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Fluid Mechanics with Engineering Applications

(Tenth Edition)

流体力学及其工程应用

（第10版）

E. John Finnemore　Joseph B. Franzini

McGraw Hill

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Fluid Mechanics with Engineering Applications

TENTH EDITION

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[1] IE=International Edition

Fluid Mechanics with Engineering Applications

影 印 版 序

本书是《流体力学及其工程应用》这部经典教材的第 10 版。本书从第 1 版问世以来，经历了三代作者，该版本主要是由其第三代作者编写的。尽管第 10 版与第 1 版已相当不同，但它仍保留了相同的基本思想，即从工程应用的角度来研究流体力学现象，这是 Robert L. Daugherty 在康奈尔大学、伦塞勒理工学院和加州理工学院多年执教生涯中首先倡导的方法。Daugherty 教授撰写的第 1 版于 1916 年出版发行，书名为《水力学》，此后他四次修订此书。在第 5 版中，Alfred C. Tngersoll 参加了编写，他们将书名更改为《流体力学及其工程应用》。第 6 版和第 7 版的修订是由 Frangini 教授完成的，他是 Daugherty 教授在加州理工学院的学生。第 8 版和第 9 版中 Frangini 得到了 Finnemore 教授的帮助，后者是 Frangini 教授在斯坦福大学的学生。在第 10 版中，除了第 15 章和第 16 章是由 Frangini 教授修订之外，其余部分主要是由 Finnemore 教授完成的。本书出版 86 年以来，在世界各国广泛发行，其西班牙语与韩语译本亦已出版。

本书特别强调对流体力学现象的描述，着重介绍在推导基本原理过程中所做的假定、应用中的限制以及如何应用这些基本原理去解决工程实际问题。书中提供了大量的实例来介绍基本原理的运用。大部分章节后面附有练习题，并提供了答案，可以帮助学生加深对有关概念的理解。每章后面还有精心挑选的课后作业，可以用于检验学生综合应用基本原理的能力。本书提供的参考文献可以作为不同领域学生进一步研究流体力学的指南。附录部分包含有表示流体物理力学性质的图表，流体力学常用的一些公式，计算机应用和编程，以及计算实例。为了便于阅读，在正文的前面还给出符号列表和常用缩写词。本书以英制作为主要单位系统，同时也给出相应的国际单位。

本书共 16 章，内容包括：绪论、流体的物理力学性质、流体静力学、流体运动的一些基本概念、恒定流的能量、流体的动量与作用力、量纲分析与相似原理、压力管道中的恒定不可压缩流动、绕流物体的受力分析、明渠恒定流、流体的量测、非恒定流问题、可压缩的恒定流动、理想流体动力学、水力机械——泵和水轮机。本书可分两个阶段进行讲授，第一阶段为流体力学基础部分，包括第 1 章到第 7 章和第 8 章的前半部分，学时多的还可以包括第 11 章（流体量测）和第 14 章（理想流体动力学）。第二阶段为专题部分，可根据不同专业要求选学部分章节。如土木、水利、环境类专业可选学第 10 章（明渠恒定流）和第 12 章（非恒定流问题）。机械等专业可选学第 9 章（绕流物体的受力分析）和第 13 章（可压缩恒定流）。水力机械专业则必须学习第 15 章和第 16 章（泵和水轮机）。

本书是一本优秀的流体力学教材，内容丰富，概念清晰，简明易懂，可作为我国高等理工院校土木、水利、环境、机械等学科有关专业流体力学课程的英文教材或主要参考书。对于从事上述专业的工程技术人员来说，本书也是一本非常实用的参考书。

李玉柱

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About the Authors

E. John Finnemore is Professor of Civil Engineering at Santa Clara University, California. Born in London, England, he received a B.Sc. (Eng.) degree from London University in 1960, and M.S. and Ph.D. degrees from Stanford University in 1966 and 1970, all in civil engineering. Finnemore worked with consulting civil engineers in England and Canada for five years before starting graduate studies, and for another seven years in California after completing his doctorate. He served one year on the faculty of Pahlavi University in Shiraz, Iran, and he has been a member of the faculty at Santa Clara University since 1979. He has taught courses in fluid mechanics, hydraulic engineering, hydrology, and water resources engineering, and has authored numerous technical articles and reports in several related fields. His research has often involved environmental protection, such as in stormwater management and onsite wastewater disposal. Professor Finnemore has served on governmental review boards and as a consultant to various private concerns. He is a Fellow of the American Society of Civil Engineers and a registered civil engineer in Britain and California. He lives with his wife Gulshan in Cupertino, California.

Joseph B. Franzini is Professor Emeritus of Civil Engineering at Stanford University. Born in Las Vegas, New Mexico, he received B.S. and M.S. degrees from the California Institute of Technology in 1942 and 1943, and a Ph.D. from Stanford University in 1950. All his degrees are in civil engineering. Franzini served on the faculty at Stanford University from 1950 to 1986. There he taught courses in fluid mechanics, hydrology, sedimentation, and water resources, and also did research on a number of topics in those fields. Since retirement from Stanford, he has been active as an engineering consultant and an expert witness. He is coauthor of the authoritative and widely used textbook, *Water Resources Engineering,* and of its predecessor, *Elements of Hydraulic Engineering.* Through the years, Franzini has been active as a consultant to various private organizations and governmental agencies in both the United States and abroad; he was associated with Nolte and Associates, a consulting civil engineering firm in San Jose, California, for over 30 years. He is a Fellow of the American Society of Civil Engineers and a registered civil engineer in California. He lives with his wife Gloria in Palo Alto, California.

To that great love which encourages humanity
in all its noble endeavors

and

to Gulshan and Gloria
for their loving support

Preface

Philosophy and History

This tenth edition of the classic textbook, *Fluid Mechanics with Engineering Applications,* continues and improves on its tradition of explaining the physical phenomena of fluid mechanics and applying its basic principles in the simplest and clearest possible manner without the use of complicated mathematics. It focuses on civil, environmental, and agricultural engineering problems, although mechanical and aerospace engineering topics are also strongly represented. The book is written as a text for a first course in fluid mechanics for engineering students, with sufficient breadth of coverage that it can serve in a number of ways for a second course if desired.

Thousands of engineering students and practitioners throughout the world have used this book for over 85 years; it is widely distributed as an International Edition, and translations into Spanish and Korean are available. The book is now in its third generation of authorship. Though this tenth edition is very different from the first edition, it retains the same basic philosophy and presentation of fluid mechanics as an engineering subject that Robert L. Daugherty originally developed over his many years of teaching at Cornell University, Rensselaer Polytechnic Institute, and the California Institute of Technology. The first edition that Professor Daugherty authored was published in 1916 with the title *Hydraulics.* He revised the book four times. On the fifth edition (fourth revision) Dr. Alfred C. Ingersoll assisted him, and they changed the title of the book to *Fluid Mechanics with Engineering Applications.* The sixth and seventh editions were entirely the work of Professor Franzini. A student of Daugherty's at Caltech, Franzini had received his first exposure to the subject of fluid mechanics from the fourth edition of the book. Professor Franzini enlisted the services of Professor Finnemore, a former student of Franzini's at Stanford, to assist him with the eighth and ninth editions. This tenth edition is the work of Dr. Finnemore, with the exception of Chapters 15 and 16, which Dr. Franzini revised.

The Book, Its Organization

We feel it is most important that the engineering student clearly visualize the physical situation under consideration. Throughout the book, therefore, we place considerable emphasis on physical phenomena of fluid mechanics. We stress the governing principles, the assumptions made in their development, and their limits of applicability, and show how we can apply the principles to the solution of practical engineering problems. The emphasis is on teachability for the instructor and on clarity for both the instructor and the student, so that they can readily grasp basic principles and applications. Numerous worked sample problems are presented to demonstrate the application of basic principles. These sample problems also help to clarify the text. Drill exercises with answers provided follow most sections to help students rapidly reinforce their understanding of the subjects and concepts. The end-of-chapter problems presented for assignment purposes were carefully selected to provide the student with a thorough workout in the application of basic principles. Only by working numerous exercises and problems will students experience the evolution so necessary to the learning process. We recommend ways to study fluid mechanics and to approach problem solving in Chapter 1.

The book is essentially "self-contained." The treatment is such that an instructor generally need not resort to another reference to answer any question that a student might normally be expected to ask. This has required more detailed discussion than that needed for a more superficial presentation of certain topics. A list of selected references is provided at the end of the book to serve as a guide for those students who wish to probe deeper into the various fields of fluid mechanics. The appendix section contains information on physical properties of fluids and other useful tables, Chapter 1 contains information on dimensions and units, and, for convenient reference, the insides of the covers contain conversion factors and important quantities and definitions.

Even though we use British Gravitational (BG) units (feet, slugs, seconds, pounds) as the primary system of units, we give the corresponding SI units in the text. We provide sample problems, and exercises and problems in BG and in SI units in near equal numbers. We have made every effort to ease the changeover from BG units to SI units; Chapter 1 includes a discussion of unit systems and conversion of units. We encourage instructors to assign problems in each system so that students become conversant with both.

Improvements to This Edition

Probably the most noticeable improvement made throughout this edition will be our addition of many figures (over 110), to help present exercises and problems, and to help explain solutions of sample problems. Also, throughout we have made the use of programming and computers optional, we have included more ways to solve trial-and-error problems, and we have added more cross-references.

In this revision, we have given special attention to the first eight chapters. There we have improved understandability by simplifying and clarifying text and sample problems that were more involved, and by thoroughly modernizing the language, as well as adding figures. Of the exercises and problems in these chapters, 40% are now new or changed from the previous edition.

Chapter 5 is strongly revised, with the basic derivation of Bernoulli's equation moved to a very early position, alternate forms of the equation added, and the assumptions on which it is based clarified. A new, clear distinction is made between wall (or pipe) friction head loss and total head loss in pipes, and this is carried forward into subsequent chapters. How cavitation causes damage is better explained with the aid of a new microphotograph of an imploding bubble.

New features in other chapters include: information about computational fluid dynamics, with a supporting figure and photograph; various aspects of single-pipe flow are now separated out into different sections; a treatment of submerged discharge into moving water; information about conveyance in open channels; a clarified treatment of optimal hydraulic efficiency of channel flow; a table summarizing damming action; descriptions of methods of measuring fluid velocity using laser light; data on the hydraulic conductivities of major geologic deposits; and a discussion of affinity laws for pumps. We have increased the total number of exercises and problems in the book to 1354.

There are two new appendices. One summarizes the characteristics and properties of the main types of equations used in fluid mechanics. The other provides examples of using equation solvers and polynomial solvers, on HP48G calculators and in Excel and Mathcad, to solve selected sample problems. In addition, Appendix C, on programming and computer applications, is upgraded by the addition of many examples of applications software that model flow systems, components, processes, and flow fields.

Use of the Book, Course Planning

An excellent, brief first course in fluid mechanics could consist of Chapters 1 through 7 and the first half of Chapter 8; however, one might wish to include parts of Chapters 11 (Fluid Measurements) and 14 (Ideal Flow Mathematics) in a first course. Schools having stringent requirements in fluid mechanics might wish to cover the entire text in their course or courses required of all engineers. At other schools only partial coverage of the text might suffice for the course required of all engineers, and they might cover other portions of the text in a second course for students in a particular branch of engineering. Thus civil, environmental, and agricultural engineers would emphasize Chapter 10 and perhaps Chapter 12 in a second course, while mechanical engineers would probably include Chapters 9 and 13 in a second course. A number of schools have used the book for courses in hydraulic machinery.

For instructors only, a companion Solutions Manual is available from McGraw-Hill that contains typed and carefully explained solutions to all the exercises and end-of-chapter problems in the book; for convenience, the problem statements and problem figures are repeated with the solutions. The manual contains suggestions on how to use it most effectively to select problems for assignment, and a Problem Selection Guide for each chapter categorizes the problems by their difficulty, length, units used, and any special features.

Acknowledgments

We appreciate the many comments and suggestions that we have received from users of the book throughout the years, and from numerous anonymous indepth reviews arranged by McGraw-Hill. In particular, we thank the following reviewers for this tenth edition: Kenneth Edwards, Ohio University; Joel Melville, Auburn University; A. R. Rao, Purdue University; Henry Santeford, Michigan Technological University; Yiannis Ventikos, Georgia Institute of Technology; Vaughan Voller, University of Minnesota; and Mark Widdowson, Virginia Polytechnic Institute and State University. They have all influenced the content and mode of presentation of the material. Further comments and suggestions for future editions of the book are always welcome.

We are very grateful for the care, assistance, and guidance that many people at McGraw-Hill and its subcontractors have provided to us in the preparation of this edition. Particularly, we appreciate the startup support that our developmental editor, Eric Munson, gave us, and the unflagging cooperation and patience of our production manager, Gloria Schiesl.

E. John Finnemore
Joseph B. Franzini

List of Symbols

The following table lists the letter symbols generally used throughout the text. Because there are so many more concepts than there are English and suitable Greek letters, certain conflicts are unavoidable. However, where we have used the same letter for different concepts, the topics are so far removed from each other that no confusion should result. Occasionally we will use a particular letter in one special case only, but we will clearly indicate this local deviation from the table, and will not use it elsewhere. We give the customary units of measurement for each item in the British Gravitational (BG) system, with the corresponding SI unit in parentheses or brackets.

For the most part, we have attempted to adhere to generally accepted symbols, but not always.

A = any area, ft^2 (m^2)
= cross-sectional area of a stream normal to the velocity, ft^2 (m^2)
= area in turbines or pumps normal to the direction of the absolute velocity of the fluid, ft^2 (m^2)
A_c = circumferential flow area, ft^2 (m^2)
A_s = area of a liquid surface as in a tank or reservoir, ft^2 or acre (m^2 or hectare)
a = area in turbines or pumps normal to the relative velocity of the fluid, ft^2 (m^2)
= linear acceleration, ft/sec^2 (m/s^2)
B = any width, ft (m)
= width of open channel at water surface, ft (m)
= width of turbine runner or pump impeller at periphery, ft (m)
b = bottom width of open channel, ft (m)
$\mathbf{C}$ = cavitation number = $(p - p_v)/(\frac{1}{2}\rho V^2)$ [dimensionless]
C = any coefficient [dimensionless]
= Chézy coefficient [ft$^{1/2}$sec^{-1} (m$^{1/2}$s^{-1})]
C_c = coefficient of contraction
C_d = coefficient of discharge
C_v = coefficient of velocity
(C_c, C_d, C_v: for orifices, tubes, and nozzles [all dimensionless])
C_D = drag coefficient [dimensionless]
C_f = average friction-drag coefficient for total surface [dimensionless]
C_{HW} = Hazen-Williams pipe roughness coefficient, ft$^{0.37}$/sec (m$^{0.37}$/s)
C_L = lift coefficient [dimensionless]
C_p = pressure coefficient = $\Delta p/(\frac{1}{2}\rho V^2)$ [dimensionless]
c = specific heat of liquid, Btu/(slug·°R) [cal/(g·K) or N·m/(kg·K)]
= wave velocity (celerity), fps (m/s)
= sonic (i.e., acoustic) velocity (celerity), fps (m/s)

c_f = local friction-drag coefficient [dimensionless]
c_j = velocity (celerity) of pressure wave in elastic fluid inside an elastic pipe, ft/sec (m/s)
c_p = specific heat of gas at constant pressure, ft·lb/(slug·°R) [N·m/(kg·K)]
c_v = specific heat of gas at constant volume, ft·lb/(slug·°R) [N·m/(kg·K)]
D = diameter of pipe, turbine runner, or pump impeller, ft or in (m or mm)
$D''V$ = product of pipe diameter in inches and mean flow velocity in fps
$\mathbf{E}$ = Euler number = $V/\sqrt{2\Delta p/\rho}$ [dimensionless]
E = specific energy in open channels = $y + V^2/2g$, ft (m)
= linear modulus of elasticity, psi (N/m^2)
E_j = "joint" volume modulus of elasticity for elastic fluid in an elastic pipe, psi (N/m^2)
E_v = volume modulus of elasticity, psi (N/m^2)
e = height of surface roughness projections, ft (mm)
= 2.71828182846 . . .
$\mathbf{F}$ = Froude number = $V/\sqrt{gL}$ [dimensionless]
F = any force, lb (N)
F_D = drag force, lb (N)
F_L = lift force, lb (N)
f = friction factor for pipe flow [dimensionless]
G = weight flow rate = $dW/dt = \dot{m}g = \gamma Q$, lb/sec (N/s)
g = acceleration due to gravity = 32.1740 ft/sec^2 (9.80665 m/s^2) (standard)
= 32.2 ft/sec^2 (9.81 m/s^2) for usual computation
H = total energy head = $p/\gamma + z + V^2/2g$, ft (m)
= head on weir or spillway, ft (m)
h = any head, ft (m)
= enthalpy (energy) per unit mass of gas = $i + p/\rho$, ft·lb/slug (N·m/kg)
h' = minor head loss, ft (m)
h_a = accelerative head = $(L/g)(dV/dt)$, ft (m)
h_c = depth to centroid of area, ft (m)
h_f = head loss due to wall or pipe friction, ft (m)
h_L = total head loss due to all causes, ft (m)
h_M = energy *added* to a flow by a machine per unit weight of flowing fluid, ft·lb/lb (N·m/N)
h_O = stagnation (or total) enthalpy of a gas = $h + \frac{1}{2}V^2$, ft·lb/slug (N·m/kg)
h_p = depth to center of pressure, ft (m)
= head added to a flow by a pump, ft (m)
h_t = head removed from a flow by a turbine, ft (m)
I = moment of inertia of area, ft^4 or in^4 (m^4 or mm^4)
= internal thermal energy per unit weight = i/g, ft·lb/lb (N·m/N)

I_c = moment of inertia about centroidal axis, ft^4 or in^4 (m^4 or mm^4)
i = internal thermal energy per unit mass = gI, ft·lb/slug (N·m/kg)
K = any constant [dimensionless]
k = any loss coefficient [dimensionless]
= specific heat ratio = c_p/c_v [dimensionless]
L = length, ft (m)
L_r = $1/\lambda$ = scale ratio = L_p/L_m [dimensionless]
ℓ = mixing length, ft or in (m or mm)
$\mathbf{M}$ = Mach number = V/c [dimensionless]
M = molar mass, slugs/slug-mol (kg/kg-mol)
m = mass = W/g, slugs (kg)
$\dot{m}$ = mass flow rate = $dm/dt = \rho Q$, slugs/sec (kg/s)
$\mathbf{N}$ = any dimensionless number
N_s = specific speed = $n_e\sqrt{\text{gpm}}/h^{3/4}$ for pumps [dimensionless]
= specific speed = $n_e\sqrt{\text{bhp}}/h^{5/4}$ for turbines [dimensionless]
NPSH = net positive suction head, ft (m)
n = an exponent or any number in general
= Manning coefficient of roughness, $sec/ft^{1/3}$ ($s/m^{1/3}$)
= revolutions per minute, min^{-1}
n_e = rotative speed of hydraulic machine at maximum efficiency, rev/min
P = power, ft·lb/sec (N·m/s)
= height of weir or spillway crest above channel bottom, ft (m)
= wetted perimeter, ft (m)
p = fluid pressure, lb/ft^2 or psi (N/m^2 = Pa)
p_{atm} = atmospheric pressure, psia (N/m^2 abs)
p_b = back pressure in gas flow, psf or psi (Pa)
p_O = stagnation pressure, psf or psi (Pa)
p_v = vapor pressure, psia (N/m^2 abs)
Q = volume rate of flow (discharge rate), cfs (m^3/s)
Q_H = heat *added* to a flow per unit weight of fluid, ft·lb/lb (N·m/N)
q = volume rate of flow per unit width of rectangular channel, cfs/ft = ft^2/sec (m^2/s)
q_H = heat transferred per unit mass of fluid, ft·lb/slug (N·m/kg)
$\mathbf{R}$ = Reynolds number = $LV\rho/\mu = LV/\nu$ [dimensionless]
R = gas constant, ft·lb/(slug·°R) or N·m/(kg·K)
R_h = hydraulic radius = A/P, ft (m)
R_m = manometer reading, ft or in (m or mm)
R_0 = universal gas constant = 49,709 ft·lb/(slug-mol·°R) [8312 N·m/(kg-mol·K)]
r = any radius, ft or in (m or mm)
r_0 = radius of pipe, ft or in (m or mm)
S = slope of energy grade line = h_L/L [dimensionless]
S_c = critical slope of open channel flow [dimensionless]
S_0 = slope of channel bed [dimensionless]
S_w = slope of water surface [dimensionless]

s = specific gravity of a fluid = ratio of its density to that of a standard fluid (water, air, or hydrogen) [dimensionless]
T = temperature, °F or °R (°C or K)
= period of time for travel of a pressure wave, sec (s)
= torque, ft·lb (N·m)
T_O = stagnation temperature of a gas = $T + \frac{1}{2}V^2/c_p$, °F or °R (°C or K)
T_r = travel time (pulse interval) of a pressure wave, sec (s)
t = time, sec (s)
= thickness, ft or in (m or mm)
t_c = time for complete or partial closure of a valve, sec (s)
U, U_0 = uniform velocity of fluid, fps (m/s)
u = velocity of a solid body, fps (m/s)
= tangential velocity of a point on a rotating body = $r\omega$, fps (m/s)
= local velocity of fluid, fps (m/s)
u' = turbulent velocity fluctuation in the direction of flow, fps (m/s)
u_* = shear stress velocity or friction velocity = $\sqrt{\tau_0/\rho}$, ft/sec (m/s)
V = mean velocity of fluid, fps (m/s)
= absolute velocity of fluid in hydraulic machines, fps (m/s)
V_c = critical mean velocity of open channel flow, fps (m/s)
V_j = jet velocity, fps (m/s)
V_m = meridional velocity, fps (m/s)
V_r = radial component of velocity = $V\sin\alpha = v\sin\beta$, fps (m/s)
V_u = tangential component of velocity = $V\cos\alpha = u + v\cos\beta$, fps (m/s)
$\forall$ = any volume, ft^3 (m^3)
v = relative velocity of fluid in hydraulic machines, fps (m/s)
= specific volume = $1/\rho$, ft^3/slug (m^3/kg)
v_r = radial component of relative velocity = $v\sin\beta$, fps (m/s)
v_u = tangential component of relative velocity = $v\cos\beta$, fps (m/s)
v' = turbulent velocity fluctuation normal to the direction of flow, fps (m/s)
u, v, w = components of velocity in x, y, z, directions, fps (m/s)
$\mathbf{W}$ = Weber number = $V/\sqrt{\sigma/\rho L}$ [dimensionless]
W = total weight, lb (N)
x = a distance, usually parallel to flow, ft (m)
x_c = distance from leading edge to point where boundary layer becomes turbulent, ft (m)
y = a distance along a plane in hydrostatics, ft (m)
= total depth of open channel flow, ft (m)
y_c = critical depth of open channel flow, ft (m)
= distance to centroid, ft (m)
y_h = hydraulic (mean) depth = A/B, ft (m)
y_0 = depth for uniform flow in open channel (normal depth), ft (m)
y_p = distance to center of pressure, ft (m)
z = elevation above any arbitrary datum plane, ft (m)

α (alpha) = an angle; between V and u in rotating machinery, measured between their positive directions
= kinetic energy correction factor [dimensionless]
β (beta) = an angle; between v and u in rotating machinery, measured between their positive directions
= momentum correction factor [dimensionless]
Γ (gamma) = circulation, ft^2/sec (m^2/s)
γ (gamma) = specific weight, lb/ft^3 (N/m^3)
δ (delta) = thickness of boundary layer, in (mm)
δ_v = thickness of viscous sublayer in turbulent flow, in (mm)
δ_t = thickness of transition boundary layer in turbulent flow, in (mm)
ε (epsilon) = kinematic eddy viscosity, ft^2/sec (m^2/s)
η (eta) = eddy viscosity, $lb \cdot sec/ft^2$ ($N \cdot s/m^2$)
= efficiency of hydraulic machine
θ (theta) = any angle
λ (lambda) = model ratio or model scale = 1/(scale ratio) = L_m/L_p [dimensionless]
μ (mu) = absolute or dynamic viscosity, $lb \cdot sec/ft^2$ ($N \cdot s/m^2$)
ν (nu) = kinematic viscosity = μ/ρ, ft^2/sec (m^2/s)
ξ (xi) = vorticity, sec^{-1} (s^{-1})
Π (pi) = dimensionless parameter
π = 3.14159265359...
ρ (rho) = density, mass per unit volume = γ/g, $slug/ft^3$ (kg/m^3)
ρ_O = stagnation density of a gas, $slug/ft^3$ (kg/m^3)
Σ (sigma) = summation
σ (sigma) = surface tension, lb/ft (N/m)
= cavitation parameter in turbomachines [dimensionless]
= submergence of weir = h_d/h_u [dimensionless]
σ_c = critical cavitation parameter in turbomachines [dimensionless]
τ (tau) = shear stress, lb/ft^2 (N/m^2)
τ_0 = shear stress at a wall or boundary, lb/ft^2 (N/m^2)
ϕ (phi) = any function
= velocity potential, ft^2/sec (m^2/s) for two-dimensional flow
= peripheral-velocity factor = $u_{periph}/\sqrt{2gh}$ [dimensionless]
ϕ_e = peripheral-velocity factor at point of maximum efficiency [dimensionless]
ψ (psi) = stream function, ft^2/sec (m^2/s) for two-dimensional flow
ω (omega) = angular velocity = $u/r = 2\pi n/60$, rad/sec (rad/s)

Values at specific points will be indicated by suitable subscripts. In the use of subscripts 1 and 2, the fluid is always assumed to flow from 1 to 2.