# Fundamentals of Fluid Mechanics

James A. Sullivan

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# FUNDAMENTALS OF FLUID MECHANICS

To Sylvia

# PREFACE

Fluid mechanics[1] is an applied study with much of its basis in experiment. It is concerned with the motion of matter that flows or tends to flow. It combines applied mathematics and physics that describe particle motions or tendencies to motion, with those special aspects of fluids that permit them to flow or govern their motion. Fluids may be liquids or gases. That branch of fluid mechanics which is concerned with the liquids water and oil is called *hydromechanics*. Hydromechanics, in turn, is divided into hydrostatics (liquids at rest), hydrodynamics (liquids in motion), and hydraulics (compressed liquids in pipes). That branch of fluid mechanics which is concerned with air and gases is called *aeromechanics*, which can be subdivided into aerostatics (air and gases at rest), aerodynamics (air and gases in motion), and aeromatics (compressed air and gases in pipes), which is commonly called pneumatics.

*Fundamentals of Fluid Mechanics* seeks to correlate the theoretical framework and concepts that describe the behavior of fluids with practical applications and work in laboratories, testing facilities, and shops. Suggested learning and performance are intended to prepare persons to assume technical positions that assist engineering and maintenance projects, or to work with equipment that processes fluids in the generation and use of power. Many of the suggested activities have been derived from laboratory exercises and tasks commonly assigned to technicians by industry. Others are taken from ASTM standardized procedures.

The International System of Units (SI), which are absolute, and English units, which are gravitational, are used throughout this text.

[1]G. A. Tokaty, *A History and Philosophy of Fluidmechanics*. Haney-on-Thames, Oxfordshire, England: G. T. Foulis and Co. Ltd., 1973.

Although SI units are given preference, except in the case of reporting derivations with origins in the English system, it is also recognized that English units will be used for some time during and even after the transition period when SI is being adopted. Quantities and units in the English system are inserted in brackets immediately following the SI designated quantities in the examples. Equivalent answers to the example problems are also bracketed in English units following the SI answers. The student with a preference for English units may wish to confirm these by working through the problems with the English units given. The review problems that follow each chapter are stated both in SI and English units, as are the answers in the appendix.

Although it is common practice to introduce technicians to calculus during the course of their preparation, it is not seen as necessary to make use of this method in the explanation and solution of problems in a first course in fluid mechanics. It is necessary, however, to be familiar with the rudiments of algebra, as these are used extensively to derive concepts that describe the behavior of fluids and to solve related problems.

Many persons and companies have assisted the author in the preparation of this work. Special thanks is extended to several reviewers for their advice, including Tobi Goldoftas and Chris R. Treleaven. K. Gita Balagopalon and S. B. Surish are acknowledged for proofing and working sample problems. Finally, Sedat Sami is acknowledged for his counsel in the subject.

*James A. Sullivan*

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# 1

# DIMENSIONS OF FLUID MECHANICS

## 1-1 INTRODUCTION

Fluid mechanics considers the behavior of fluids at rest and in motion, in open and closed systems. Fluids at rest are treated in the study of hydrostatics and aerostatics, whereas fluids in motion are treated in the study of hydrodynamics, hydraulics, and aeronautics. Liquids and gases are both considered to be fluids. Open systems contain fluids in conveyances open to the atmosphere, whereas closed systems confine liquids and gases in pipes, typically under pressure. Hydraulics, which considers the flow and control of liquids in pipes, is an example of a closed system.

When fluids are in equilibrium—that is, in a balanced condition—they cannot sustain a shear stress. This is the case when a fluid is not flowing. Shear stresses are those forces acting in opposite directions at a tangent to adjacent surfaces. A bolt such as that in Fig. 1-1, for example, used to hold two plates together, is withstanding a shear stress when the forces are acting in opposite directions at a tangent. If the outer surface of the bolt were imaginary, and water were substituted for the material within the bolt, the plates would move, indicating that the water could not sustain the stress required to keep the plates from slipping.

Fluids in equilibrium cannot withstand shear stresses because of the loose arrangement of the molecules within the substance. The spaces between the molecules are large and other cohesive forces between the molecules are small, permitting considerable freedom of movement between the molecules. The difference between liquids and gases can be defined in part from the relative spacing of the molecules. This is much larger in the case of gases, contributing to the reason that they flow more readily than liquids. The larger spacing in gases also accounts for the

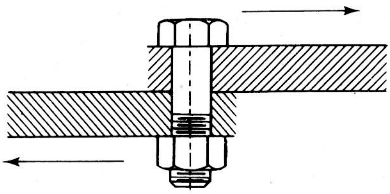

**Fig. 1-1** Shear stress in bold fastener

greater compressibility of gases as compared with liquids.

Solutions to problems in applied fluid mechanics are derived from data secured from instruments that monitor system performance, as well as from a knowledge of certain properties of the fluids themselves. Pressure and flow rate, for example, are monitored with instruments attached directly to operational systems, whereas fluid properties such as density and viscosity are determined beforehand in the laboratory under controlled conditions. In both cases, however, units for the quantitative measurement must be established which make the available data intelligible. That is, a uniform system of units must be adopted so that both the data used in computing solutions to fluid mechanics problems and the solutions themselves will be understood and useful to people who are concerned. Until recently, both English and metric units have been used in computing the solutions to fluid mechanics problems, causing the student considerable difficulty in making the transition between the two systems and creating confusion when the same units have two apparent meanings. Use of the kilogram to measure both force and mass is an excellent example of a conflicting definition that causes confusion.

## 1-2 HISTORICAL PERSPECTIVE

Metric measurement has received widespread use for several hundred years in the sciences in America and abroad. Recent emphasis by international bodies to standardize metrication for all countries has resulted in agreement on a practical system of units of measurement termed in French the Système International d'Unités (International System of Units), with SI being the official abbreviation.

There are three classes of SI units: base units, derived units, and supplementary units.[1] Seven base units have been designated for length, mass, time, electric current, thermodynamic temperature, amount of substance, and luminous intensity (Table 1-1). Derived units are formed by

[1]*The International System of Units* (*SI*), National Bureau of Standards, U.S. Department of Commerce, NBS Special Publication 330 (Washington, D.C.: U.S. Government Printing Office, 1971), pp. 1–17.

combining base units according to the algebraic relations linking the corresponding quantities (Table 1-2). Several of these algebraic expressions in terms of base units can be replaced by special names and symbols which can themselves be used to form other derived units. Table 1-3 lists several examples of SI derived units expressed by means of special names. Supplementary units are those that the General Conference of Weights and

**TABLE 1-1 SI base units**

| *Quantity* | *Name* | *SI Symbol* |
|---|---|---|
| length | meter | m |
| mass | kilogram | kg |
| time | second | s |
| electric current | ampere | A |
| thermodynamic temperature | kelvin | K |
| luminous intensity | candela | cd |
| amount of substance | mole | mol |

**TABLE 1-2 SI derived units expressed in terms of base units**

| *Quantity* | *Name* | *SI Symbol* |
|---|---|---|
| area | square meter | $m^2$ |
| volume | cubic meter | $m^3$ |
| speed, velocity | meter per second | m/s |
| acceleration | meter per second squared | $m/s^2$ |
| density, mass density | kilogram per cubic meter | $kg/m^3$ |
| concentration (of amount of substance) | mole per cubic meter | $mol/m^3$ |
| specific volume | cubic meter per kilogram | $m^3/kg$ |
| luminance | candela per square meter | $cd/m^2$ |

**TABLE 1-3 Examples of SI derived units expressed by means of special names**

| *Quantity* | *SI Units* | | |
|---|---|---|---|
| | *Name* | *Symbol* | *Expression in terms of SI base units* |
| force | newton | N | $m \cdot kg \cdot s^{-2}$ |
| pressure | pascal[7] | Pa | $m^{-1} \cdot kg \cdot s^{-2}$ |
| energy, work, quantity of heat | joule | J | $m^2 \cdot kg \cdot s^{-2}$ |
| power, radiant flux | watt | W | $m^2 \cdot kg \cdot s^{-3}$ |
| quantity of electricity, electrical charge | coulomb | C | $s \cdot A$ |
| dynamic viscosity | pascal second | $Pa \cdot s$ | $m^{-1} \cdot kg \cdot s^{-1}$ |
| moment of force | newton meter | $N \cdot m$ | $m^2 \cdot kg \cdot s^{-2}$ |
| surface tension | newton per meter | N/m | $kg \cdot s^{-2}$ |
| specific heat capacity, specific entropy | joule per kilogram kelvin | $J/(kg \cdot K)$ | $m^2 \cdot s^{-2} \cdot K^{-1}$ |
| specific energy | joule per kilogram | J/kg | $m^2 \cdot s^{-2}$ |
| energy density | joule per cubic meter | $J/m^3$ | $m^{-1} \cdot kg \cdot s^{-2}$ |

Measures (CGPM) has not yet classified as base or derived units of the International System. Two supplementary units, the plane angle, or radian, the solid angle, or steradian, have been identified.

## 1-3 THE INTERNATIONAL SYSTEM OF UNITS

The unit of length illustrated in Fig. 1-2 is the meter. It is defined as being equal to 1 650 763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels $2p_{10}$ and $5d_5$ of the krypton-86 atom.[2] The previous international prototype of platinum-iridium, which was legalized by the first CGPM is kept at the International Bureau of Weights and Measures (BIPM) in Paris, France under the conditions specified in 1889.

The unit of mass shown in Fig. 1-3 is the kilogram; it conforms to the prototype made of platinum-iridium kept at the BIPM under the conditions specified by the first CGPM.[3] A duplicate in the National Bureau of Standards, U.S. prototype kilogram 20, serves as the mass standard for the United States. This is the only base unit still defined by an artifact. Mass is not weight or force; rather, it is the molecular amount of a substance.

The unit of time is the second. Originally, the second was defined as a fraction of the solar day, but the definition was changed because measurements have shown that because of irregularities in the rotation of the earth the mean solar day does not guarantee the desired accuracy. The thirteenth CGPM (1967) passed a resolution that defined the second as the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom (Fig. 1-4).

The unit of electrical current illustrated in Fig. 1-5 is the ampere; it is defined as that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section, and placed one meter apart in vacuum, would produce between these conductors a force equal to $2 \times 10^{-7}$ newton per meter of length.[4]

The unit of thermodynamic temperature is the kelvin and is defined as the fraction $1/273.16$ of the thermodynamic temperature of the triple point of water.[5] In addition to the thermodynamic temperature expressed in kelvins (symbol $T$), use is also made of Celsius temperature (symbol $t$), defined by the equation

$$t = T - T_0$$

[2]11th CGPM (1960), Resolution 6.
[3]Third CGPM (1901).
[4]Ninth CGPM (1948).
[5]Thirteenth CGPM (1967), Resolution 3 and Resolution 4.

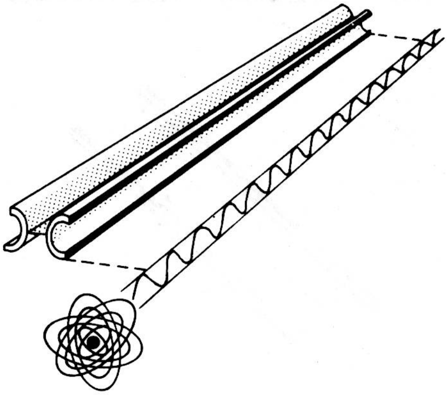

**Fig. 1-2 Unit of length—meter**

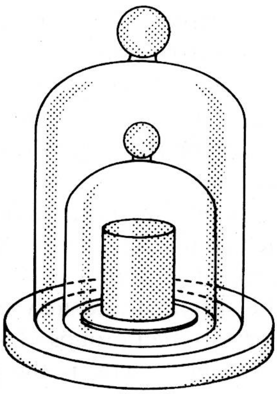

**Fig. 1-3 Unit of mass—kilogram**

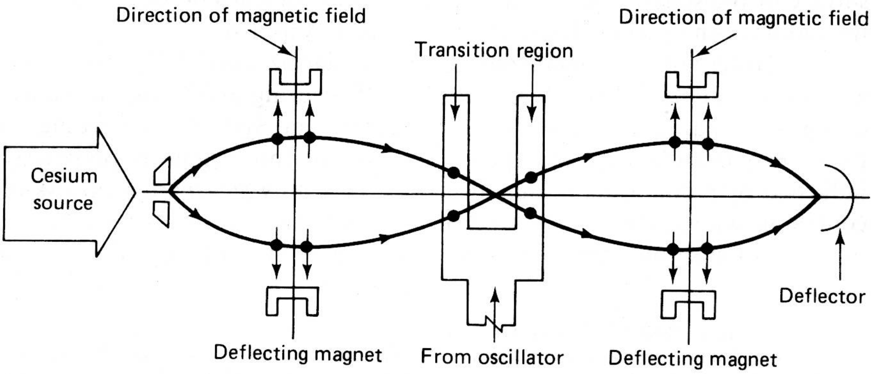


**Fig. 1-4 Unit of time—second**

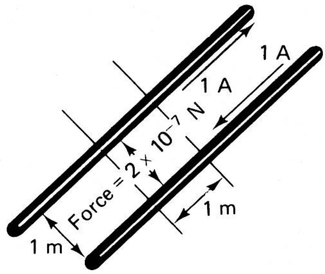


**Fig. 1-5 Unit of electrical current—ampere**

where $T_0 = 273.15°K$ by definition. The unit "degree Celsius" is thus equal to the unit "kelvin" and an interval of difference of Celsius temperature may also be expressed in degrees Celsius.

The unit of luminous intensity, the candela, is measured in the perpendicular direction on the surface of 1/600,000 square meter of a blackbody at the temperature of freezing platinum under a pressure of 101,325 newtons per square meter.[6]

The unit of a substance is the mole, defined as the amount of a substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.

The supplementary unit, the radian, is the plane angle between two radii of a circle which cut off on the circumference an arc equal in length to the radius. The supplementary unit, the steradian, is the solid angle which, having its vertex in the center of a sphere, cuts off an area of the surface of the sphere equal to that of a square with sides of length equal to the radius of the sphere. These are illustrated in Fig. 1-6.

The International Organization for Standardization (ISO) has issued additional recommendations with the aim of securing uniformity in the use of units, in particular those of the International System.[7] According to these recommendations, the product of two or more units is preferably indicated by a dot. The dot may be dispensed with when there is no risk of confusion with another unit symbol, for example, Nm or N·m, but not mN. A solidus (oblique stroke,/), a horizontal line, or negative powers

[6]Thirteenth CGPM (1967), Resolution 5.
[7]International Organization for Standardization in publication ISO 2944-1974 (E) defines the unit of pressure as the bar, where 1 bar = 100 kPa ≈ 14.5 lbf/in$^2$. However, the official designation for pressure in SI units is the Pascal (Pa). Because the Pascal is a small unit, pressure gauges are commonly constructed with dials graduated in units of one thousand Pascals (kPa).