

H y d r a u l i c s

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Preface

TO FIFTH EDITION

THE purpose of this revision is (1) to improve the clarity and arrangement of the text and problems in the light of continued experience in the use of the book with classes in elementary hydraulics, (2) to add new problems illustrating applications of basic theory to certain engineering problems not previously covered, and (3) to expand the text material somewhat to include new developments in theory and practice which have been accepted in the past few years as an integral part of hydraulic engineering.

Changes to improve the wording and clarify the meaning have been made in many places throughout the book. Nearly all the problems of the fourth edition have been retained, although with some rearrangement to provide a more logical order. A number of new examples and problems have been added.

New text material is introduced on the variation of hydrostatic pressure with altitude in a compressible fluid, on the flow through gates and over dams, on the general consideration of the flow of liquids in pipes, on the analysis of flow in pipe networks, and on the resistance offered to motion of objects through a fluid. To give students an elementary knowledge in the field of hydraulic model testing, in which they are finding employment in increasing numbers, a chapter on hydraulic similitude and dimensional analysis has been added.

Although a quarter century has elapsed since this book was first prepared, the authors have no fault to find with the statements made in the preface to the first edition. The book is still intended to present to the engineering student or to the practicing engineer the fundamental principles relating to fluids at rest or in motion as they apply to engineering practice and to illustrate those principles with practical problems.

Thanks are due to many friends and associates whose suggestions and advice have greatly helped with the revision, in par-

ticular: A. T. Lenz, G. A. Rohlich, J. A. Borchardt, J. R. Villemonete, and A. C. Ingersoll of the University of Wisconsin; E. R. Dodge of Montana State College; E. F. Brater of the University of Michigan; R. D. Goodrich of the University of Wyoming; and F. W. Greve and W. E. Howland of Purdue University. Professor Howland read the manuscript and offered many valuable suggestions.

H. W. K.
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Preface

TO FIRST EDITION

THIS book deals with the fundamental principles of hydraulics and their application in engineering practice. Though many formulas applicable to different types of problems are given, it has been the aim of the authors to bring out clearly and logically the underlying principles which form the basis of such formulas rather than to emphasize the importance of the formulas themselves.

Our present knowledge of fluid friction has been derived largely through experimental investigation, and this has resulted in the development of a large number of empirical formulas. Many of these formulas have necessarily been included, but, in so far as possible, the base formulas to which empirical coefficients have been applied have been derived analytically from fundamental consideration of basic principles.

The book is designed as a text for beginning courses in hydraulics and as a reference book for engineers who may be interested in the fundamental principles of the subject. Tables of coefficients are given which are sufficiently complete for classroom work, but the engineer in practice will need to supplement them with the results of his own experience and with data obtained from other published sources. Acknowledgment for material taken from many publications is made at the proper place in the text.

H. W. K.
C. O. W.

University of Michigan
April 1922

Contents

CHAPTER I

FUNDAMENTAL PROPERTIES OF FLUIDS

PAGE

ART. 1. The Science of Hydraulics. 2. Fluids. 3. Units Used in Hydraulics. 4. General Properties of Fluids. 5. Properties of Water. 6. Properties of Other Fluids. 7. Accuracy of Computations.	1
---	---

CHAPTER II

PRINCIPLES OF HYDROSTATIC PRESSURE

ART. 8 Unit Pressure, p . 9. Direction of Resultant Pressure. 10. Pascal's Law. 11. Free Surface of a Liquid. 12. Atmospheric Pressure. 13. Vacuum. 14. Absolute and Gage Pressure. 15. Variation of Pressure with Depth in a Fluid. 16. Pressure Head. 17. Transmission of Pressure. 18. Vapor Pressure. 19. The Mercury Barometer. 20. Manometers. 21. Piezometer. 22. Open Manometer. 23. Single-tube Manometers. 24. Differential Manometer. 25. Micromanometers. 26. Determination of Specific Gravity by U-tube. 27. Hydrostatic Relations for Compressible Fluids.	14
---	----

CHAPTER III

HYDROSTATIC PRESSURE ON SURFACES

ART. 28. Total Pressure on Plane Surfaces. 29. Center of Pressure on Plane Surfaces. 30. Semigraphic Method of Location of Center of Pressure. 31. Position of Center of Pressure with Respect to Center of Gravity. 32. Horizontal and Vertical Components of Total Hydrostatic Pressure on Any Surface. 33. Hoop Tension in Circular Pipes and Tanks. 34. Dams. 35. Principle of Archimedes. 36. Statical Stability of Floating Bodies. 37. Determination of Metacentric Height and Righting Moment.	41
--	----

CHAPTER IV

RELATIVE EQUILIBRIUM OF LIQUIDS

ART. 38. Relative Equilibrium Defined. 39. Vessel Moving with Constant Linear Acceleration. 40. Vessel Rotating about a Vertical Axis.	77
--	----

CONTENTS

CHAPTER V

FUNDAMENTALS OF FLUID FLOW

	PAGE
ART. 41. Introduction. 42. Path Lines and Stream Tubes. 43. Laminar and Turbulent Flow. 44. Discharge. 45. Steady Flow. 46. Uniform Flow. 47. Continuous Flow. 48. Energy and Head. 49. Kinetic Energy in Stream with Non-uniform Distribution of Velocity. 50. Power. 51. Frictional Loss. 52. Bernoulli's Energy Theorem. 53. Venturi Meter. 54. Nozzle. 55. Pitot Tube. . . .	83

CHAPTER VI

ORIFICES, TUBES, AND WEIRS

ART. 56. Description. 57. Velocity of Discharge. 58. Coefficient of Velocity. 59. Coefficient of Contraction. 60. Coefficient of Discharge. 61. Velocity of Approach. 62. Flow of Gases through Orifices. 63. Head Lost in an Orifice. 64. Inversion of the Jet. 65. Experimental Determination of Orifice Coefficients. 66. Coordinate Method of Determining Velocity of Jet. 67. Standard Orifice Coefficients. 68. Variation in Orifice Coefficients. 69. Submerged Orifice. 70. Orifices under Low Heads. 71. Gates. 72. Discharge under Falling Head. 73. Standard Short Tube. 74. Converging Tubes. 75. Nozzles. 76. Diverging Tubes. 77. Re-entrant Tubes. 78. Submerged Tubes. 79. Description and Definitions. 80. Fundamental Theory. 81. Accuracy of Weir Measurements. 82. Standard Weir. 83. Standard Weir Formulas. 84. Measurement of Head. 85. Rectangular Contracted Weirs. 86. Triangular Weirs. 87. Trapezoidal Weirs. 88. Weirs not Sharp-crested. 89. Submerged Weirs.	118
---	-----

CHAPTER VII

PIPES

ART. 90. Description. 91. Critical Velocities in Pipes. 92. Analysis of Velocities. 93. Velocity Head in a Pipe. 94. Continuity of Flow in Pipes. 95. Loss of Head. 96. Loss of Head Due to Pipe Friction. 97. Values of f for Water. 98. Frictional Loss with Laminar Flow. 99. General Method of Determining f in Darcy-Weisbach Formula. 100. Wetted Perimeter and Hydraulic Radius. 101. Hydraulic Gradient and Energy Gradient. 102. Alternate Forms of Pipe Formulas. 103. The Chezy Formula. 104. Other Pipe Formulas. 105. Pipe Diagrams. 106. Minor Losses. 107. Loss of Head Due to Contraction. 108. Loss of Head Due to Enlargement. 109. Loss of Head Due to Obstructions. 110. Loss of Head Due to Bends. 111. Pipe Discharging from Reservoir. 112. Part of Pipe above Hydraulic Gradient. 113. Pipe Connecting Two Reservoirs. 114. Pipes of Different Diameters Connected in Series. 115. Pipe System with Branches in Parallel. 116. Flow in Pipe Networks. 117. Branching Pipe Connecting Reservoirs at Different Elevations. The "Three-Reservoir" Problem. 118. Pipe Line with Pump. . . .	175
---	-----

CONTENTS

xi

CHAPTER VIII

OPEN CHANNELS

PAGE

ART. 119. Description.	120. Uses of Open Channels.	121. Distribution of Velocities.	122. Wetted Perimeter and Hydraulic Radius.
123. Steady, Uniform, and Continuous Flow.	124. Energy in an Open Channel.	125. Lost Head.	126. The Chezy Formula.
127. Formulas for Determining the Chezy C.	128. Determination of Roughness Coefficient.	129. Comparison of Open-Channel Formulas.	130. Alternate Stages of Flow.
131. Critical Slope.	132. Cross Section of Greatest Efficiency.	133. Circular Sections.	134. Irregular channels.
135. Obstructions and Bends.	136. Velocity Distribution in Natural Streams.	137. General.	138. Gradually Accelerated and Retarded Flow.
139. Conditions Producing Accelerated and Retarded Flow.	140. Effect of High Stage Downstream.	141. Hydraulic Jump.	142. Position of Hydraulic Jump.
143. Translatory Waves.	144. The Abrupt Wave.	145. The Sloping Wave.	146. Effect of Frictional Loss on Waves.
			240

CHAPTER IX

HYDRODYNAMICS

ART. 147. Fundamental Principles.	148. Interpretation of Newton's Laws.	149. Vectors.	150. Relative and Absolute Velocities.
151. Force Exerted by a Jet.	152. Work Done on Moving Vanes.	153. Forces Exerted upon Closed Channels.	154. Resistance to Object Moving through Fluid.
155. Terminal Velocity.	156. Water Hammer in Pipe Lines.	157. Rise in Pressure when $T \approx 2L/v_w$.	158. Rise in Pressure when $T > 2L/v_w$
			291

CHAPTER X

HYDRAULIC SIMILITUDE AND DIMENSIONAL ANALYSIS

ART. 159. Introduction.	160. Principles of Similitude.	161. Geometric Similarity.	162. Kinematic Similarity.	163. Dynamic Similarity.
164. Gravitational Forces Predominant—Froude's Law.	165. Froude's Number.	166. Viscous Forces Predominant—Reynolds' Law.	167. Reynolds' Number.	168. Surface Tension Forces Predominant—Weber's Law.
169. Summary.	170. Dimensional Analysis.			
				318

GENERAL NOTATION

A	area, total cross-sectional	P	wetted perimeter; also height of weir
A_m	area, mean in reach	P_m	wetted perimeter, mean in a reach
B	width of canal bed	p	pressure, intensity of
b	breadth of weir	p_a	pressure, atmospheric
C	coefficient of discharge; also Chezy coefficient	p_v	pressure, vapor
C_c	coefficient of contraction	Q	discharge, total
C_v	coefficient of velocity	q	discharge, per unit width
C_1	Hazen-Williams coefficient	R	hydraulic radius, A/P
D	diameter	R_m	hydraulic radius, mean in a reach
d	depth	S	slope of energy gradient
d_c	depth, critical	S_0	slope of channel bed
d_m	depth, mean in reach	S_w	slope of stream surface
E	energy	s	side slope (s horizontal to 1 vertical)
F	force	V	velocity, mean, Q/A
f	pipe friction coefficient (Darcy-Weisbach)	V_c	velocity, critical
G	work, or power	V_m	velocity, mean in a reach
g	acceleration, gravitational	V_w	velocity of wave
H	head, total	W	weight
H_0	head, above stream bed	w	weight per unit volume
h_f	head lost by friction	Z	elevation above datum
h_v	head, velocity	α	coefficient, unequal velocities in cross section
K	coefficient of loss	μ	viscosity, dynamic (absolute)
k	roughness, of pipe wall	ν	viscosity, kinematic, μ/ρ
L	length along stream bed; also crest length of weir	ρ	density, mass per unit volume, w/g
m	coefficient of roughness (Bazin)	σ	surface tension
N_F	Froude's number		
N_R	Reynolds' number		
N_W	Weber's number		
n	coefficient of roughness (Kutter and Manning)		

Chapter I

FUNDAMENTAL PROPERTIES OF FLUIDS

1. The Science of Hydraulics. Hydraulics is defined as that branch of science which treats of water or other fluid in motion. A prerequisite to the understanding of the motion of fluids, however, is a knowledge of the pressure exerted by fluids at rest. This study, called hydrostatics, is usually included in hydraulics. The field of hydraulics also includes hydrodynamics, which relates to the forces exerted by or upon fluids in motion.

2. Fluids. Fluids are substances capable of flowing, having particles which easily move and change their relative position without a separation of the mass. Fluids offer practically no resistance to change of form. They readily conform to the shape of the solid body with which they come in contact.

Fluids may be divided into liquids and gases. The principal differences between them are:

1. A liquid has a free surface, and a given mass of a liquid occupies only a given volume in a container, whereas a gas does not have a free surface, and a given mass occupies all portions of any container regardless of its size.

2. Liquids are practically incompressible and usually may be so considered without introducing appreciable error. On the other hand, gases are compressible and usually must be so treated.

The theory and the problems of this text deal mainly with fluids which may be considered incompressible. A few examples and problems require the use of the simple gas laws which give the relationship of pressure, volume, and temperature.

The distinctions between a solid and a fluid should be noted here:

1. A solid is deformed by a shearing stress, the *amount* of unit deformation up to a certain point being proportional to the unit stress; a fluid is also deformed by a shearing stress but at a *time rate* of deformation which is proportional to the stress.

2. If the elastic limit is not exceeded, the application of a given unit shearing stress to a solid produces a certain unit deformation

which is independent of the time of application of the force, and when the stress is removed the solid returns to its original form. On the other hand, if a given shearing stress is applied to a fluid, deformation continues to take place at a uniform rate with time, and when the stress is removed the fluid does not, through forces contained within itself, return to its original form.

The application of sufficient heat will change many solids into a fluid state. The hardest steel can be melted so that it will flow easily. A block of cold tar shows properties of a solid but if heated becomes fluid and can be poured into small cracks in concrete. The change from solid rock to molten lava is a well-known occurrence in nature. Relatively high temperatures are required for these changes. The change from solid ice to fluid water, however, occurs at 32° F.

The mechanics of the borderline condition in which a substance may be either a plastic solid or a very viscous fluid has not been as thoroughly studied in engineering as have the strictly solid and the strictly fluid states.

3. Units Used in Hydraulics. Engineering practice in the United States is generally based on the *foot-pound-second* system of units. In practically all hydraulic formulas these units are used, and if not otherwise stated they are understood. Frequently the diameters of pipes or orifices are expressed in inches, pressures are usually stated in pounds per square inch, and volumes may be expressed in gallons. Before applying such data to problems, conversion to the foot-pound-second system of units should be made. Care in the conversion of units is essential. Errors in hydraulic computations result more frequently from wrong use of units than from any other cause.

Since it is frequently necessary to interchange metric and foot-pound-second units, the relations of these systems of units are briefly reviewed here.

The fundamental equation relating force F , mass M , and acceleration a is

$$F = kMa$$

where k is a proportionality factor. The value of k is made equal to 1 by two different systems of defining units.

1. *Gravitational system*, in which k is made equal to 1 by defining the unit of mass. If a body of unit weight falls freely, unit force

is acting and the acceleration is g . Thus for unit force to produce unit acceleration the unit of mass must consist of g units of weight.

(a) Foot-pound-second system: 1 lb force = 1 slug mass \times 1 ft per sec per sec, in which 1 slug mass = g pounds weight divided by g feet per second per second. An average, commonly used value of g is 32.2 ft per sec per sec.

(b) Metric system: 1 gram force = 1 unit of mass \times 1 cm per sec per sec, in which a unit of mass = g grams weight divided by g centimeters per second per second. An average, commonly used value of g is 981 cm per sec per sec.

2. *Absolute system*, in which k is made equal to 1 by defining the unit of force.

(a) Foot-poundal-second system: Unit force is that force which, acting on a body of 1 lb mass, gives it an acceleration of 1 ft per sec per sec, and is called a poundal. Therefore, 1 poundal force = 1 lb mass \times 1 ft per sec per sec. By 1 lb mass is meant an amount of matter equivalent to that in a block of metal, known as the standard pound, which is kept in Washington, D. C.

(b) Metric system: Unit force is that force which, acting on a body of 1 gram mass, gives it an acceleration of 1 cm per sec per sec, and is called a dyne. Therefore, 1 dyne force = 1 gram mass \times 1 cm per sec per sec. The unit of mass is the gram, which is defined as 1/1000 of the mass of a block of platinum kept in Sèvres and known as the kilogram prototype.

The metric and foot-pound-second systems are related by the following units of length and weight:

$$1 \text{ meter} = 3.2808 \text{ ft}$$

$$1 \text{ kilogram} = 2.2046 \text{ lb}$$

EXAMPLE. How many dynes force are equivalent to 1 lb force?

Solution. 1 slug mass weighs g lb or 453.6 g grams. Also 1 ft per sec per sec = 30.48 cm per sec per sec. Therefore 1 lb force = 453.6 $g \times 30.48 = 444,800$ dynes.

4. General Properties of Fluids. The properties of fluids which are of fundamental importance in the study of hydraulics are defined here.

Unit Weight w : The weight of a unit volume of a fluid. In foot-pound-second units, the unit weight is expressed in pounds per cubic foot.

which is independent of the time of application of the force, and when the stress is removed the solid returns to its original form. On the other hand, if a given shearing stress is applied to a fluid, deformation continues to take place at a uniform rate with time, and when the stress is removed the fluid does not, through forces contained within itself, return to its original form.

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1. *Gravitational system*, in which k is made equal to 1 by defining the unit of mass. If a body of unit weight falls freely, unit force

But by assumption 3, the unit shearing stress

$$\tau \text{ (tau)} = \mu \frac{dv}{dx} \quad (2)$$

where μ is a proportionality factor called the coefficient of viscosity. Thence

$$\frac{V}{x} = \frac{\tau}{\mu} \quad (3)$$

and

$$\mu = \frac{\tau x}{V} \quad (4)$$

If the plates are unit distance apart and moving with unit relative velocity

$$\mu = \tau \quad (5)$$

In this case μ is known as the dynamic, or absolute, viscosity and is thus defined as the force required to move a flat surface of unit area at unit relative velocity parallel to another surface at unit distance away, the space between the surfaces being filled with the fluid.

The foot-pound-second units in which dynamic viscosity is expressed can be evaluated from equation 4. Unit shear τ is in pounds per square foot, distance x is in feet, and velocity v is in feet per second. Hence, the units of μ are

$$\frac{\text{lb/ft}^2 \times \text{ft}}{\text{ft/sec}} = \frac{\text{lb sec}}{\text{ft}^2} = \frac{\text{slug}}{\text{ft sec}}$$

In the metric system, the unit of viscosity is called the poise, 1 poise being 1 dyne sec per cm^2 . A centipoise is 0.01 poise. It has been found experimentally that the dynamic viscosity of water at 68° F (20° C) is 1 centipoise. The ratio of the dynamic viscosity of any fluid to the dynamic viscosity of water at 68° F is termed the relative viscosity. Therefore, when expressed in centipoises, the dynamic viscosity and relative viscosity of any fluid are numerically equal.

Kinematic Viscosity ν (nu): The ratio of the dynamic viscosity of a fluid to its mass density. Thus

$$\nu = \frac{\mu}{\rho}$$

Mass Density ρ (rho): The mass per unit of volume. Thus, in engineers' gravitational units,

$$\rho = \frac{w}{g} \quad \text{or} \quad w = \rho g$$

where g equals the acceleration due to gravity. In foot-pound-second units, mass density is thus slugs per cubic foot, or also

$$\frac{\text{lb/ft}^3}{\text{ft/sec}^2} = \frac{\text{lb sec}^2}{\text{ft}^4}$$

In the metric system density is measured in grams per cubic centimeter and is therefore numerically equal to specific gravity.

Specific Gravity s : The ratio of the unit weight of a fluid to the unit weight of water at 4° C (39.2° F).

Viscosity μ (mu): Viscosity is that property of a fluid which determines the amount of its resistance to a shearing stress. A perfect fluid would have no viscosity. There is no perfect fluid, but gases show less variation in viscosity than liquids. Water is one of the least viscous of all liquids, whereas glycerine, heavy oil, and molasses are liquids having comparatively high viscosities.

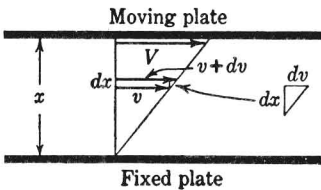


FIG. 1

The viscosity of liquids decreases with increasing temperature, whereas the viscosity of gases increases with increasing temperature.

The mathematical basis of viscosity may be derived from Fig. 1. Consider two parallel plates of indefinite extent at distance x apart, the space between them being filled with a fluid. Consider further that one of these plates moves at velocity V parallel to the other plate. Three assumptions are made:

1. That the fluid particles in contact with a moving surface have the velocity of that surface.
2. That the rate of change of velocity is uniform in the direction perpendicular to the direction of motion.
3. That the shearing stress in the fluid is proportional to the rate of change of velocity.

By assumption 2, from similar triangles

$$\frac{V}{x} = \frac{dv}{dx} \tag{1}$$

in the tube higher than the level outside, the meniscus being concave upward. The tube *B* is immersed in mercury or some other liquid which does not wet the tube. In this case the meniscus is convex upward and the level of the liquid in the tube is depressed.

The effect of capillarity decreases as the size of tube increases. The liquid in a tube $\frac{1}{2}$ inch in diameter is approximately at the same level as the outside liquid, but it is appreciably different in smaller tubes. Water-proofing liquids

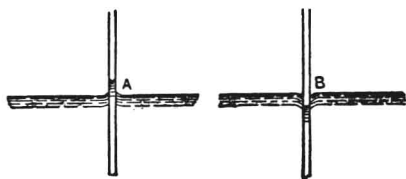


FIG. 2. Capillary action.

have been developed which, when applied to the inside of small glass tubes, greatly reduce the capillary rise of water in the tubes.

The dimensions of surface tension are pounds per foot, the surface film being considered of zero thickness. The surface tension of liquids decreases as their temperature rises.

5. Properties of Water. Various properties of water which are used in hydraulics are shown in the table on page 8. Certain properties are discussed briefly in this article.

Unit Weight. Water has its maximum unit weight at a temperature of 4°C (39.2°F). At this temperature pure water serves as a standard of specific gravity for all substances. Under atmospheric pressure at sea level, water freezes at 32° and boils at 212°F . The weight of pure water at its temperature of maximum density is 62.427 lb per cu ft.

As water occurs in nature, it invariably contains salts and mineral matter in solution. Silt or other impurities may also be carried in suspension. These substances, being heavier than water, increase its weight. The impurities contained in rivers, inland lakes, and ordinary ground waters do not usually add more than 0.1 lb to the weight per cubic foot. Ocean water weighs about 64 lb per cu ft. After long-continued droughts the waters of Great Salt Lake and of the Dead Sea have been found to weigh as much as 75 lb per cu ft.

Since the weight of inland water is not greatly affected by ordinary impurities or changes of temperature, an average weight of water may be used which will give results sufficiently accurate for ordinary purposes. In this book the weight of a cubic foot of water is ordinarily taken as 62.4 lb. In precise work, when the