FLUID MECHANICS

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KATARIA

S.K. KATARIA & SONS®
Publisher of Engineering and Computer Books
4885/109, Prakash Mahal, Dr. Subhash Bhargav Lane,
Opposite Delhi Medical Association, Daryaganj, New Delhi–110002
Phone: +91-11-23243489, 23269324; Telefax: +91-11-23243489
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Website: www.skkatariaandsons.com

Published by:

S.K. Kataria & Sons®

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Opp. Clock Tower, Ludhiana (Pb)
Ph. : 2726401

First Edition: July, 2009-2010; Reprint: 2010; Reprint: 2011; Reprint: 2012; Reprint: 2013; Reprint: 2014

Price: ₹ 295/-

Laser Type Setting:
PLUS COMPUTERS, Shahdara, Delhi

Printed at:
New A.S. Printing Press, Delhi

Preface

The author has been teaching the subject of Fluid Mechanics for the past several years and the first edition of his book **Fluid Mechanics** and **Fluid Power Engineering** was published in 1987. This book has served and continues to serve as a useful text for the students of engineering curriculum, AMIE and other professional examinations in the subject of fluid mechanics, fluid flow and hydraulic machines.

Basic concpets of fluids and fluid flow are essential in all the engineering disciplines to get better understanding of courses in professional programmes, and obviously its importance as a core subject need not be overemphasised. While the earlier monograph will continue to remain in circulation, the present book will provide an edited and reorganized version to cater to the specific needs of the course in **Fluid Mechanics** offered to 3rd semester engineering students of UP Technical University. This course aims at developing an understanding of the behaviour of fluids in motion or at rest and the subsequent effects of fluid on the boundaries. A study of the subject matter included in this book will help the reader to have conceptual understanding of fluids and their properties; understanding of fluid statics, fluid kinematics and fluid dynamics; basic knowledge of dimensional analysis and similitude; understanding of laminar and turbulent flows, and flow measurement.

The key features of this edited and reorganized version of the book are :

- Concise covering of each topic in a simple, lucid and easily understandable language.
- Full use of line diagrams made to supplement the text and explain a particular phenomenon as clearly as possible.
- Solutions provided to a wide variety of problems of standard comparable to those set for engineering degree, AMIE, GATE and Engineering Service Examinations.
- Consistent use of SI units and notations throughout the text
- Inclusion of section on multiple choice questions and short answer questions keeping in view the recent trend of such questions being asked in the various University and competitive examinations.

The author expresses his gratitude to his departmental colleagues with whom he had hours of useful discussion during the revising, updating and editing of the text. The author thanks the publishers also for their considerable patience and good co-operation throughout. Further, the author would be extremely thankful to the readers for their constructive suggestions and healthy criticism with a view to enhance the usefulness of the book. Author and the publishers would gratefully acknowledge if misprints and errors discovered are brought to their notice.

Finally, the author wishes to place on record his apologies and sincere thanks to his near and dear ones who willingly endured certain hardships which resulted from his preoccupation with this work.

MREI, Faridabad D.S. Kumar
July, 2009

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INTRODUCTION

Fluid Mechanics is basically a study of the :

(*i*) physically behaviour of fluids and fluid systems, and of the laws governing this behaviour,

(*ii*) action of forces on fluids and of the resulting flow pattern.

Fluid mechanics may be divided into three divisions :

1. *Hydrostatics* that studies the mechanics of fluids at absolute and relative rest; the fluid elements are free from shearing stresses.

2. *Kinematics* that deals with translation, rotation and deformation of fluid elements without considering the force and energy causing such a motion.

3. *Dynamics* that prescribes the relations between velocities and accelerations and the forces which are exerted by or upon the moving fluids.

Analysis of fluid flow problems is generally made by considering certain fundamental principles of conservation of mass, momentum and energy; the first and second laws of thermodynamics; equation of state relating to fluid properties; Newton's law of viscosity and the restrictions caused by presence of boundaries.

After reading this chapter, the reader would be able to :

(*i*) make distinction between the three states of matter (solid, liquid and gas).

(*ii*) understand the concept of a fluid, real and ideal fluid.

(*iii*) make a brief review about the development of the exciting and fascinating subject of fluid mechanics.

(*iv*) appreciate the unlimited practical applications of fluid mechanics.

1.1 SOLIDS, LIQUIDS AND GASES

Matter exists in two principal forms : solid and fluid. Fluid is further sub-divided into liquid and gas. Distinguishing features amongst these are :

(*i*) The solids, liquids and gases exhibit different characteristics on account of their different molecular structure. Spacing and the latitude of the motion of molecules is large in a gas, small in a liquid and extremely small in a solid. Accordingly the intermolecular bonds are very weak in a gas, weak in a liquid and very strong in a solid. It is due to these aspects that solid is very compact and rigid in form, liquid accommodates itself to the shape of its container, and gas fills up the whole of the vessel containing it.

(*ii*) For a given mass, the liquids have a definite volume irrespective of the size of the container. The variation of volume with temperature and pressure is insignificant. Liquid occupies the vessel fully or partially depending on its mass, and that it forms a free surface with the atmosphere. The gas, however, expands to fill any vessel in which it is contained and does not form any free surface. Accordingly, it may be stated; ***The solid has volume and shape; a liquid has volume but no shape; a gas has neither.***

(*iii*) For all practical purposes, the liquids like solids can be regarded as incompressible. This means that pressure and temperature changes have practically no effect on their volume. The gases are, however, readily compressible fluids. They expand infinitely in the absence of pressure and contract easily under pressure. Never-the-less density variation is small. For example in flow of air in a ventilating system, the gas flow can also be treated as incompressible without involving any appreciable error.

When a gas can be readily condensed to a liquid, we call it a ***vapour*** such as steam and ammonia.

(*iv*) The deformation due to normal and tangential forces for solids is such that within elastic limits, the deformation disappears and the solid body is restored to its original shape when the stress causing the deformation is removed. A fluid at rest can, however, sustain only normal stresses and deforms continuously when subjected to a shear stress; no matter how small that shear stress may be. Even though the fluid comes to rest when the shear stress is removed, yet there is no tendency to restore the fluid body to its original shape or position.

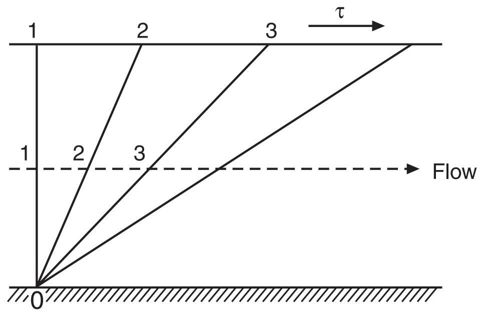

Fig. 1.1 Fluid flow

Thus a fluid can offer no permanent resistance to shear force and possesses a characteristic ability to flow or change its shape. Flow means that the constituent fluid particles continuously change their positions relative to one another. This concept of fluid flow under the application of a shear stress is illustrated in Fig. 1.1. A fluid element occupying the initial position 011 continues to move or deform to new position 022, 033 etc., when a shear stress τ is applied to it.

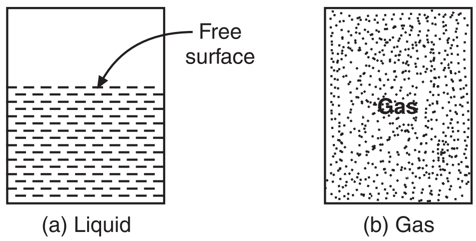

Fig. 1.2 Behaviour of a fluid in a container

The tendency of continuous deformation of a fluid is called ***fluidity***, and the act of continuous deformation is called ***flow***.

The above discussion can be summed up as :

Liquid	Gas
(*i*) A given mass of liquid has a definite volume independent of the size or shape of the container; however, it changes its shape easily and acquires the shape of its container.	(*i*) A given mass of gas has no fixed volume; and it expands continuously to completely fill any container in which it is placed.
(*ii*) A free surface is formed if the volume of the container is greater than that of the liquid.	(*ii*) No free surface is formed.
(*iii*) Liquids can be regarded as incompressible for all practical purposes.	(*iii*) Gases are readily compressible.
(*iv*) Pressure and temperature changes have practically no effect on the volume of a liquid.	(*iv*) A gas expands infinitely in the absence of pressure and contracts easily under pressure.
(*v*) Water, kerosene, petrol etc. are liquids.	(*v*) Air, ammonia, carbon dioxide etc. are gases.

1.2 IDEAL AND REAL FLUIDS

A fluid is said to be ideal if it is assumed to be both incompressible and inviscid (non-viscous). Further an ideal fluid has no surface tension. For an inviscid fluid, viscosity is zero and no frictional forces are set up even during fluid motion.

$$\mu = 0$$

$$\rho = \text{constant};\ K = \frac{-dp}{dv/v} = \infty$$

$$\sigma = 0$$

Ideal fluids are imaginary and do exist in nature. However most common fluids such as air and water have very low value of viscosity and can be treated as ideal fluids for all practical purposes without introducing any appreciable error. Since water is incompressible, it is move near to an ideal fluid than air.

Real or practical fluids have viscosity (μ), compressibility (K) and surface tension (σ). Whenever motion takes place, the tangential or shear forces always come into play due to viscosity and some frictional work is done.

1.3 CONTINUUM

Although fluids consist of discrete molecules, analysis of the fluid flow problems is made by a concept that treats fluid as continuous media. All voids or cavities, microscopic or macroscopic, which may occur in the fluids are ignored. The physical properties of the fluids are then continuous from point to point and can be expressed by continuous algebraic functions of space and time co-ordinates. In other words, the fluid properties are treated to be same at a point and identical in all directions from a specified point. Molecular size and the movement of fluid elements about their mean path are generally insignificant with reference to the dimensions of the equipment and as such this assumption of homogeneity and isotropy is quite justifiable except in the field of aerodynamics and rarefied gas dynamics. A continuous and homogeneous fluid medium is called ***continuum***. From the continuum view point, the overall properties and the behaviour of fluids can be studied without regard for its atomic and molecular structure.

1.4 DEVELOPMENT OF FLUID MECHANICS

The beginning and development of the science of fluid mechanics dates back to the times when the ancient races had their irrigation systems, the Greeks their hydraulic mysteries, the Romans their methods of water supply and disposal, the Middles ages their wind mills and water wheels. It is quite evident from the excavations of Egyptian ruins and Indus Valley Civilization that the concepts of fluid flow and flow resistance, which form the basis of irrigation, drainage and navigation systems, were known to the man who lived at that time about 4000 years ago.

Through their sustained and continued efforts, a host of research workers contributed so extensively to the subject that by the end of 19th century all the essential tools of hydraulics were at hand; the principles of continuity, momentum and energy; the Bernoulli theorem; resistance formulae for pipes and open channels; manometers, Pitot tubes and current meters; towing tanks, wind tunnels and whirling arms; model techniques; and Froude and Reynolds laws of similarity; and the equations of motion of Euler, Navier-Stokes and Reynolds.

Historically the development of fluid mechanics has been influenced by two bodies of scientific knowledge; empirical hydraulics and classical hydrodynamics. ***Hydraulics*** is an applied science that deals with practical problems of flow of water and is essentially based on empirical formulae deduced from laboratory experiments. ***Classical Hydrodynamics*** has been hydraulics' mathematical counterpart that deals with a hypothetical ideal fluid having no viscosity. However, neither hydraulics not classical hydrodynamics could provide a scientific support to the rapidly developing field of aeronautics; the former because of its strong empirical slant with little regard for reason, and the latter because of its very limited contact with reality. The solution to the dilemma was provided by Ludwieg Prandtl in 1904 who proposed that flow around immersed bodies be approximated by a boundary zone of viscous influence and a surrounding zone of irrotational frictionless motion. This approach has a tremendous effect upon understanding of the motion of real fluids and eventually permitted analysis of lifting vanes, control surfaces and propellers.

The subject of fluid mechanics has grown into a major field in engineering science and its basic principles are embodied in essentially every field involving fluid motion; the subject branches out into various specialities such as hydraulic and marine engineering; aero and gas dynamics, meteorology and oceanography; plasma and geophysics etc.

1.5 SIGNIFICANCE OF FLUID MECHANICS

The subject of fluid mechanics encompasses a great many fascinating areas like :

- design of a wide range of hydraulic structures (dams, canals, weirs etc.) and machinery (pumps, turbines and fluid couplings)
- design of a complex network of pumping and pipelines for transporting liquids; flow of water through pipes and its distribution to domestic service lines
- fluidic control devices both pneumatic and hydraulic
- design and analysis of gas turbines, rocket engines, conventional and supersonic aircraft
- power generation from conventional methods such as hydroelectric, steam and gas turbines, to newer ones involving magneto fluid dynamic
- methods and devices for the measurement of various parameters, *e.g.*, the pressure and velocity of a fluid at rest or in motion.
- study of men's environment in the subjects like meteorology, oceanography and geology
- human circulatory system, *i.e.*, flow of blood in veins and the vital role it plays in a variety of engineering applications.

The numerous natural phenomenon such as the rain cycle, weather patterns, the rise of groundwater to the top of trees, winds, ocean waves and currents in large water bodies are also governed by the principles of fluid mechanics.

The significance of fluid mechanics can be well judged by citing just one example of automobile drive where suspension is provided by pneumatic tyres, road shocks are reduced by hydraulic shock absorbers, gasoline is pumped through tubes and later atomized, air resistance creates a drag on the vehicle as whole and the confidence that hydraulic brakes would operate when the vehicle is made to stop.

Undoubtedly, a study of the science of fluid mechanics is a must for an engineer so that he can understand the basic principles of fluid behaviour and apply the same to flow situations encountered in engineering and physical problems.

REVIEW QUESTIONS

A : Conceptual and conventional questions/problems

1. Define a fluid and distinguish between :
   (*i*) ideal and real fluids; (*ii*) compressible and incompressible fluids.

2. How does :
   (*i*) a fluid differ from a solid.
   (*ii*) a liquid differ from a gas.
3. Discuss the concept that "a fluid continues to deform so long it is acted upon by a shear force."
4. Define the term continuum as applied to the mechanism of flow. Is the continuum model valid in upper atmosphere ?
5. Write a note on the historical development of fluid mechanics.
6. Cite some examples to illustrate the importance of fluid mechanics in the engineering field.
7. Discuss the application of fluid mechanics to the flow of blood in our veins and to the pumping action of heart.

B : Fill in the blanks with appropriate word/words

(*i*) A substance in the liquid or gas phase is referred to as a _______.
(*ii*) Intermolecular bonds are strongest in _______ and weakest in _______.
(*iii*) In solids stress is proportional to strain, but in fluids stress is proportional to _______.
(*iv*) When a gas can be readily condensed to a liquid, we call it a _______.
(*v*) An ideal fluid is defined as the fluid which is _______ and ______.
(*vi*) A continuous, homogenous medium with no voids or empty spaces is called _______.
(*vii*) The inability of fluids to resist _______ gives them the characteristics property to change shape or flow.

Answers : (*i*) fluid; (*ii*) solids, gases; (*iii*) strain rate; (*iv*) vapour; (*v*) incompressible, non-viscous; (*vi*) continuum; (*vii*) shearing stress.

C : Indicate if the following statements are true or false. If false, then write the correct statement.

(*i*) A fluid always expands to fill its container.
(*ii*) Only normal forces exist in a fluid at rest.
(*iii*) Fluids possess a characteristic ability to flow or change its shape.
(*iv*) When subjected to shear force, fluid deforms continuously no matter how small the shear stress may be.
(*v*) An ideal fluid is both frictionless and incompressible.
(*vi*) An ideal fluid can sustain tangential forces when set in motion.
(*vii*) Vapour refers to a gaseous fluid which can be readily condensed into a liquid.
(*viii*) A fluid exhibits equal shear stresses at all points when in motion.
(*ix*) Continuum is synonymous with uniformity and homogeneity of fluid medium.
(*x*) The concept of continuum in a fluid flow assumes that movements of fluid elements about their mean path is quite significant.
(*xi*) Fluid mechanics is a blend of hydraulics and hydrodynamics, and offers rational solution to practical problems.

Answers : (*i*) False; (*ii*) True; (*iii*) True; (*iv*) False; (*v*) True; (*vi*) False; (*vii*) True; (*viii*) False; (*ix*) True; (*x*) False; (*xi*) True

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PHYSICAL PROPERTIES OF FLUIDS

INTRODUCTION

Every fluid has certain characteristics by means of which its physical condition may be described. Such characteristics are called ***properties*** of the fluid. Before an analyst of fluid flow problems can venture to formulate the physical principles governing the flow situation, he has to be thoroughly familiar with the physical properties of fluids. Towards that end, this section seeks to provide basic insight into the fluid properties and their behaviour.

2.1 SPECIFIC WEIGHT, MASS DENSITY AND SPECIFIC GRAVITY

(*a*) ***Specific weight*** (w) of a fluid is its weight per unit volume.

$$w = \frac{W}{V} \qquad \text{... (2.1)}$$

where W is the weight of the fluid having volume V. The weight of a body is the force with which the body is attracted to the centre of the earth. It is the product of its mass and the local gravitational acceleration, *i.e.*, $W = mg$. The value of g at sea level is 9.807 m/s^2 approximately. Since weight is expressed in newton, the unit of measurement of specific weight is N/m^3. In terms of fundamental units, the dimensional formula of specific weight is $\left[\frac{F}{L^3}\right]$ or $\left[\frac{M}{L^2 T^2}\right]$.

For pure water under standard atmospheric pressure of 760 mm of mercury at mean sea level and a temperature of 4°C, the specific weight is 9810 N/m^3. For sea water, the specific weight equals 10 000 – 10 105 N/m^3. The increased value of specific weight of water is due to the presence of dissolved salts and suspended matter. The specific weight of petroleum and petroleum products varies from 6 350 – 8 350 N/m^3 and that of mercury at 0°C is 13 420 N/m^3. Air has a specific weight of 11.9 N/m^3 at 15°C temperature and at standard atmospheric pressure. The specific weight of a fluid changes from one place to another depending upon changes in the gravitational acceleration.

(*b*) ***Density*** (ρ-pronounced rho) is a measure of the amount of fluid contained in a given volume and is defined as the mass per unit volume.

$$\rho = \frac{m}{V} \qquad \text{... (2.2)}$$

where m is the mass of fluid having volume V. Fluid mass is a measure of the ability of a fluid particle to resist acceleration and is approximately independent of its location on the earth's surface. The units of density correspond to those of mass and volume. The dimensional formula of density in fundamental units is $\left[\frac{M}{L^3}\right]$ or $\left[\frac{FT^2}{L^4}\right]$ and the corresponding units are kg/m^3 or N s^2/m^4.

The density of a fluid diminishes with rise of temperature except for water which has a maximum value at 4°C. The mass density of water at 15.5°C is 1000 kg/m^3, and for air at 20°C and at atmospheric pressure the mass density is 1.24 kg/m^3.

The weight W and the mass m of a fluid are related to each other by the expression $W = mg$. Dividing this expression throughout by volume V of the fluid, we obtain :

$$\frac{W}{V} = \frac{m}{V}\,g \quad \text{or} \quad w = \rho\, g \qquad \text{... (2.3)}$$

Equations (2.3) reveals that specific weight w changes with location depending upon gravitational pull.

(*c*) ***Specific gravity*** (s) refers to the ratio of specific weight (or mass density) of a fluid to the specific weight (or mass density) of a standard fluid. For liquids the standard fluid is water at 4°C, and for gases the standard fluid is taken either air at 0°C or hydrogen at the same temperature. Specific gravity is dimensionless and has no units.

A statement that the specific gravity of mercury is 13.6 implies that its weight (or mass) is 13.6 times that of same volume of water. In other words, mercury is 13.6 times heavier than water.

(*d*) ***Specific volume*** (v) represents the volume per unit mass of fluid; specific volume is the inverse of the mass density.

$$v = \frac{V}{m}\ ;\ v = \frac{1}{\rho} \qquad \text{... (2.4)}$$

The concept of specific volume is found to be practically more useful in the study of flow of compressible fluids, *i.e.*, gases.

EXAMPLE 2.1

2 litre of petrol weighs 14 N. Calculate the specific weight, mass density, specific volume and specific gravity of petrol with respect to water.

Solution : 2 litre = 2×10^{-3} m^3

Specific weight is a measure of the weight per unit volume :

$\therefore$ Specific weight $w = \dfrac{14}{2 \times 10^{-3}} = \mathbf{7000\ N/m^3}$

Mass density is related to specific volume by the relation : $w = \rho\, g$

$$\text{Mass density } \rho = \frac{w}{g} = \frac{7000}{9.81} = \mathbf{713.56\ kg/m^3}$$

Specific volume v is the inverse of mass density

$$v = \frac{1}{\rho} = \frac{1}{713.56} = \mathbf{1.4 \times 10^{-3}\ m^3/kg}$$

$$\text{Specific gravity } s = \frac{\text{density of oil}}{\text{density of water}} = \frac{713.56}{1000} = \mathbf{0.7136}$$