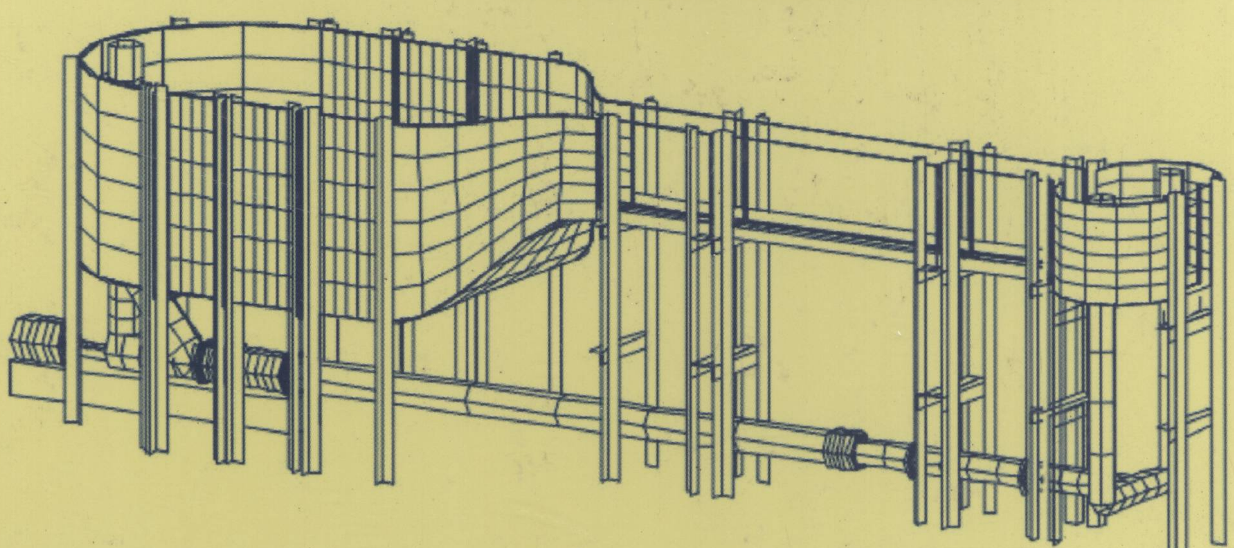
MEASUREMENT *in* FLUID MECHANICS



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Measurement in Fluid Mechanics

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MEASUREMENT IN FLUID MECHANICS

Measurement in Fluid Mechanics is an introductory, up-to-date, general reference in experimental fluid mechanics, describing both classical and state-of-the-art methods for flow visualization and for measuring flow rate, pressure, velocity, temperature, concentration, and wall shear stress. Particularly suitable as a textbook for graduate and advanced undergraduate courses, *Measurement in Fluid Mechanics* is also a valuable tool for practicing engineers and applied scientists. This book is written by a single author, in a consistent and straightforward style, with plenty of clear illustrations, an extensive bibliography, and over 100 suggested exercises. *Measurement in Fluid Mechanics* also features extensive background materials in system response, measurement uncertainty, signal analysis, optics, fluid mechanical apparatus, and laboratory practices, which shield the reader from having to consult with a large number of primary references. Whether for instructional or reference purposes, this book is a valuable tool for the study of fluid mechanics.

Stavros Tavoularis has received a Dipl. Eng. from the National Technical University of Athens, Greece, an M.Sc. from Virginia Polytechnic Institute and State University and a Ph.D. from The Johns Hopkins University. He has been a professor in the Department of Mechanical Engineering at the University of Ottawa since 1980, where he has served terms as the Department Chair and Director of the Ottawa-Carleton Institute for Mechanical and Aerospace Engineering. His research interests include turbulence structure, turbulent diffusion, vortical flows, aerodynamics, biofluid dynamics, nuclear reactor thermal hydraulics and the development of experimental methods. Professor Tavoularis is a Fellow of the Engineering Institute of Canada, a Fellow of the Canadian Society for Mechanical Engineering and a recipient of the George S. Glinski Award for Excellence in Research.

To Sofia, Christina and Jason

Preface

The purpose of experimental fluid mechanics is to measure the properties of a flowing fluid. Combined with theoretical analysis, measurements are used for understanding the operation of a fluid-containing system and then applying this knowledge towards designing improved systems and predicting their future operation. One may also use measurement to monitor and control a physical process, thus ensuring efficient and safe operation of a system. Performing a fluid mechanics experiment requires theoretical and practical knowledge and skills from a variety of fields of science and engineering. The experimental fluid mechanicist will likely need, in addition to a solid education in fluid mechanics, an advanced background in material properties, physics, mathematics, statistics, and electronics, with the list often expanding to include computer science, chemistry, biology, physiology, and environmental sciences. Much of the necessary background is covered in typical engineering education curricula, although segmented and presented in ways that are not focussed on the needs of experimental fluid mechanics. The diversity of background information, combined with the need for in-depth understanding of many different topics, can be intimidating to the novice in this field. Conducting an apprenticeship of substantial length under the guidance of an experienced experimentalist would certainly be the most sensible approach, but not one that is always available or compatible with time constraints. The next option is to learn through published literature. A literature search in even a narrow aspect of experimental fluid mechanics will most likely reveal an overwhelmingly lengthy list of related sources, widely uneven in scope, objectives, and styles. One would have to steer judiciously among these sources in order to identify and extract the truly needed material. This is by no means a negative reflection on the fluid mechanics community, which has put extraordinary efforts in disseminating the available knowledge in hundreds of books, review articles, and reports, both at introductory and advanced levels. It reflects on the understandable frustration of the non-expert when dealing with expert-written material. Some sources are very specialized and advanced, presuming that the reader is already familiar with the topic and has readily available all required background. Many available sources of broad scope constitute collections of separate articles, with little or no connecting material among the different topics. In other cases, the information presented is practical and targeted towards a specific audience, such as process engineers or technologists.

The present book is an attempt to fill in the observed need for a consistently written, introductory-level, up-to-date, general reference in experimental fluid mechanics. Its main intended use is as a textbook in an introductory graduate course, and, in fact, the material is based on a set of notes I developed over several years for such a course at the University of Ottawa. Selected sections may also serve as a textbook in an advanced undergraduate or a combined undergraduate–graduate course on this topic. The book contains extensive background material to shield the reader from having to consult a large number of primary references in diverse areas of science and engineering. The book may also be of interest to practicing engineers and applied scientists in many areas of application, as much of the instrumentation and methods described here are used not only in fluid mechanics research but also in many other fundamental and applied fields.

Like all areas of engineering and science, experimental fluid mechanics has been profoundly influenced by recent advances in electronics, optics, computers, and information technology. Yet most experimental methods are based on classical scientific principles, which must be understood well for their correct application. The emphasis in selecting and presenting the material was on time-resisting fundamentals, rather than on giving a detailed description of the latest technologies, which, in any case, would likely be of ephemeral duration. A main strength of any educational material is its use of illustrations. I have tried to supplement the text with simple, consistent sketches and plots, the great majority of which are original, although often based on previously published illustrations. Considering the breadth of the included topics and the diversity, in quality and style, of the available information, this represents an option for uniformity and clarity, rather than exactness in scale and completeness. To restrict the length of the exposition and the cost of publication, a significant number of methods discussed briefly in the text have not been accompanied by illustrations, and the reader is referred to the cited references for further details. Fluid mechanics is a field that is distinguished by the ample availability of images, often spectacular ones, illuminating the physical phenomena under study and suitable for both qualitative and quantitative purposes. Once more, restrictions on the length and cost of the present book have dictated the inclusion of only a small number of such images, mostly obtained by relatively modest means. The reader and instructors who consider using this book as a textbook are encouraged to augment the material with images easily accessible in collective works. Examples of suitable sources include *An Album of Fluid Motion* (assembled by M. Van Dyke, Parabolic Press, Stanford, California, 1982), *A Gallery of Fluid Motion* (edited by M. Samimy et al., Cambridge University Press, Cambridge, UK, 2003), *Visualized Flow* (compiled by the Japan Society of Mechanical Engineers, Pergamon, Oxford, UK, 1988), and the website *www.efluids.com.*

It is impossible to acknowledge all persons who provided ideas, specific material, or criticisms on the different topics discussed in this book. The long-lasting influence of my mentor, the late Stan Corrsin, has unquestionably affected the style and organization of the material, particularly the urge for clarity of presentation, whether it was actually achieved or not. The input and feedback of the many students who attended my classes have had a strong effect on the selection of topics and the level and scope of the

presentation. During recent years, while the book was getting formalized, I gratefully acknowledged the valuable suggestions of the following individuals, in alphabetical order: Yiannis Andreopoulos, Sean Bailey, Warren Dunn, Mohamed Gad-el-Hak, Gordon Holloway, Jacques Lewalle, Martin Maxey, Cliff Weissman, and Phil Zwart. Conscious of possible limitations in the present edition, I welcome any feedback and suggestions of all readers, which I would gladly consider in future amendments or revisions.

Stavros Tavoularis
Ottowa, 2005

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PART ONE

GENERAL CONCEPTS

1 Flow properties and basic principles

Before being able to measure a flow property, it is necessary to understand its nature and its relationship to other properties. Furthermore, for a proper use of a measuring instrument, one must be thoroughly familiar with the principles of its operation, which usually involve concepts and relationships from several different fields. In this chapter, the basic principles of fluid mechanics are reviewed and the properties of interest and their groupings in dimensionless form are identified. This is meant to be a refresher of familiar concepts, as well as to identify a possible need for more in-depth reviews of fluid mechanics [1–3], thermodynamics [4], and heat transfer [5]. Background material from system dynamics, signal analysis, and optics is reviewed separately in later chapters.

1.1 Forces, stresses, and the continuum hypothesis

All material objects are subjected to external forces, which are of two types, body forces and surface forces. *Body forces* act on the bulk of the object from a distance and are proportional to its mass; the most common examples are gravitational and electromagnetic forces. *Surface forces* are exerted on the surface of the object by other objects in contact with it; they generally increase with increasing contact area.

Any surface force acting on an elementary surface section of an object can be decomposed into a *normal* component, with a direction normal to the local tangent plane, and a *tangential* or *shear* component, with a direction parallel to the local tangent plane (see Fig. 1.1).

The *stress* at a point of an object is defined as the corresponding surface force per unit area; consequently there are two types of stresses, *normal stresses* and *shear stresses*. With respect to a Cartesian coordinate system, all stresses acting on three planes normal to the three axes form a second-order Cartesian tensor, which has nine components, only six of which (three normal stresses and three shear stresses) are independent. In classical fluid mechanics, the (static) *pressure* is defined as the average normal stress along any three orthogonal directions.

According to the classical definition, a *fluid* is a material that cannot withstand a shear stress when at rest; in other words, a fluid subjected to a shear stress will always be in motion or deformation. Fluids are easily deformable materials and take the shape of

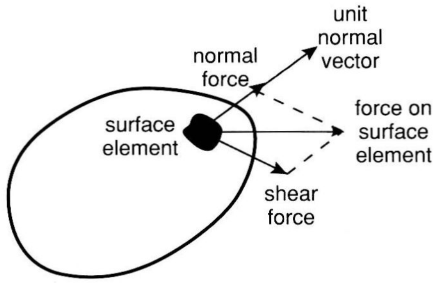

Figure 1.1. Force on a surface element and its decomposition to normal and shear components.

any container in which they are contained. They are further distinguished into *liquids*, which have a relatively high density and require an extremely large change of normal stresses for a change of their volume, and *gases*, which have a relatively low density and can easily change their volume. Unlike liquids, gases tend to occupy the entire available volume of their container. Besides 'simple' liquids and gases, there are a number of materials that, although not satisfying all properties of classical fluids, exhibit fluid-like properties. Examples include viscoelastic materials, which may sustain a certain amount of shear stress without being set in motion but behave like fluids when the shear stress exceeds a certain level, and plasmas, which form when gases are exposed to extremely high temperatures, in which case their molecules are dissociated into free atoms.

In most applications within the scope of conventional fluid mechanics, the phenomena of interest are characterized by scales that are far larger than the distances between molecules. Then the flow properties are defined as statistical averages over a volume that contains a very large number of molecules. In such cases, one need not be concerned about individual molecular or atomic motions and masses; instead, one should invoke the *continuum hypothesis*, by which any property of the fluid is assumed to have a continuous distribution within the volume of the fluid. Thus one may define the *local* value of the property as the limit of the volume-averaged value of this property as the volume collapses towards a mathematical point. One may refer to a *fluid element*, or *fluid particle*, as a material entity that has an infinitesimal volume, in which case its properties are uniform within this volume. In multiphase flows of immiscible fluids, the continuum hypothesis applies within each individual fluid, whereas some properties may be considered as discontinuous at the interface. Obviously there are also situations in which the continuum hypothesis does not apply at all; for example, in rarefied gases, in which the distances between gas molecules are relatively large, one must account for individual molecules and their motions.

1.2 Measurable properties

A property of a fluid element can be measured directly or estimated from measurements of other properties only if it has a precise and unambiguous scientific definition, associated with a measurement procedure. The following list identifies measurable properties of common interest, classified into four general classes.

- *Material properties:*

mass	density	specific volume
viscosity	thermal conductivity	molecular diffusivity
specific heat under constant pressure	specific heat under constant volume	gas constant
bulk modulus of elasticity	coefficient of thermal expansion	electric conductivity
surface tension	index of refraction	fluorescence

- *Kinematic properties*, namely properties that describe the motion of a fluid without consideration of applied forces:

position	displacement	velocity
volume flow rate	mass flow rate	acceleration
vorticity	strain rate	angular position
angular displacement	angular velocity	angular acceleration
momentum	angular momentum	

- *Dynamic properties*, namely properties related to the applied forces:

force	stress	torque
pressure (mechanical definition)		

- *Thermodynamic properties*, namely properties related to heat and work:

temperature	internal energy	enthalpy
entropy	heat flux	work
energy	pressure (thermodynamic definition)	

Material properties are usually not the subject of experimental fluid mechanics, as their values can be found in handbooks [6] or other sources. However, if a material property is unknown or overly sensitive to the particular experimental conditions, its value may have to be determined either as part of the overall experiment or by a specific experimental investigation.

1.3 Flow velocity and velocity fields

A position in space is specified in terms of its coordinates x_i, $i = 1, 2, 3$, with respect to a Cartesian coordinate system. At any time t, this position is occupied by some fluid element, assumed to maintain its mass within an infinitesimally small volume. With the fluid considered as a continuum, we may define the flow velocity at a given position and a given time as the velocity of a fluid element that occupies that position at that time. We are also interested in defining the *velocity field*, which consists of the velocities of all fluid elements that comprise a material system. Thus it becomes necessary to distinguish the fluid element in question from any other fluid element. For clarity, we specify as X_i the coordinates of the fluid element that occupies position x_i at time t. This element moves along its trajectory, indicated by the dotted curve in Fig. 1.2. At time $t + \delta t$, the