the most efficient flight, whereas golf balls are made with rough surfaces (dimpled) to increase their efficiency. Numerous interesting questions can be answered by using relatively simple fluid mechanics ideas. For example:

- How can a rocket generate thrust without having any air to push against in outer space?
- Why can't you hear a supersonic airplane until it has gone past you?
- How can a river flow downstream with a significant velocity even though the slope of the surface is so small that it could not be detected with an ordinary level?
- How can information obtained from model airplanes be used to design the real thing?
- Why does a stream of water from a faucet sometimes appear to have a smooth surface, but sometimes a rough surface?
- How much greater gas mileage can be obtained by improved aerodynamic design of cars and trucks?

The list of applications and questions goes on and on—but you get the point: fluid mechanics is a very important, practical subject. It is very likely that during your career as an engineer you will be involved in the analysis and design of systems that require a good understanding of fluid mechanics. It is hoped that this introductory text will provide a sound foundation in the fundamental aspects of fluid mechanics.