HYDRAULICS

LECTURE 1: FLUID STATICS & FLOW

PE REVIEW COURSE
PENN STATE BEAVER CONTINUING EDUCATION

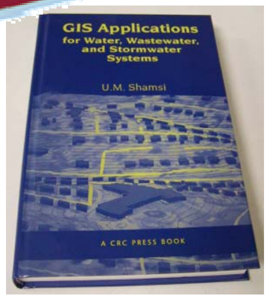
Uzair (Sam) Shamsi, Ph.D., P.E.

OUTLINE

- General
  - Instructor introduction
  - Signup sheet
  - Schedule
  - Textbook
  - Class monitor
  - How to prepare for PE Exam?
  - Useful resources
- Lecture 1: Fluid Statistics And Flow
  - Chapter 14: Fluid Properties
  - Chapter 15: Fluid Statics
  - Chapter 16: Fluid Flow Parameters
  - Chapter 17: Fluid Dynamics

ABOUT YOUR PROFESSOR

- ☑ Senior Technical Manager, Michael Baker Jr., Inc. Pittsburgh, PA
  - Water and wastewater engineering
  - Hydrologic & hydraulic modeling and GIS
- ☑ Professor
  - University of Pittsburgh, GIS and Hydrology
  - Penn State University, Continuing Education
  - Youngstown State University, GIS and Hydrology
- ☑ Education:
  - Ph.D. (Civil Engineering), University of Pittsburgh, 1988
- ☑ 20 years of experience, 100+ projects, 80+ publications
- ☑ Books:
  - GIS Tools for Water, Wastewater, and Stormwater Systems, An ASCE Press Best-seller, 2002.
  - GIS Applications for Water, Wastewater, and Stormwater Systems, CRC Press, 2005.
- ☑ Professional Engineer in PA, WV, OH, GA
- ☑ PE problem writer, NCEES, 1990's
- ☑ 2006 Civil Engineer of the year, ASCE Pittsburgh



Contact: sshamsi@mbakercorp.com
Office phone (9 AM – 6 PM) 412-375-3076

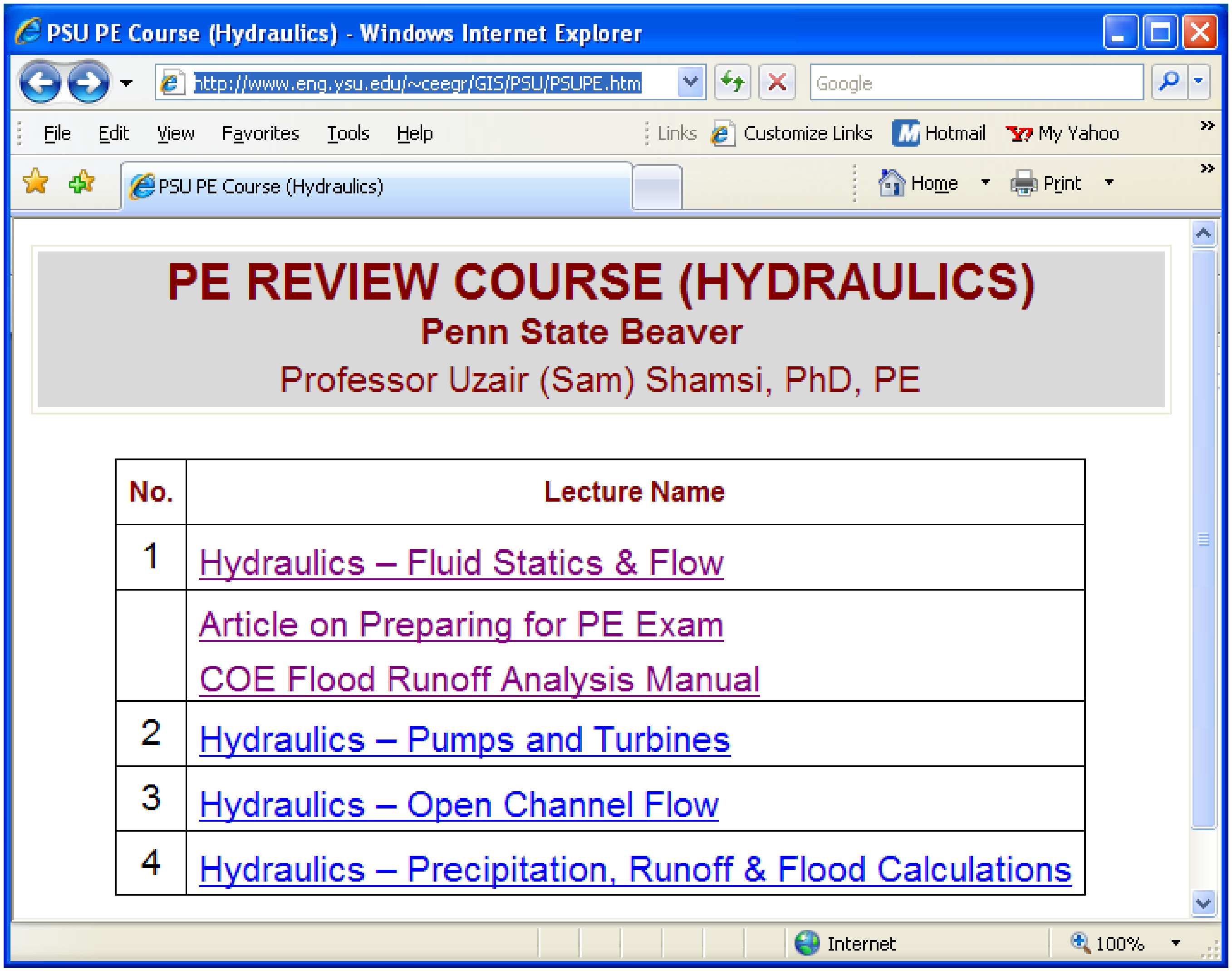
SCHEDULE

Date	Topic	Chapter No.
10/22/09	Hydraulics – Fluid Statics & Flow	14 to 17
10/29/09	Hydraulics – Pumps and Turbines	18
11/5/09	Hydraulics – Open Channel Flow	19
11/12/09	Hydraulics – Precipitation, Runoff & Flood Calculations	20

- **Chapter numbers refer to Michael Lindeburg's Civil Engineering Reference Manual, 9th (2003) to 11th (2008) editions.**
- **Please note that the Open Channel Flow lecture (Chapter 19) has been moved before the Precipitation and Runoff lecture (Chapter 20) to maintain consistency with the chapter order in the text book.**

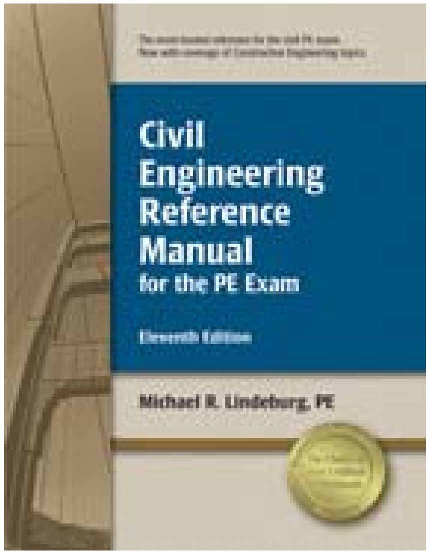
COURSE WEB SITE

www.eng.ysu.edu/~ceegr/GIS/PSU/PSUPE.htm



TEXT BOOK

- Title: Civil Engineering Reference Manual
- Author: Michael R. Lindeburg, P.E.
- Publisher: Professional Publications Inc. (PPI) www.ppi2pass.com
- Type: Hardcover
- Edition: 11 (Edition 9 or 10 will also work for my lectures)
- Pages: 1456 (9th edition had 576 pages)
- Price: $169.95 (9th edition was $96.60)
- ISBN: 978-159126-129-2 (9th edition 0131716859)



CLASS MONITOR

1. Must have a cell phone
2. Must attend all classes on time
3. Communicate with students on Professor's behalf (e.g., if the professor will be late or absent)

Any volunteer: ???

LICENSED ENGINEER

- "Engineering Practice Act" -- to protect the health, safety and welfare of the citizens of that state (1989).
- Having an engineering license means more than just meeting a State's minimum requirements. It means you have accepted both the technical and the ethical obligations of the engineering profession.
  - Ref: ASCE Policy Statement # 433

PREPARING FOR AND TAKING THE P.E. EXAM

- Based on three articles on "Preparing for and Taking Licensing Exams" by Dr. Ben Buckner, P.E.
- Part 1, 2, and 3 published in May, June, and July 1999 in Professional Surveyor Magazine
- Scanned copy of the articles is available on the course Web site.

Preparing for and Taking Licensing Exams: Part I—Introduction to Taking Exams

Dr. Ben Buckner, LS, PE

Editor's note: The following is the first of a four-part series. The material is adapted from Appendix B of the author's book, Land Survey Review Manual.

Preparing for and taking exams involves more than simply acquiring knowledge, although knowledge of the exam material is the most important variable. Most of us could pass most multiple-choice or true-false exams with very little knowledge of the subject, depending on the standard set for the passing score. This series of articles is not on how to study, but rather on how to focus on the examination itself, including consideration of prior preparation. To ensure a passing score, you must become an astute exam-taker. This series will explain attitudes you can take toward an exam and techniques to apply that will improve scores over simply sitting and racking your brain trying to recall basic knowledge.

Analyze the Questions

One technique, which permeates all aspects of exam-taking, is analyzing the questions, rather than simply perusing or reading them. Without a certain level of reading and analytical ability and willingness to concentrate, it is difficult to pass any exam. This is true even if you have acquired basic knowledge and gained appropriate experience. Do not expect miracles in the exam room. An exam is the proof of the knowledge. This must be communicated to the grader. You must be fully involved with the exam to do this. Knowing the anatomy of exam questions will help you analyze them. Because most licensing exams are now in the multiple-choice format, most of the discussion in this series will focus on this style, although some points will be made concerning discussion questions or problems requiring solutions.

Multiple-Choice Format

The statement of the question is called the "stem." The stem can be written as a question, a statement to be completed or a presentation of a problem. Within these formats, the level of the questions varies. Some questions simply test knowledge of facts, some test ability to recognize or associate concepts, and others test ability to analyze and solve problems. In land surveying licensing exams, the subject matter can be anything related to the fundamentals or the principles and practices of land surveying as embraced by the National Council of Examiners for Engineers and Surveyors (NCEES) "content areas" or as decided by individual state licensing boards.

The responses provide alternative answers to questions, completions of statements or answers to numerical problems. There are usually either four or five answer choices. One of these will be correct or best. Sometimes there is only one true answer in the choices, and the others are false. At other times there may be elements of truth in all responses, but one has more truth than the others. The incorrect choices are called *logical distractors*, or *decoys*.

The reasons boards and other groups use this format are related to grading and objectivity. First, multiple choice exam grading is easy, with no need for examiners to plod through examinees' answers and render judgments. Also, the objective, rather than subjective, nature of the grading is more "defensible"—when questions are multiple choice, an examinee cannot easily argue or bring suit against a board for showing arbitrariness or favoritism.

The advantage to the examinee is that all of the correct answers are provided. They are surrounded by some distractions, but a skilled examinee views these distractors as minor annoyances or clutter. The responses serve as prompts to "jog" your memory or as clues leading to the best answer. You do not have to recall information—as you would for a short-answer or essay question—and compose an original answer. This makes it easier.

Multiple Choice Is a Game of Probability

Most exams today have four choices for the answer to each question. Because all questions are worth the same point value, if you randomly guessed on the entire exam, the score would theoretically be 25 percent. However, if you could eliminate one response from consideration on each question and guess from among the remaining three choices, the score would increase to about 33 percent. Eliminating two responses from consideration would raise the score to about 50 percent, and so on. Much of the discussion in this series will be on developing ways to throw out choices, leaving a shorter list from which to choose. There are many ways to do this. Combining the methods can significantly increase exam scores and even result in passing scores when your knowledge of the subjects may be somewhat lacking, simply based on the laws of probability in selecting from a shorter list of choices.

To become an astute exam-taker, you must learn how to recognize whether a question has been carefully or poorly written. The first of sev-

PREPARING FOR AND TAKING THE P.E. EXAM

1. Preparing for and taking exams involves more than simply acquiring knowledge.
2. To ensure a passing score, you must become an smart exam taker.
3. Many multiple-choice questions are answered incorrectly, not because of lack of knowledge, but because of failure to read and understand questions.
4. Understanding what is being asked requires sufficient time, concentration, and attention to detail.
5. Identify distracters; they present the greatest challenge.
6. Selecting one response without carefully considering the others is jumping to conclusions.

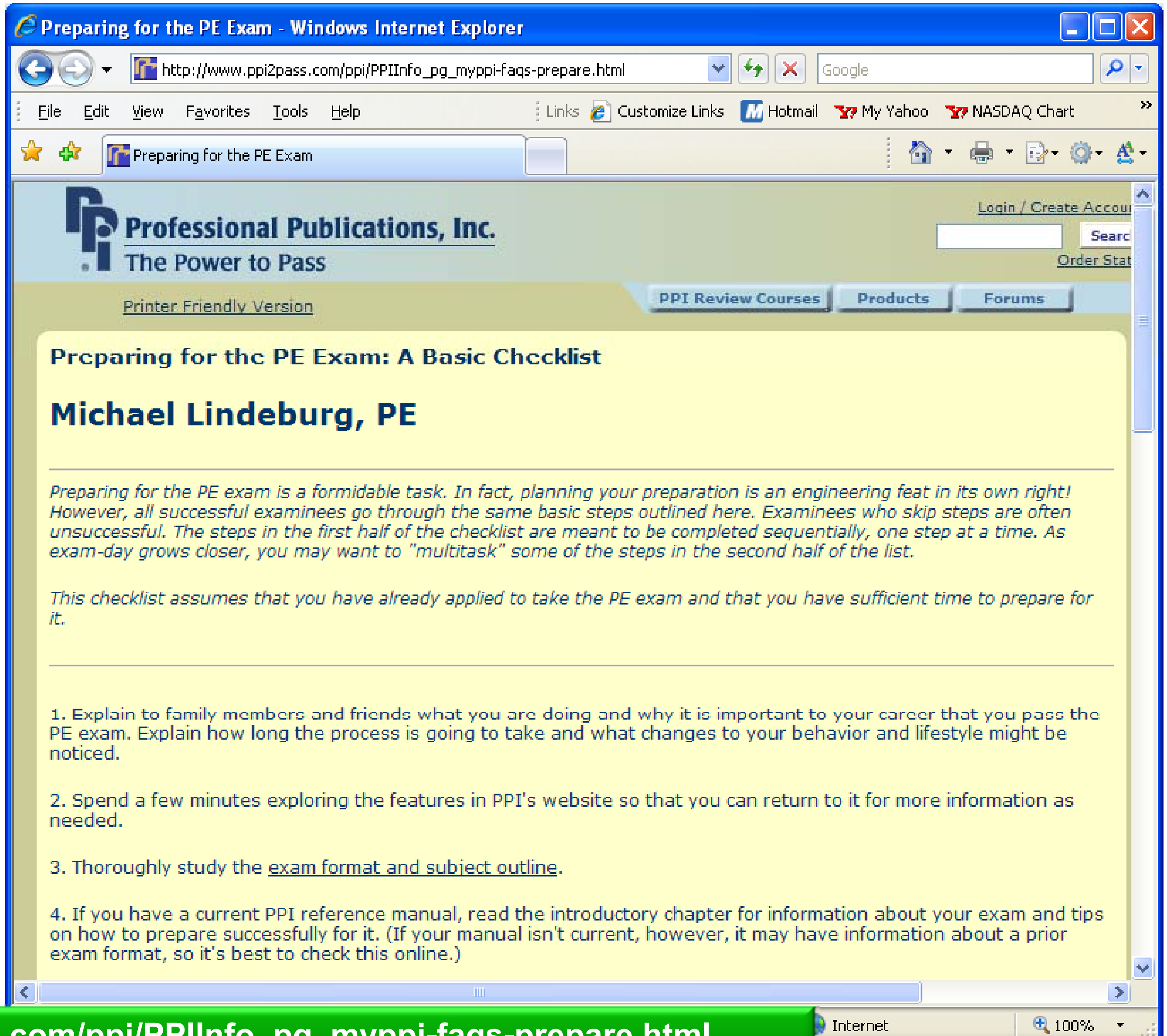
PREPARING FOR AND TAKING THE P.E. EXAM

7. Wrong answers are often relatively longer or shorter than the correct one. And wording could be less formal than that of the correct answer.
8. Don't quit prematurely. Dig a little deeper.
9. A positive attitude toward learning is critical.
10. Collect a library of references.
11. Form good study habits. Set aside some favorite habits to allow for study time. Attend review courses during the final preparation stage (no less than six months before the exam).

SAM'S TIPS

1. Make a list of reference material and which book contains what.
2. Put tabs and bookmarks in your reference material for quick searches.
3. Practice how to use the index at the end of a book.
4. Highlight important topics in the table of contents and the index.
5. Repeat calculations if time permits. Don't leave early.
6. Start guessing the answers if don't have enough time (25% probability of correct answers).
7. Review test book carefully
   - One student from the 2005 class missed to see an easy problem (similar to covered in this class) because some test book pages were "stuck" together.

PREPARING FOR THE P.E. EXAM: CHECKLIST (30 ITEMS)



Preparing for the PE Exam: A Basic Checklist

Michael Lindeburg, PE

Preparing for the PE exam is a formidable task. In fact, planning your preparation is an engineering feat in its own right! However, all successful examinees go through the same basic steps outlined here. Examinees who skip steps are often unsuccessful. The steps in the first half of the checklist are meant to be completed sequentially, one step at a time. As exam-day grows closer, you may want to "multitask" some of the steps in the second half of the list.

This checklist assumes that you have already applied to take the PE exam and that you have sufficient time to prepare for it.

1. Explain to family members and friends what you are doing and why it is important to your career that you pass the PE exam. Explain how long the process is going to take and what changes to your behavior and lifestyle might be noticed.

2. Spend a few minutes exploring the features in PPI's website so that you can return to it for more information as needed.

3. Thoroughly study the exam format and subject outline.

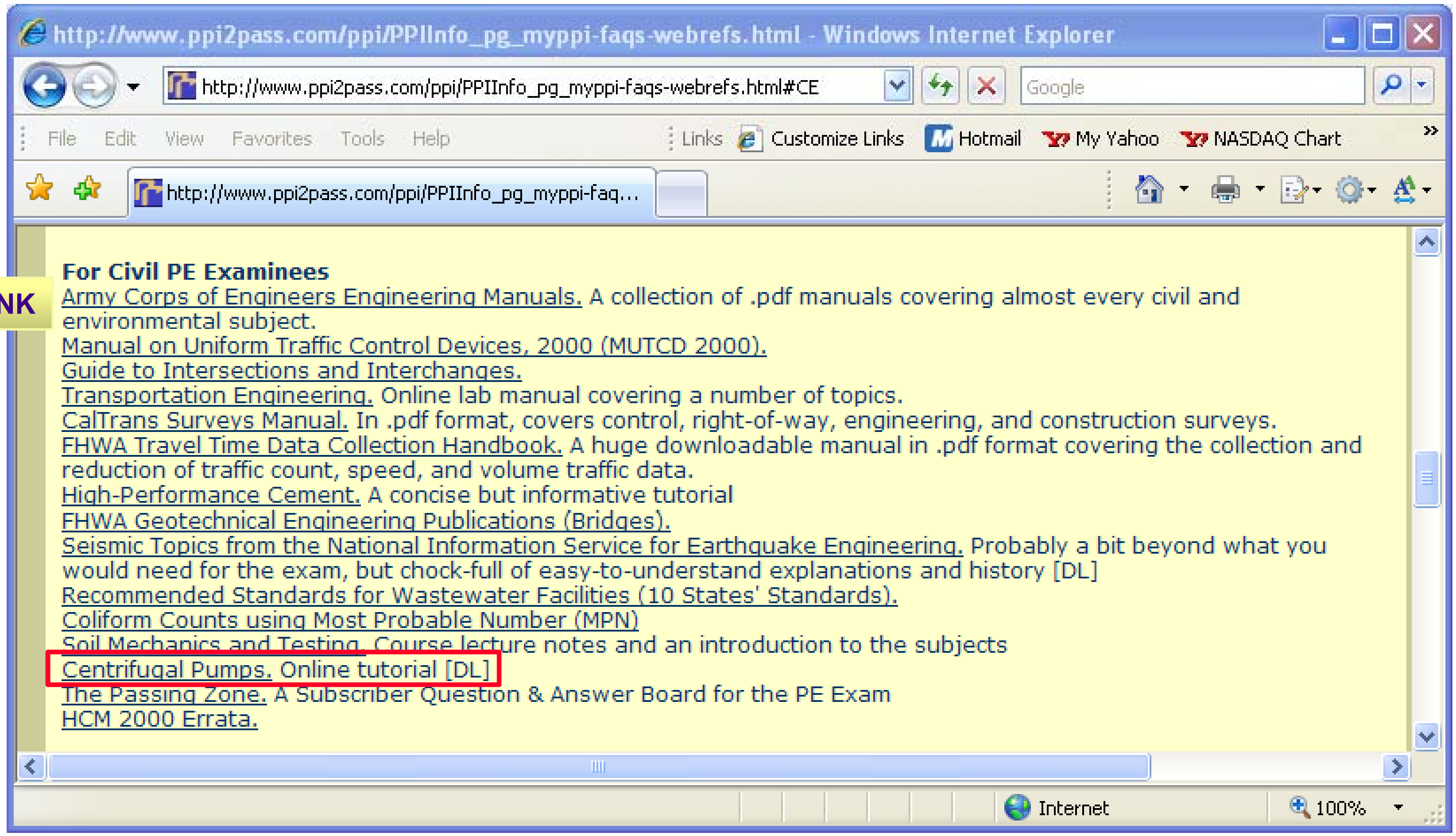
4. If you have a current PPI reference manual, read the introductory chapter for information about your exam and tips on how to prepare successfully for it. (If your manual isn't current, however, it may have information about a prior exam format, so it's best to check this online.)

www.ppi2pass.com/ppi/PPIInfo_pg_myppi-faqs-prepare.html

ONLINE RESOURCES

- Downloads from the Professional Publications Website
- www.ppi2pass.com/ppi/PPIInfo_pg_myppi-faqs-webrefs.html#CE
- Centrifugal pumps online tutorial

OBSOLETE LINK



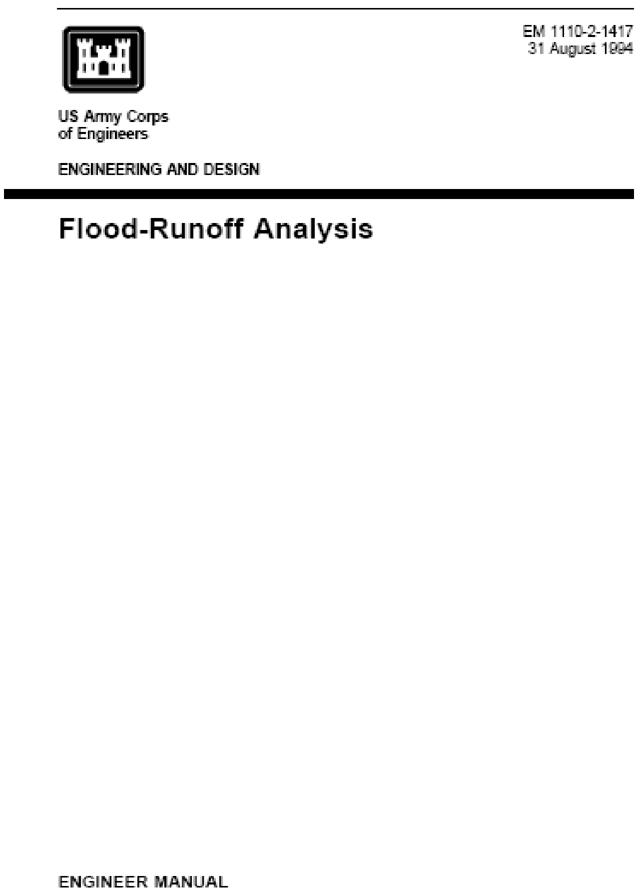
ONLINE RESOURCES

- **Current link for COE's engineering manuals**
- http://140.194.76.129/publications/eng-manuals

EM 1110-2-1413	089	CECW-EH-Y	Hydrologic Analysis of Interior Areas	15 Jan 87
EM 1110-2-1415	149	CECW-EH-Y	Hydrologic Frequency Analysis	05 Mar 93
EM 1110-2-1416	168	CECW-EH-Y	River Hydraulics	15 Oct 93
EM 1110-2-1417	213	CECW-EH-Y	Flood Run-off Analysis	31 Aug 94
EM 1110-2-1418	114	CECW-EH-D	Channel Stability Assessment for Flood Control Projects	31 Oct 94
EM 1110-2-1419	050	CECW-EH-Y	Hydrologic Engineering Requirements for Flood Damage Reduction Studies	31 Jan 95
EM 1110-2-1420	148	CECW-EH-Y	Hydrologic Engineering Requirements for Reservoirs	31 Oct 97
EM 1110-2-1421	121	CECW-EH	Groundwater Hydrology	28 Feb 99
EM 1110-2-1424 Change 1 Change 2	197	CECW-ET	Lubricant and Hydraulic Fluids	28 Feb 99 31 Jul 06 26 Oct 07
EM 1110-2-1601	080	CECW-EH-D	Hydraulic Design of Flood Control Channels Change 1 ENG 4794-R	30 Jun 94
EM 1110-2-1602	199	CECW-EH-D	Hydaulic Design of Reservoir Outlet Works	15 Oct 80
EM 1110-2-1603	169	CECW-EH-D	Hydraulic Design of Spillways	16 Jan 90
EM 1110-2-1604	196	CECW-CE	Hydraulic Design of Navigation Locks	01 May 06
EM 1110-2-1605	192	CECW-EH-D	Hydraulic Design of Navigation Dams	12 May 87
EM 1110-2-1606	014	CECW-EH-D	Hydraulic Design - Surges in Canals Change 1	01 Mar 49
EM 1110-2-1607	154	CECW-EH-D	Tidal Hydraulics	15 Mar 91
EM 1110-2-1610	058	CECW-EH-D	Hydraulic Design of Lock Culvert Valves	15 Aug 75

ONLINE RESOURCES

- **Link for COE's Flood Runoff Analysis Manual**
- http://140.194.76.129/publications/eng-manuals/em1110-2-1417/toc.htm
- Or download from the course Web site


EM 1110-2-1417
31 August 1994

US Army Corps
of Engineers

ENGINEERING AND DESIGN

Flood-Runoff Analysis

ENGINEER MANUAL


TABLE OF CONTENTS

Publication Number: **EM 1110-2-1417**
Title: **Engineering and Design - Flood-Runoff Analysis**
Proponent: **CECW-EH**
Publication Date: **31 August 1994**
Distribution Restriction Statement: **Approved for public release; distribution is unlimited.**
File Format: **Adobe Acrobat.pdf.** Adobe Acrobat Reader software is required to read portable document files (pdf). Click Viewers to access free Adobe Acrobat Reader software and follow installation instructions or go directly to the Adobe homepage at http://www.adobe.com.

Entire document (This file contains all elements of the document inclusive of appendices. File size: 2.5MB.)
Transmittal Letter
Table of Contents
Chapter 1 - Introduction
Chapter 2 - Introduction to Flood-Runoff Analysis
Chapter 3 - Study Formulation and Reporting
Chapter 4 - Rainfall Analysis
Chapter 5 - Snow Analysis
Chapter 6 - Infiltration/Loss Analysis
Chapter 7 - Precipitation Excess-Runoff Transformation
Chapter 8 - Subsurface Runoff Analysis
Chapter 9 - Streamflow and Reservoir Routing
Chapter 10 - Multisubbasin Modeling
Chapter 11 - Simplified Techniques
Chapter 12 - Frequency Analysis of Streamflow Data
Chapter 13 - Analysis of Storm Events
Chapter 14 - Period-of-Record Analysis
Chapter 15 - Data Colleciton and Management
Chapter 16 - Ungauged Basin Analysis
Chapter 17 - Development of Frequency-Based Estimates
Chapter 18 - Evaluating Change
Appendix A - References
Appendix B - Hydrologic Engineering Management Plan for Flood Damage Reduction Feasibility-Phase Studies

1. FLUID STATICS & FLOW

CONVERSION FACTORS

Length
1.0 mm = 0.1 cm = 0.03937 in. = 0.001 m
1.0 cm = 0.3937 in. = 0.03281 ft = 0.01 m
1.0 in. = 1000 milli-inch = 25.4 mm = 2.54 cm = 0.0833 ft = 0.0254 m
1.0 ft = 30.48 cm = 12 in. = 0.3333 yd = 0.3048 m
1.0 yd = 91.44 cm = 36 in. = 3.0 ft = 0.9144 m
1.0 m = 1000 mm = 100 cm = 3.28 ft = 1.094 yd
1.0 fathom = 72 in. = 6 ft = 1.83 m
1.0 km = 10^6 mm = 3280 ft = 1094 yd = 1000 m = 0.621 mi
1.0 mi = 5280 ft = 1760 yd = 1609 mm = 1.609 km

Area
1.0 cm^2 = 100 mm^2 = 0.155 $in.^2$ = 10^{-4} m^2
1.0 $in.^2$ = 6.45 cm^2 = 0.006944 ft^2
1.0 ft^2 = 929 cm^2 = 144 $in.^2$ = 0.1111 yd^2 = 0.0929 m^2
1.0 yd^2 = 8361 cm^2 = 1296 $in.^2$ = 9.0 ft^2 = 0.836 m^2
1.0 m^2 = 10^4 cm^2 = 1550 $in.^2$ = 10.76 ft^2 = 1.20 yd^2 = 0.01 ac
1.0 ac = 43,560 ft^2 = 4840 yd^2 = 4074 m^2 = 0.0015625 mi^2
1.0 ha = 107,600 ft^2 = 2.471 ac = 0.01 km^2 = 0.00386 mi^2
1.0 km^2 = 10^6 m^2 = 247 ac = 0.3861 mi^2
1.0 mi^2 = 27.9 x 10^6 ft^2 = 2.6 x 10^6 m^2 = 640 ac

Volume
1.0 cm^3 = 1.0 mL = 0.06102 $in.^3$ = 0.001 L
1.0 $in.^3$ = 16.39 cm^3 = 0.01639 L = 0.00433 gal
1.0 qt = 946.4 mL = 57.75 $in.^3$ = 0.9464 L = 0.25 gal
1.0 ft^3 = 28320 cm^3 = 1728 $in.^3$ = 28.32 L = 7.481 gal
1.0 m^3 = 10^6 mL = 1000 L = 264.2 gal = 35.31 ft^3 = 1.0 stere
1.0 ac-ft = 1,233,619 L = 325,900 gal = 43,560 ft^3 = 1233 m^3
1.0 mg = 3.78 x 10^6 L = 10^6 gal = 133,672 ft^3 = 3785 m^3 = 3.068 ac-ft

Force
1.0 lb = 7000 grains = 16 oz = 4.4482 Newton = 444,823 dynes
1.0 Newton (N) = 100,000 dynes = 0.2248 lb
1.0 ton = 2000 lb

Mass and weight-mass equivalents (in Earth gravity)
1.0 g = 1000 mg = 0.001 kg
1.0 kg = 1000 g = 0.0685 slug
1.0 slug = 14.594 kg
1.0 lb = 453.6 g = 0.4356 kg
1.0 kg = 2.204 lb
1.0 slug of mass = 14.59 kg = 32.174 lb

Time
1.0 d = 24 h = 1440 min = 86,400 s

Flow rates
1.0 gal/min = 63.08 mL/s = 1440 gal/d
1.0 L/s = 22,827 gal/d = 86.4 m^3/d = 15.85 gal/min
1.0 ac-ft/d = 325,872 gal/d = 226 gal/min = 14.28 L/s = 0.325 mgd
1.0 ft^3/s = 448.86 gal/min = 1.98 ac-ft/d = 0.646 mgd
1.0 mgd = 694 gal/min = 43.8 L/s = 3.07 ac-ft/d = 1.55 ft^3/s
1.0 m^3/s = 15,852 gal/min = 1000 L/s = 70 ac-ft/d = 22.8 mgd

Pressure–head relationships
1.0 ft of water = 62.4 lb/ft^2 = 22.4 mm of mercury = 0.4335 lb/$in.^2$ = 0.0295 atmosphere (atm)
1.0 in. of mercury = 70.5 lb/ft^2 = 3.38 kP = 1.133 ft of water = 0.490 lb/$in.^2$
1.0 lb/$in.^2$ = 6894 N/m^2 = 144 lb/ft^2 = 2.307 ft of water = 0.0680 atm = 6894 P = 6.89 kP
1.0 atm = 760 mm of mercury = 33.8995 ft of water = 29.92 in. of mercury = 14.696 lb/$in.^2$ = 101.3 kP

Energy and/or work
1.0 ft-lb = 13.6 × 10^6 dyne-cm = 1.356 J = 1.356 N-m = 0.324 cal = 0.00128 Btu
1.0 Btu = 252 cal = 1056 J = 0.293 W-h
1.0 hp-h = 1.98 × 10^6 ft-lb = 2546 Btu = 0.746 Kw-h = 2.68 X 10^6 J
1.0 kW-h = 3.6 × 10^6 J = 2.65 × 10^6 ft-lb = 1000 W-h = 1.341 hp-h

Power
1.0 W = 1.0 N-m = 1.0 J/s = 0.735 ft-lb/s = 0.057 Btu/min
1.0 hp = 33,000 ft-lb/min = 746 W = 550 ft-lb/s = 0.746 kW
1.0 kW = 1000 W = 1000 J/s =44,250 ft-lb/min = 56.8 Btu/min = 0.95 Btu/s

Concentration or dosage (assuming solution density = 1.0 g/cm^3)
1.0 ppm = 1.0 mg/L = 8.34 lb/million gal = 0.058 grain/gal
1.0 grain/gal = 17.1 mg/L

Specific weight and density of water
1.0 gal = 8.34 lb
1.0 ft^3 = 62.4 lb
1.0 L = 1.0 kg (mass) = 2.204 lb (weight)
1.0 mL = 1.0 g = 1000 mg
Mercury (Hg) is 13.58 times as dense or heavy as water.

ESSENTIAL DATA FLUID PROPERTIES

1. g_c = gravitational constant = $32.2 \dfrac{lbm - ft}{lbf - sec^2}$

2. R_{air} = specific gas constant for air = $53.3 \dfrac{ft - lbf}{lbm - {}^\circ R}$

3. Standard temperature = $32^\circ F$

4. Standard pressure = 14.7 psi (lb/in^2)
   = atmospheric pressure
   = 33.9 ft of water

5. $^\circ R = {}^\circ ABS = {}^\circ F + 460$

6. $^\circ C = ({}^\circ F - 32)\dfrac{5}{9}$

7. $^\circ F = 32 + \dfrac{9}{5}\,{}^\circ C$

8. k_{air} = specific heat ratio = 1.4

9. Specific gravity of water = SG = 1.0

10. ρ_w = density of water = 62.4 lbm/ft^3
    = 0.0361 lbm/in^3

11. ρ_{Hg} = density of mercury = 848.45 lbm/ft^3
    = 0.491 lbm/in^3

ESSENTIAL DATA FLUID PROPERTIES

(12) ρ_a = density of air = 0.075 lbm / ft³

(13) h (ft of liquid) = $\frac{\text{psi} \times 2.31}{SG_{liquid}}$ $\left(2.31 = \frac{144}{62.4}\right)$

h (ft of water) = psi × 2.31

h (ft of air) = psi × 1920

(14) Height of water = 1.136 × Height of mercury

$h_{water} = 1.136 \times h_{Hg}$

(15) $Q_{gpm} = Q_{cfs} \times 448.831$

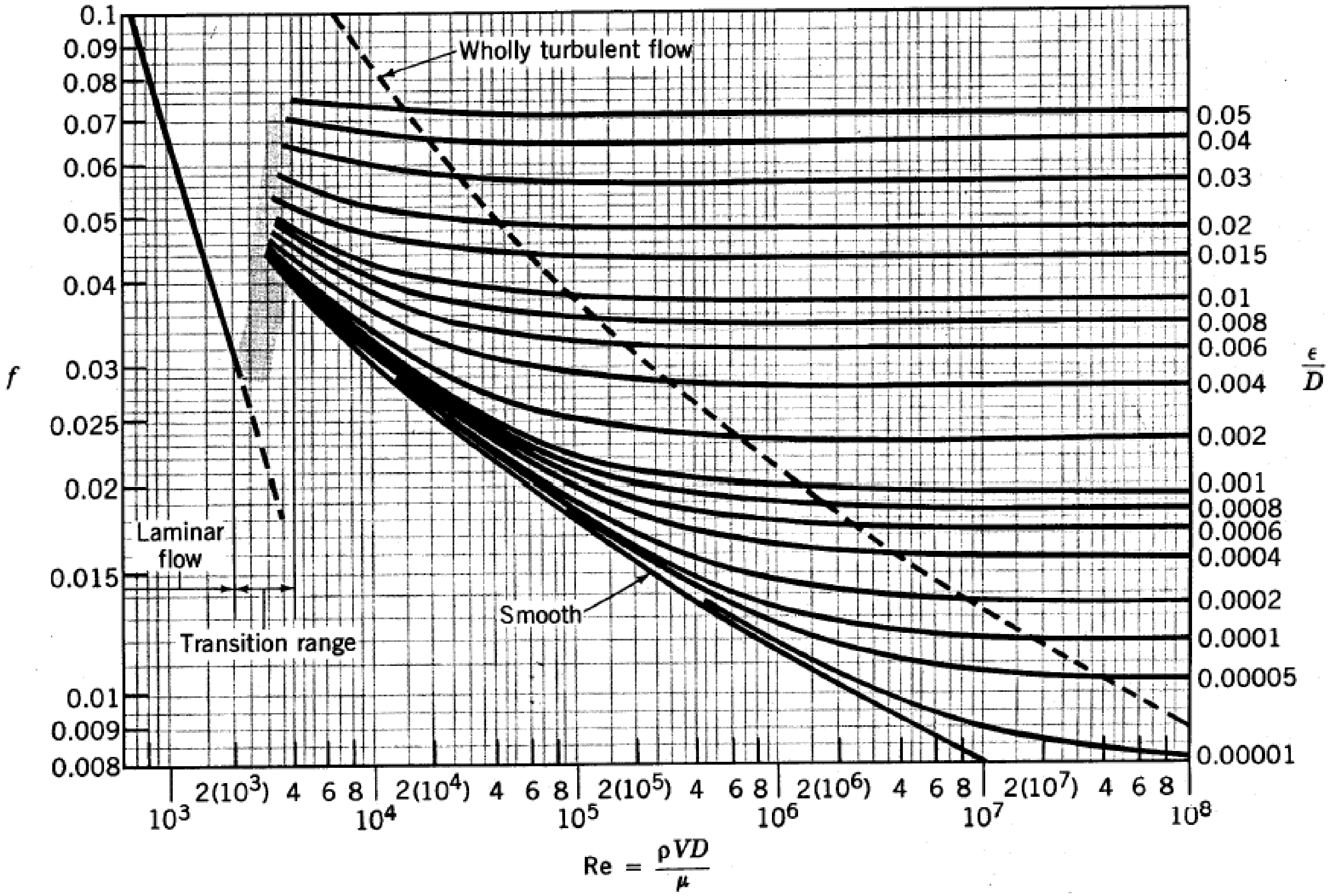
(16) Brake horse power = HP = $\frac{h \, \rho \, Q_{cfs}}{550 \, \eta}$

$= \frac{0.00025 \, h \, Q_{gpm}}{\eta}$

Where h = head added by pump
ρ = density of water.
η = pump efficiency (eta)

(17) γ_{water} = 0.0361 lbf / in³ specific weight
= 62.4 lbf / ft³

MOODY CHART: RELATIONSHIP BETWEEN FRICTION FACTOR (f), REYNOLDS NUMBER, AND RELATIVE ROUGHNESS FOR CIRCULAR PIPES



■ FIGURE 8.23 Friction factor as a function of Reynolds number and relative roughness for round pipes—the Moody chart (Data from Ref. 7 with permission).

METRIC TEMPERATURES

lamar.colostate.edu/~hillger/temps.htm

Temperature conversions between the three temperature scales:

kelvin / degree Celsius conversions (exact):

- kelvin = degree Celsius + 273.15
- degree Celsius = kelvin - 273.15

degree Fahrenheit / degree Celsius conversions (exact):

- degree F = degree C x 1.8 + 32.
- degree C = (degree F - 32.) / 1.8

Some baseline temperatures in the three temperature scales:

temperature	kelvin	degree Celsius	degree Fahrenheit
symbol	K	°C	°F
boiling point of water	373.15	100.	212.
melting point of ice	273.15	0.	32.
absolute zero	0.	-273.15	-459.67

Common temperature comparisons:

temperature	degree Celsius	degree Fahrenheit
symbol	°C	°F
boiling point of water	100.	212.
average human body temperature	37.	98.6
average room temperature	20. to 25.	68. to 77.
melting point of ice	0.	32.

ESSENTIAL FLUID MECHANICS TABLES AND CHARTS

From: Engineering Fluid Mechanics
Authors: John A. Roberson and C.T. Crowe

Paperback: 794 pages
Publisher: Jaico Publishing House (June 30, 2005)
ISBN-10: 817224780X
ISBN-13: 978-8172247805

GREEK LETTERS

GREEK LETTERS

α	...	Angular measure
α	...	Lapse rate
α	...	Kinetic energy coefficient
α	...	Angle of attack
β	...	Angular measure
β	...	Momentum coefficient
β	...	Intensive property
Γ	L^2/T	Circulation
γ	F/L^3	Specific weight
Δ	...	Increment
δ	L	Boundary-layer thickness
δ'	L	Laminar sublayer thickness
δ'_N	L	Nominal laminar sublayer thickness
η	...	Efficiency
θ	...	Angular measure
κ	...	Turbulence constant
μ	FT/L^2	Viscosity, dynamic
μ	...	Micro, multiple $= 10^{-6}$
τ	F/L^2	Shear stress
ν	L^2/T	Kinematic viscosity
π	...	3.14
ρ	FT^2/L^4	Mass density

ESSENTIAL FORMULAE: AREA AND VOLUME OF VARIOUS SHAPES

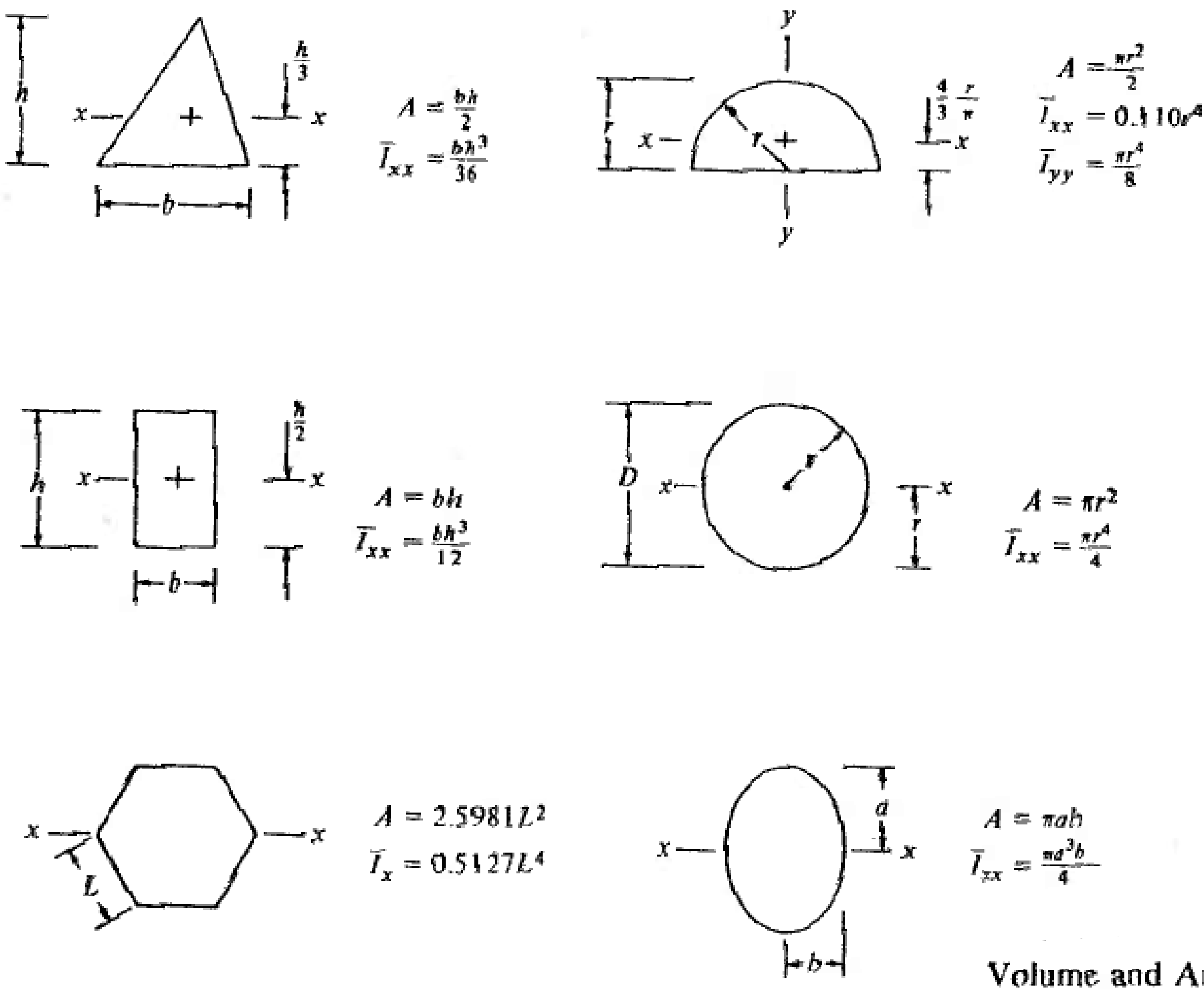


FIGURE A-1 Centroids and moments of inertia of plane areas.

Volume and Area Formulas:

$A_{circle} = \pi r^2 = \pi D^2/4$

$A_{sphere\ surface} = \pi D^2$

$\forall_{sphere} = \frac{1}{6}\pi D^3$

ABSOLUTE AND KINEMATIC VISCOSITIES

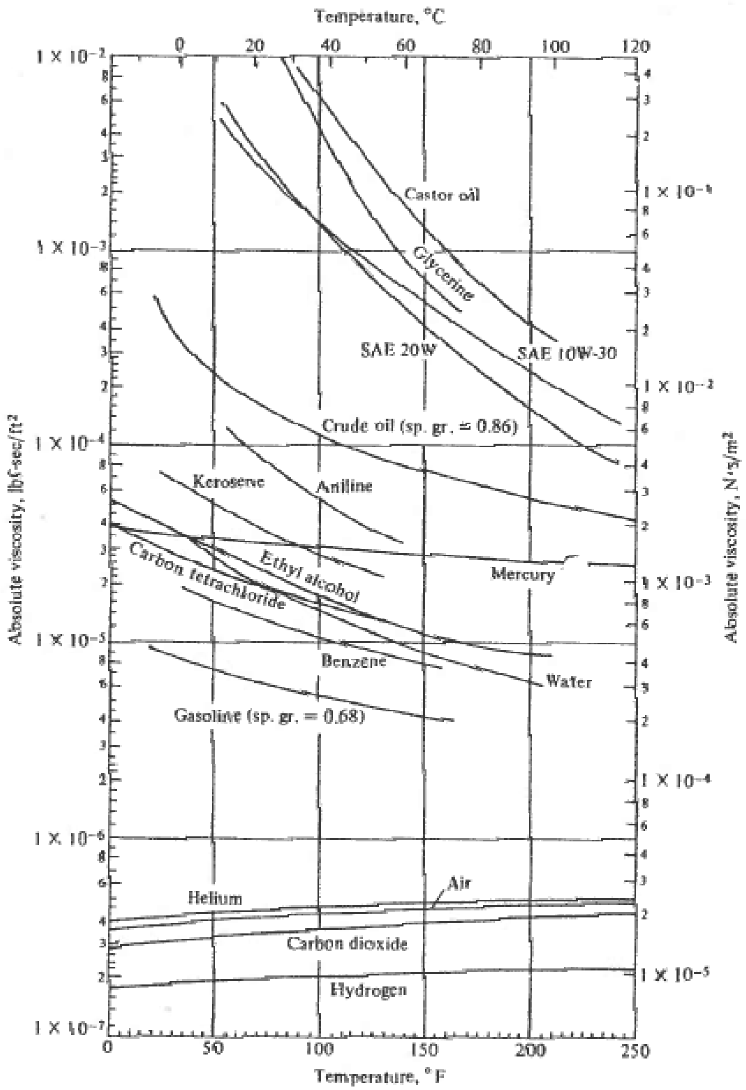


FIGURE A-2 Absolute viscosities of certain gases and liquids. [Adapted from *Fluid Mechanics*, 5th ed., by V. L. Streeter. Copyright © 1971, McGraw-Hill Book Company, New York. Used with permission of the McGraw-Hill Book Company.]

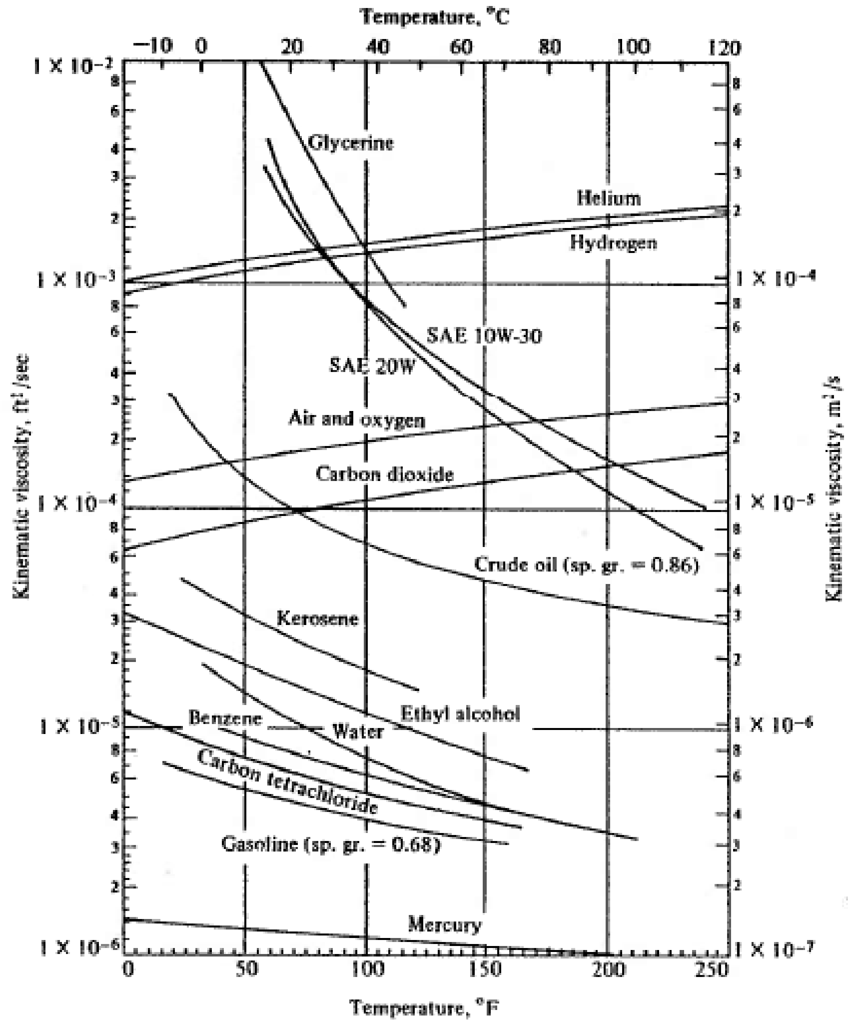


FIGURE A-3 Kinematic viscosities of certain gases and liquids. The gases are at standard pressure. [Adapted from *Fluid Mechanics*, 5th ed., by V. L. Streeter. Copyright © 1971, Mc-Graw Hill Book Company, New York. Used with permission of the McGraw-Hill Book Company.]

PHYSICAL PROPERTIES OF GASES

TABLE A-2 PHYSICAL PROPERTIES OF GASES AT STANDARD ATMOSPHERIC PRESSURE AND 15°C (59°F)

Gas	Density, kg/m³ (slug/ft³)	Kinematic viscosity, m²/s (ft²/sec)	R Gas constant, J/kg K (ft-lbf/slug-°R)	c_p $\frac{J}{kg\ K}$ $\left(\frac{Btu}{lbm\text{-}°R}\right)$	$k = \frac{c_p}{c_v}$
Air	1.22 (0.00237)	1.46×10^{-5} (1.58×10^{-4})	287 (1,716)	1,004 (0.240)	1.40
Carbon dioxide	1.85 (0.0036)	7.84×10^{-5} (8.48×10^{-4})	189 (1,130)	841 (0.201)	1.30
Helium	0.169 (0.00033)	1.14×10^{-4} (1.22×10^{-3})	2,077 (12,419)	5,187 (1.24)	1.66
Hydrogen	0.0851 (0.00017)	1.01×10^{-4} (1.09×10^{-3})	4,127 (24,677)	14,223 (3.40)	1.41
Methane (natural gas)	0.678 (0.0013)	1.59×10^{-5} (1.72 × 10[illegible])	518 (3,098)	2,208 (0.528)	1.31
Nitrogen	1.18 (0.0023)	1.45×10^{-5} (1.56×10^{-4})	297 (1,776)	1,041 (0.249)	1.40
Oxygen	1.35 (0.0026)	1.50×10^{-5} (1.61×10^{-4})	260 (1,555)	916 (0.219)	1.40

SOURCES: V. L. Streeter (ed.), *Handbook of Fluid Dynamics*, McGraw-Hill Book Company, New York, 1961; Also R. E. Bolz and G. L. Tuve, *Handbook of Tables for Applied Engineering Science*, CRC Press, Inc., Cleveland, 1973, *Handbook of Chemistry and Physics*, Chemical Rubber Company, 1951.

MECHANICAL PROPERTIES OF AIR

TABLE A-3 MECHANICAL PROPERTIES OF AIR AT STANDARD ATMOSPHERIC PRESSURE

Temperature		Density	Specific weight	Dynamic viscosity	Kinematic viscosity
		kg/m^3	N/m^3	$N \cdot s/m^2$	m^2/s
−20°C		1.40	13.7	1.61×10^{-5}	1.16×10^{-5}
−10°C		1.34	13.2	1.67×10^{-5}	1.24×10^{-5}
0°C		1.29	12.7	1.72×10^{-5}	1.33×10^{-5}
10°C		1.25	12.2	1.76×10^{-5}	1.41×10^{-5}
20°C		1.20	11.8	1.81×10^{-5}	1.51×10^{-5}
30°C		1.17	11.4	1.86×10^{-5}	1.60×10^{-5}
40°C		1.13	11.1	1.91×10^{-5}	1.69×10^{-5}
50°C		1.09	10.7	1.95×10^{-5}	1.79×10^{-5}
60°C		1.06	10.4	2.00×10^{-5}	1.89×10^{-5}
70°C		1.03	10.1	2.04×10^{-5}	1.99×10^{-5}
80°C		1.00	9.81	2.09×10^{-5}	2.09×10^{-5}
90°C		0.97	9.54	2.13×10^{-5}	2.19×10^{-5}
100°C		0.95	9.28	2.17×10^{-5}	2.29×10^{-5}
120°C		0.90	8.82	2.26×10^{-5}	2.51×10^{-5}
140°C		0.85	8.38	2.34×10^{-5}	2.74×10^{-5}
160°C		0.81	7.99	2.42×10^{-5}	2.97×10^{-5}
180°C		0.78	7.65	2.50×10^{-5}	3.20×10^{-5}
200°C		0.75	7.32	2.57×10^{-5}	3.44×10^{-5}
	lb/ft^3	$slugs/ft^3$	lbf/ft^3	$lbf\text{-}sec/ft^2$	ft^2/sec
0°F	.0865	0.00269	0.0866	3.39×10^{-7}	1.26×10^{-4}
20°F	.0827	0.00257	0.0828	3.51×10^{-7}	1.37×10^{-4}
40°F	.0795	0.00247	0.0794	3.63×10^{-7}	1.47×10^{-4}
60°F	.0762	0.00237	0.0764	3.74×10^{-7}	1.58×10^{-4}
80°F	.0733	0.00228	0.0735	3.85×10^{-7}	1.69×10^{-4}
100°F	.0708	0.00220	0.0709	3.96×10^{-7}	1.80×10^{-4}
120°F		0.00213	0.0685	2.47×10^{-7}	1.16×10^{-4}
150°F		0.00202	0.0651	4.23×10^{-7}	2.09×10^{-4}
200°F		0.00187	0.0601	4.48×10^{-7}	2.40×10^{-4}
300°F		0.00162	0.0522	4.96×10^{-7}	3.05×10^{-4}
400°F		0.00143	0.0462	5.40×10^{-7}	3.77×10^{-4}

SOURCE: Reprinted with permission from R. E. Bolz and G. L. Tuve, *Handbook of Tables for Applied Engineering Science*, CRC Press, Inc., Cleveland, 1973. Copyright 1973 by The Chemical Rubber Co., CRC Press, Inc.

PHYSICAL PROPERTIES OF LIQUIDS

TABLE A-4 APPROXIMATE PHYSICAL PROPERTIES OF COMMON LIQUIDS AT ATMOSPHERIC PRESSURE

Liquid and temperature	Density kg/m³ (slugs/ft³)	Specific gravity (sp. gr.) water at 4°C is ref.	Specific weight, N/m³ (lbf/ft³)	Dynamic viscosity, N · s/m² (lbf-sec/ft²)	Kinematic viscosity, m²/s (ft²/sec)	Surface tension, N/m* (lbf/ft)
Ethyl alcohol[1,3] 20°C (68°F)	799 (1.55)	0.79	7,850 (50.0)	1.2×10^{-3} (2.5×10^{-5})	1.5×10^{-6} (1.6×10^{-5})	2.2×10^{-2} (1.5×10^{-3})
Carbon tetrachloride[3] 20°C (68°F)	1,590 (3.09)	1.59	15,600 (99.5)	9.6×10^{-4} (2.0×10^{-5})	6.0×10^{-7} (6.5×10^{-6})	2.6×10^{-2} (1.8×10^{-3})
Glycerine[3] 20°C (68°F)	1,260 (2.45)	1.26	12,300 (78.5)	6.2×10^{-1} (1.3×10^{-2})	5.1×10^{-4} (5.3×10^{-3})	6.3×10^{-2} (4.3×10^{-3})
Kerosene[1,2] 20°C (68°F)	814 (1.58)	0.81	8,010 (51)	1.9×10^{-3} (4×10^{-5})	2.37×10^{-6} (2.55×10^{-5})	2.9×10^{-2} (2.0×10^{-3})
Mercury[1,3] 20°C (68°F)	13,550 (26.3)	13.55	133,000 (847)	1.5×10^{-3} (3.2×10^{-5})	1.2×10^{-7} (1.3×10^{-6})	4.8×10^{-1} (3.3×10^{-2})
Sea water 10°C at 3.3% salinity	1,026 (1.99)	1.03	10,070 (64.1)	1.4×10^{-3} (3×10^{-5})	1.4×10^{-6} (1.5×10^{-5})	
Oils—38°C (100°F)						
SAE 10W[4]	870 (1.69)	0.87	8,530 (54.4)	3.6×10^{-2} (7.4×10^{-4})	4.1×10^{-5} (4.4×10^{-4})	
SAE 10W-30[4]	880 (1.71)	0.88	8,630 (55.1)	6.7×10^{-2} (1.4×10^{-3})	7.6×10^{-5} (8.2×10^{-4})	
SAE 30[4]	880 (1.71)	0.88	8,630 (55.1)	1.0×10^{-1} (2.0×10^{-3})	1.1×10^{-4} (1.2×10^{-3})	

* Liquid-air surface tension values.

SOURCES: (1) V. L. Streeter, *Handbook of Fluid Dynamics*, McGraw-Hill Book Company, New York, 1961; (2) V. L. Streeter, *Fluid Mechanics*, 4th ed., McGraw-Hill Book Company, New York, 1966; (3) J. Vennard, *Elementary Fluid Mechanics*, 4th ed., John Wiley & Sons, Inc., New York, 1961; (4) R. E. Bolz and G. L. Tuve, *Handbook of Tables for Applied Engineering Science*, CRC Press, Inc., Cleveland, 1973.

PHYSICAL PROPERTIES OF WATER

TABLE A-5 APPROXIMATE PHYSICAL PROPERTIES OF WATER* AT ATMOSPHERIC PRESSURE

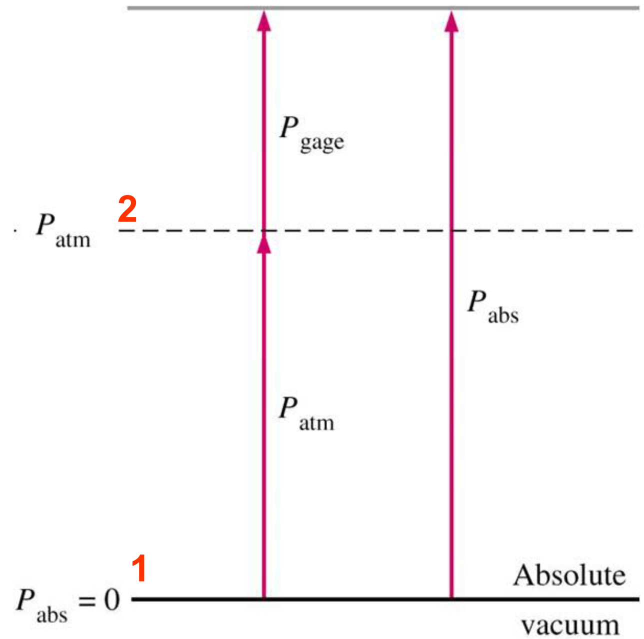
Temperature	Density	Specific weight	Dynamic viscosity	Kinematic viscosity	Vapor pressure
	kg/m³	N/m³	N · s/m²	m²/s	N/m² abs.
0°C	1,000	9,810	1.79×10^{-3}	1.79×10^{-6}	611
5°C	1,000	9,810	1.51×10^{-3}	1.51×10^{-6}	872
10°C	1,000	9,810	1.31×10^{-3}	1.31×10^{-6}	1,230
15°C	999	9,800	1.14×10^{-3}	1.14×10^{-6}	1,700
20°C	998	9,790	1.00×10^{-3}	1.00×10^{-6}	2,340
25°C	997	9,781	8.91×10^{-4}	8.94×10^{-7}	3,170
30°C	996	9,771	7.96×10^{-4}	7.99×10^{-7}	4,250
35°C	994	9,751	7.20×10^{-4}	7.24×10^{-7}	5,630
40°C	992	9,732	6.53×10^{-4}	6.58×10^{-7}	7,380
50°C	988	9,693	5.47×10^{-4}	5.54×10^{-7}	12,300
60°C	983	9,643	4.66×10^{-4}	4.74×10^{-7}	20,000
70°C	978	9,594	4.04×10^{-4}	4.13×10^{-7}	31,200
80°C	972	9,535	3.54×10^{-4}	3.64×10^{-7}	47,400
90°C	965	9,467	3.15×10^{-4}	3.26×10^{-7}	70,100
100°C	958	9,398	2.82×10^{-4}	2.94×10^{-7}	101,300
lb sec²/ft⁴	slugs/ft³	lbf/ft³	lbf-sec/ft²	ft²/sec	psia
40°F	1.94	62.43	3.23×10^{-5}	1.66×10^{-5}	0.122
50°F	1.94	62.40	2.73×10^{-5}	1.41×10^{-5}	0.178
60°F	1.94	62.37	2.36×10^{-5}	1.22×10^{-5}	0.256
70°F	1.94	62.30	2.05×10^{-5}	1.06×10^{-5}	0.363
80°F	1.93	62.22	1.80×10^{-5}	0.930×10^{-5}	0.506
100°F	1.93	62.00	1.42×10^{-5}	0.739×10^{-5}	0.949
120°F	1.92	61.72	1.17×10^{-5}	0.609×10^{-5}	1.69
140°F	1.91	61.38	0.981×10^{-5}	0.514×10^{-5}	2.89
160°F	1.90	61.00	0.838×10^{-5}	0.442×10^{-5}	4.74
180°F	1.88	60.58	0.726×10^{-5}	0.385×10^{-5}	7.51
200°F	1.87	60.12	0.637×10^{-5}	0.341×10^{-5}	11.53
212°F	1.86	59.83	0.593×10^{-5}	0.319×10^{-5}	14.70

* Notes: (1) Bulk modulus E_v of water is approximately 2.2 G P_a (3.2×10^5 psi); (2) Water-air surface tension is approximately 7.3×10^{-2} N/m (5×10^{-3} lbf/ft) from 10°C to 50°C.

CHAPTER 14
FLUID PROPERTIES

FLUID PRESSURE

- Definition: Force of a fluid per unit area
- Equation: p = F / A
- Units
  - US: Pounds per square inch (psi) or lbf/in^2
  - SI: Pascals (Pa) and Kilopascals (kPa)
    - SI = Système International (International System)
  - 1 Pa = 1 N/m^2
- Measured with respect to two references:
  1. Zero pressure: called absolute pressure (p_a)
  2. Atmospheric pressure: called gage pressure (p_g)
  - $P_a = p_g + p_{atm}$ … 14.1
- Hydrostatic Pressure: Pressure exerted by a fluid on an immersed object or container walls



STANDARD TEMPERATURE AND PRESSURE

- Temperature units
  - US:°F, SI:°K (Kelvin) or °C, English:°R (Rankine)
  - R = F + 459.69
  - K = C + 273.15
  - F = (C x 1.8) + 32
- Standard room temperature = 68°F = 20°C
- From Table 14.1,
  standard atmospheric pressure = 1.000 atm (atmosphere)
  = 14.696 psia (absolute)
  = 101.3 kPa
  = 33.93 ft of water
  = 29.921 in of Hg
  = 1.013 bars
- Standard Temperature and Pressure (STP) - Table 14.3
  - US: 32°F and 14.696 psia
  - SI: 273.15°K and 101.325 kPa

DENSITY OR MASS DENSITY

- Definition: Mass of a fluid per unit volume
- Equation: ρ (rho) = m / V
- Units
  - US: lbm/ft^3 or $slugs/ft^3$
  - SI: Kg/m^3
- $\rho_{water} = 62.4\ lbm/ft^3$ or $1000\ Kg/m^3$ at room temperature (Table 14.2)
- Density of an ideal gas $= \rho = \dfrac{p}{RT}$ *Ideal Gas Law* ⋯ 14.5
  - T = Absolute temperature °R (Rankine)
  - R = Specific Gas Constant (Appendix 24.B) $53.35 = \dfrac{\text{ft} - \text{lbf}}{\text{lbm} - °\text{R}}$ for air at 100°F

SPECIFIC VOLUME & SPECIFIC GRAVITY

- Specific Volume: Reciprocal of density
  - $v = 1 / \rho$ … 14.6
- Specific Gravity: ratio of fluid density to some standard reference density (pure water)

$$SG_{\text{liquid}} = \frac{\rho_{\text{liquid}}}{\rho_{\text{water}}} \qquad \cdots 14.7$$

$$SG_{\text{gas}} = \frac{\rho_{gas}}{\rho_{\text{air}}} \qquad \cdots 14.8$$

SPECIFIC WEIGHT

- Definition: Weight of a fluid per unit volume
  - γ (gamma) = $\rho \times g$ [SI] … 14.14a
  - $\gamma = \rho \times (g/g_c)$ [US] … 14.14b

    g_c is always on opposite side of ρ
    - g = gravitational acceleration = 32.2 ft/sec^2
    - g_c = gravitational conversion constant = 32.174 lbm-ft/lbf-sec^2
  - Units of γ: lbf/ft^3
- Because at most places $g = g_c$, from Eq. 14.14b: $\gamma = \rho$
  - *Detailed discussion on g vs. g_c: Chapter 1, Section 6, "The English Engineering System."*
- γ_{water} = 62.4 lbf/ft^3 at room temperature (Table 14.2)

  = 62.4 / (12 × 12 × 12) = 0.0361 lbf/in^3

VISCOSITY

- Definition: a measure of a fluid's resistance to flow when acted upon by an external force such as, pressure or gravity
- Viscous fluids: Jelly, syrup, heavy oils
- Higher the temperature, lower the viscosity, easier the fluid flow.
- Viscosity is expressed by μ (mu) = Absolute Viscosity (also known as coefficient of viscosity) in lbf-sec/ft^2
- Kinematic Viscosity ν (nu): Ratio of absolute viscosity to mass density

$$\nu = \frac{\mu}{\rho} \qquad [SI] \cdots \; 14.19a$$

$$\nu = \frac{\mu . g_c}{\rho} \qquad [US] \cdots \; 14.19b$$

g_c is always on opposite side of ρ

CHAPTER 15
FLUID STATICS

RELATIONSHIP BETWEEN PRESSURE AND DEPTH

- Pressure varies linearly with depth

$$p = \rho g h \qquad [SI] \cdots 15.7a$$

$$= \frac{\rho g h}{g_c} = \gamma h \qquad [US] \cdots 15.7b$$

g_c is always on opposite side of ρ

Where h = depth of fluid = hydrostatic head

- Barometer: An example of measurement of pressure by the height of a fluid column
- If atmospheric pressure = p_a
  vapor pressure of barometer liquid = p_v

$$p_a - p_v = \rho g h = \gamma h \quad (\because \gamma = \rho g \ \textit{from Eq.14.14a}) \qquad [SI] \cdots 15.10a$$

$$= \frac{\rho g h}{g_c} = \gamma h \quad (\because \gamma = \frac{\rho g}{g_c} \ \textit{from Eq.14.14b}) \qquad [US] \cdots 15.10b$$

EXAMPLE 15.2: PRESSURE-DEPTH

- **A vacuum pump is used to drain a flooded mine shaft of 68°F (20°C) water. The vapor pressure of water at this temperature is 0.34 psi (2.34 kPa). The pump is incapable of lifting the water higher than 400 in (10.16 m). What is the atmospheric pressure?**
- **Given Data:**
  - Fluid = water
  - T = 68°F (20°C)
  - p_v = 0.34 psi (2.34 kPa)
  - h = 400 in (10.16 m)
- Standard (Known) Data:
  - γ = 0.0361 lbf/in^3 (Table 14.2 or 15.2)
- **Calculate (?)**
  - Atmospheric pressure = p_a
- **Solution:**
  - From Eq. 15.10b, $p_a = p_v + \gamma h = 0.34 + (0.0361 \times 400) =$ **14.78 lbf/in^2 (psia)**

    ANSWER

CHAPTER 16
FLUID FLOW PARAMETERS

FLUID ENERGY

- Three forms:
  - Kinetic
  - Potential
  - Pressure

1. Kinetic Energy: Energy required to accelerate a fluid to velocity v

$$E_v = \frac{v^2}{2.g_c} = \frac{(\text{ft/sec})^2}{(\text{lbm} - \text{ft/lbf - sec}^2)} \qquad [\text{US}] \cdots \; 16.3\text{b}$$

h_v = velocity head or dynamic head = kinetic energy in units of feet

2. Potential Energy: Energy required to raise a fluid to an elevation z.

$$E_z = \frac{z.g}{g_c} = \frac{\text{ft - lbf}}{\text{lbm}} \qquad [\text{US}] \cdots \; 16.5\text{b}$$

h_z = potential or gravitational head = potential energy in units of feet

∵ (Because) at most places, $g = g_c = 32.2 \text{ ft/sec}^2$

∴ (therefore) $E_z = z$

FLUID ENERGY

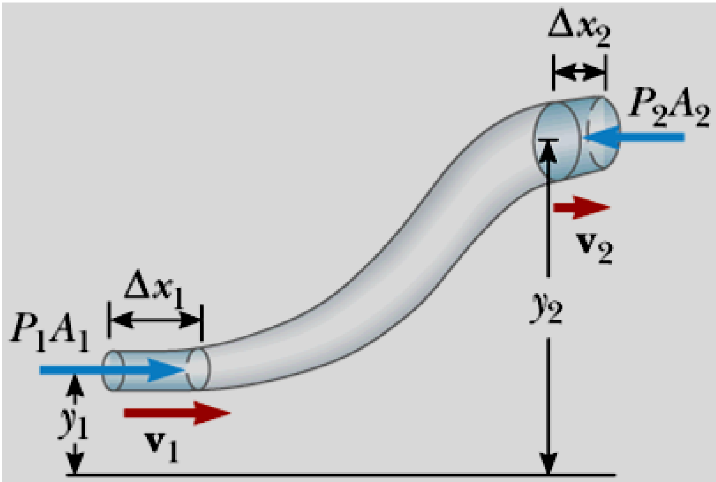
3. Pressure Energy: Energy required to raise a fluid to pressure p

$$E_p = \frac{p}{\rho} = \frac{\text{lbf / ft}^2}{\text{lbm / ft}^3} = \frac{\text{ft - lbf}}{\text{lbm}} \qquad \text{[US]} \cdots \ 16.6$$

h_p = pressure head or static head = pressure energy in units of feet

BERNOULLI EQUATION

- The total energy of a fluid flowing without friction losses in a pipe is constant.
  - An energy conservation equation



$$E_t = E_v + E_z + E_p \qquad \cdots \quad 16.10$$

$$= \frac{v^2}{2g_c} + \frac{z.g}{g_c} + \frac{p}{\rho} \qquad \cdots \quad 16.11b$$

$$= \frac{v^2}{2g_c} + z + \frac{p}{\rho}$$

- Because total energy cannot change between points 1 and 2

$$\frac{p_1}{\rho} + \frac{v_1^{\,2}}{2g_c} + z_1 = \frac{p_2}{\rho} + \frac{v_2^{\,2}}{2g_c} + z_2$$

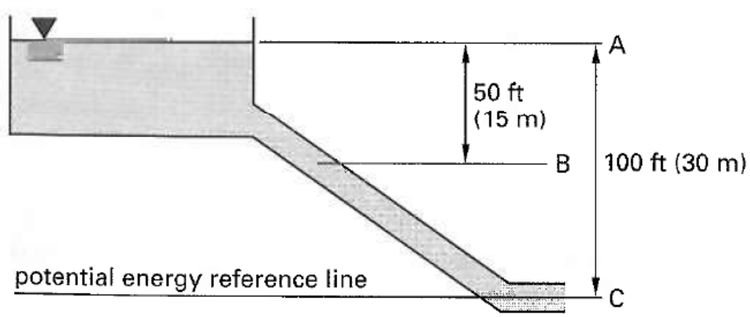
if losses are present;

$$\frac{p_1}{\rho} + \frac{v_1^{\,2}}{2g_c} + z_1 = \frac{p_2}{\rho} + \frac{v_2^{\,2}}{2g_c} + z_2 + losses \quad \cdots \quad \textit{Extended Bernoulli Equation } 17.64$$

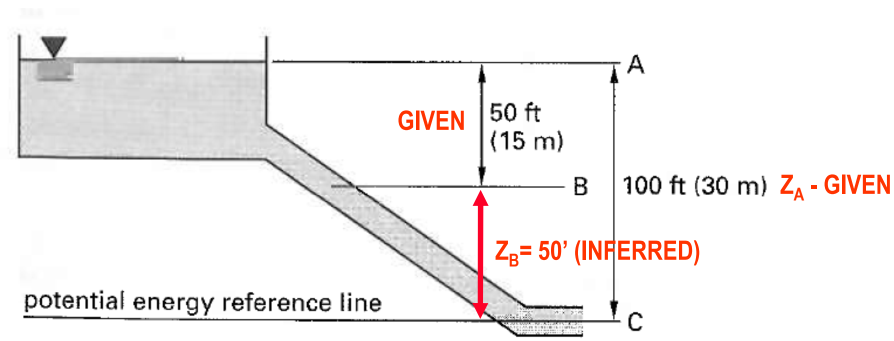
EXAMPLE 16.1: BERNOULLI EQUATION

Example 16.1

A pipe draws water from the bottom of a reservoir and discharges it freely at point C, 100 ft (30 m) below the surface. The flow is frictionless. (a) What is the total specific energy at an elevation 50 ft (15 m) below the water surface (i.e., point B)? (b) What is the velocity at point C?



- **Given Data:**
  - Z_A = 100 ft (Assume Z = 0 at C or Z_c = 0)
  - Z_B = 50 ft



- **Calculate (?)**
  - Total energy at B = E_B
  - Velocity at C = v_c
- **Solution:**
  - At Point A:

    p_A = 0 (open to air; gage pressure is zero)

    v_A=0 (water is not flowing; no head – no velocity)

$$E_A = \frac{p_A}{\rho} + \frac{v_A^{\ 2}}{2g_c} + z_A = 0 + 0 + 100 = 100\ ft$$

From Bernoulli Eqn., $E_B = E_A = \boxed{100\text{ ft}}$ ANSWER 1

EXAMPLE 16.1: BERNOULLI EQUATION

- At Point C:
  p_C = 0 (discharge at atmospheric pressure)
  z_c=0 (since z = 0 at C)

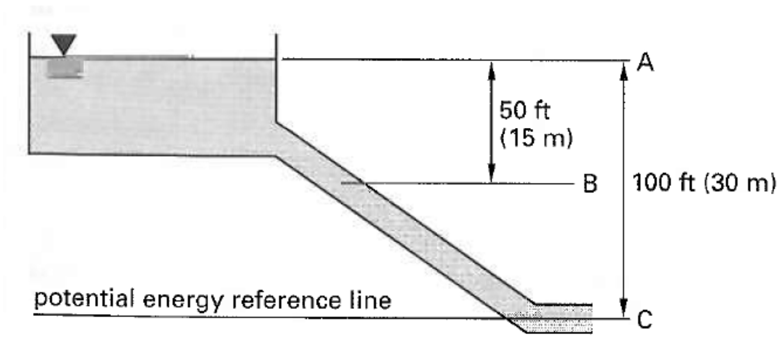
$$E_C = \frac{p_C}{\rho} + \frac{v_C^{\,2}}{2g_c} + z_C = 100$$

$$0 + \frac{v_C^{\,2}}{2g_c} + 0 = 100$$

$$V_C^2 = 2 \times 32.2 \times 100$$

$$V_C = \boxed{80.2 \quad ft/\sec}$$

ANSWER 2



ENERGY GRADE LINE (EGL)

- EGL: A graph of total energy versus position along the conduit length
- Elevation of EGL = $h_p + h_v + h_z$ … Eq. 16.33
- For a frictionless pipe without pumps, EGL will be constant (horizontal)
- Hydraulic Grade Line (HGL): A graph of sum of pressure and gravitational heads versus position along the conduit length
- Elevation of HGL = $h_p + h_z$ … Eq. 16.34
  - Not always horizontal
- By comparing Eqs. 16.33 and 16.34:
  h_v = elevation of EGL – elevation of HGL … Eq. 16.35

EQUIVALENT DIAMETER: D_e

- Equivalent diameter of a conduit of a given cross section (shape) is the diameter of a circular pipe that gives the same pressure loss.
- For a circular pipe flowing full, D_e = inside diameter of pipe.
- For other cross sections: use Table 16.1

Table 16.1 Equivalent Diameters for Common Conduit Shapes

conduit cross section	D_e
flowing full	
annulus (outer diameter D_o, inner diameter D_i)	$D_o - D_i$
square (side L)	L
rectangle (sides L_1 and L_2)	$\frac{2L_1L_2}{L_1 + L_2}$
flowing partially full	
half-filled circle (diameter D)	D
rectangle (h deep, L wide)	$\frac{4hL}{L + 2h}$
wide, shallow stream (h deep)	$4h$
triangle (h deep, L broad, s side)	$\frac{hL}{s}$
trapezoid (h deep, a wide at top, b wide at bottom, s side)	$\frac{2h(a + b)}{b + 2s}$

HYDRAULIC RADIUS: r_h

- Area in flow divided by wetted perimeter

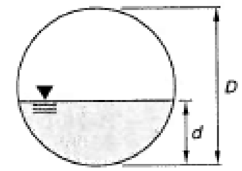
$$r_h = \frac{A}{s} \qquad \cdots \; 16.18$$

For a pipe flowing full or half full:

$$r_h = \frac{\pi r^2}{2\pi r} = \frac{r}{2} = \frac{D}{4} \qquad \cdots \; 16.19$$

- For other flow depths: use Appendix 16.A
- Relationship between D_e and r_h: $D_e = 4\, r_h \qquad \ldots \; 16.20$

APPENDIX 16.A
Area, Wetted Perimeter, and Hydraulic Radius of Partially Filled Circular Pipes

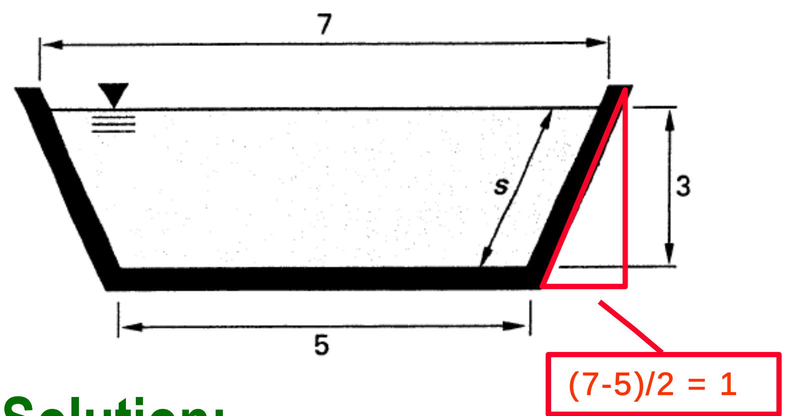


$\frac{d}{D}$	$\frac{\text{area}}{D^2}$	$\frac{\text{wetted perimeter}}{D}$	$\frac{r_h}{D}$	$\frac{d}{D}$	$\frac{\text{area}}{D^2}$	$\frac{\text{wetted perimeter}}{D}$	$\frac{r_h}{D}$
0.01	0.0013	0.2003	0.0066	0.51	0.4027	1.5908	0.2531
0.02	0.0037	0.2838	0.0132	0.52	0.4127	1.6108	0.2561
0.03	0.0069	0.3482	0.0197	0.53	0.4227	1.6308	0.2591
0.04	0.0105	0.4027	0.0262	0.54	0.4327	1.6509	0.2620
0.05	0.0147	0.4510	0.0326	0.55	0.4426	1.6710	0.2649
0.06	0.0192	0.4949	0.0389	0.56	0.4526	1.6911	0.2676
0.07	0.0242	0.5355	0.0451	0.57	0.4625	1.7113	0.2703
0.08	0.0294	0.5735	0.0513	0.58	0.4723	1.7315	0.2728
0.09	0.0350	0.6094	0.0574	0.59	0.4822	1.7518	0.2753
0.10	0.0409	0.6435	0.0635	0.60	0.4920	1.7722	0.2776
0.11	0.0470	0.6761	0.0695	0.61	0.5018	1.7926	0.2797
0.12	0.0534	0.7075	0.0754	0.62	0.5115	1.8132	0.2818
0.13	0.0600	0.7377	0.0813	0.63	0.5212	1.8338	0.2839
0.14	0.0688	0.7670	0.0871	0.64	0.5308	1.8546	0.2860
0.15	0.0739	0.7954	0.0929	0.65	0.5404	1.8755	0.2881
0.16	0.0811	0.8230	0.0986	0.66	0.5499	1.8965	0.2899
0.17	0.0885	0.8500	0.1042	0.67	0.5594	1.9177	0.2917
0.18	0.0961	0.8763	0.1097	0.68	0.5687	1.9391	0.2935
0.19	0.1039	0.9020	0.1152	0.69	0.5780	1.9606	0.2950
0.20	0.1118	0.9273	0.1206	0.70	0.5872	1.9823	0.2962
0.21	0.1199	0.9521	0.1259	0.71	0.5964	2.0042	0.2973
0.22	0.1281	0.9764	0.1312	0.72	0.6054	2.0264	0.2984
0.23	0.1365	1.0003	0.1364	0.73	0.6143	2.0488	0.2995
0.24	0.1449	1.0239	0.1416	0.74	0.6231	2.0714	0.3006
0.25	0.1535	1.0472	0.1466	0.75	0.6318	2.0944	0.3017
0.26	0.1623	1.0701	0.1516	0.76	0.6404	2.1176	0.3025
0.27	0.1711	1.0928	0.1566	0.77	0.6489	2.1412	0.3032
0.28	0.1800	1.1152	0.1614	0.78	0.6573	2.1652	0.3037
0.29	0.1890	1.1373	0.1662	0.79	0.6655	2.1895	0.3040
0.30	0.1982	1.1593	0.1709	0.80	0.6736	2.2143	0.3042
0.31	0.2074	1.1810	0.1755	0.81	0.6815	2.2395	0.3044
0.32	0.2167	1.2025	0.1801	0.82	0.6893	2.2653	0.3043
0.33	0.2260	1.2239	0.1848	0.83	0.6969	2.2916	0.3041
0.34	0.2355	1.2451	0.1891	0.84	0.7043	2.3186	0.3038
0.35	0.2450	1.2661	0.1935	0.85	0.7115	2.3462	0.3033
0.36	0.2546	1.2870	0.1978	0.86	0.7186	2.3746	0.3026
0.37	0.2642	1.3078	0.2020	0.87	0.7254	2.4038	0.3017
0.38	0.2739	1.3284	0.2061	0.88	0.7320	2.4341	0.3008
0.39	0.2836	1.3490	0.2102	0.89	0.7384	2.4655	0.2995
0.40	0.2934	1.3694	0.2142	0.90	0.7445	2.4981	0.2980
0.41	0.3032	1.3898	0.2181	0.91	0.7504	2.5322	0.2963
0.42	0.3130	1.4101	0.2220	0.92	0.7560	2.5681	0.2944
0.43	0.3229	1.4303	0.2257	0.93	0.7612	2.6061	0.2922
0.44	0.3328	1.4505	0.2294	0.94	0.7662	2.6467	0.2896
0.45	0.3428	1.4706	0.2331	0.95	0.7707	2.6906	0.2864
0.46	0.3527	1.4907	0.2366	0.96	0.7749	2.7389	0.2830
0.47	0.3627	1.5108	0.2400	0.97	0.7785	2.7934	0.2787
0.48	0.3727	1.5308	0.2434	0.98	0.7816	2.8578	0.2735
0.49	0.3827	1.5508	0.2467	0.99	0.7841	2.9412	0.2665
0.50	0.3927	1.5708	0.2500	1.00	0.7854	3.1416	0.2500

EXAMPLE 16.5: EQUIVALENT DIAMETER

Example 16.5

Determine the equivalent diameter and hydraulic radius for the open trapezoidal channel shown.



- **Given Data:**
  - Flow type = open channel
  - Shape = trapezoidal
  - Top width, a = 7
  - Bottom width, b = 5
  - Depth, h = 3
- **Calculate (?):**
  - Equivalent diameter, D_e
  - Hydraulic radius, r_h

- **Solution:**
  - Base of the triangle = (7-5)/2 = 1
  - Channel side = s = $\sqrt{(3^2+1^2)} = 3.16$
  - From Table 16.1:

$$D_e = \frac{2h(a+b)}{b+2s} = \frac{2\times 3\times(7+5)}{5+2\times 3.16} = \boxed{6.36}$$

ANSWER 1

  - From Eq. 16.20:

$$r_h = \frac{D_e}{4} = \frac{6.36}{4} = \boxed{1.59}$$

ANSWER 2

REYNOLDS NUMBER: R_e

- A dimensionless number interpreted as the ratio of inertial forces to viscous forces in the fluid
- R_e = (inertial forces / viscous forces) … 16.21
- Inertial forces are due to momentum of flow
- Inertial forces are proportional to:
  - Flow diameter (D_e)
  - Velocity (v)
  - Density (ρ)
- Viscous forces are proportional to:
  - Absolute viscosity (μ) (mu)
- Therefore,
- Laminar flow: Re < 2,100
- Turbulent flow: Re > 4,000
- Critical flow: 2,100 < Re < 4,000
  - More in Chapter 19 (Open Channel Flow)

$$R_e = \frac{D_e v \rho}{\mu} \quad \text{[SI]} \cdots \; 16.22a$$

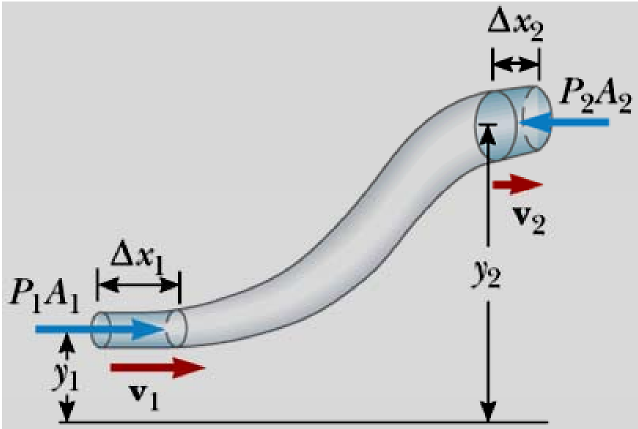
$$= \frac{D_e v \rho}{g_c \mu} \quad \text{[US]} \cdots \; 16.22b$$

$$\text{Since } \nu = \text{kinematic viscosity} = \frac{\mu g_c}{\rho}$$

$$R_e = \frac{D_e v}{\nu} \quad \cdots \; 16.23$$

CHAPTER 17
FLUID DYNAMICS

CONSERVATION OF MASS



- Fluid mass is always conserved
- $\dot{m}_1 = \dot{m}_2$ … 17.1
- For fluid flow, conservation of mass law is known as Continuity Equation

  $\rho_1.A_1.v_1 = \rho_2.A_2.v_2$ … 17.2

  A = Area

  v = Velocity
- If fluid is incompressible, $\rho_1 = \rho_2$

  $A_1.v_1 = A_2.v_2$ … 17.3
- Or, $\dot{v}_1 = \dot{v}_2$ … 17.4

  $\dot{v}$ = Q = volumetric flow rate or flow rate

  units: cfs (cubic-ft/sec) or MGD (million gallons / day)
- Or, $Q_1 = Q_2$ ($\because$ Q = A.v)

CONSERVATION OF ENERGY

- Extended Bernoulli Equation
- $(E_p + E_v + E_z)_1 + E_A = (E_p + E_v + E_z)_2 + E_E + E_f + E_m$ … 17.64

  E_p = pressure energy

  E_v = kinetic energy

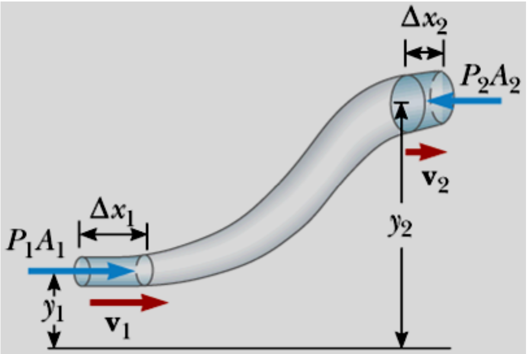
  E_z = potential energy

  E_A = Energy (or head) added by a pump

  E_E = Energy (or head) extracted by a turbine

  E_f = Energy (or head) extracted by friction

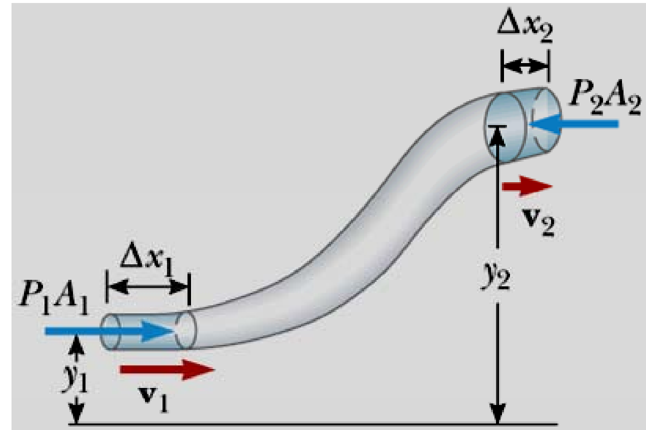
  E_m = Energy (or head) extracted by minor losses (e.g., fittings and bends)



$$\frac{p_1}{\rho} + \frac{v_1^{\,2}}{2g_c} + z_1\frac{g}{g_c} + E_A = \frac{p_2}{\rho} + \frac{v_2^{\,2}}{2g_c} + z_2\frac{g}{g_c} + E_E + E_f + E_m \cdots \quad 17.65b$$

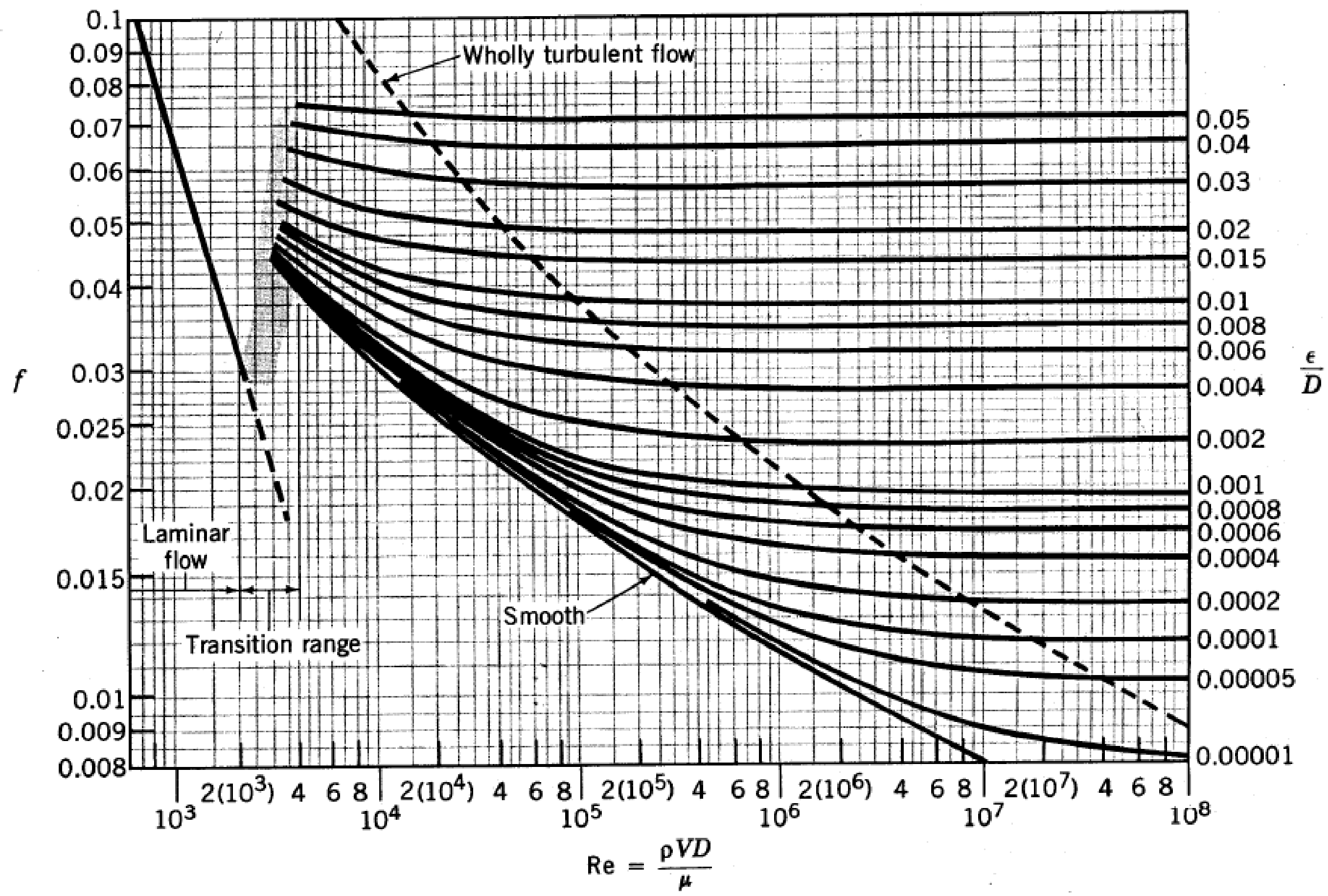
HEAD LOSS DUE TO FRICTION

- Loss in energy or head due to friction
- $E_1 = E_2 + E_f$ … 17.15
  $E_f = h_f$ = head loss due to friction
- Three head loss calculation methods
  1. Moody friction factor chart
  2. Darcy formula
  3. Hazen-Williams formula



MOODY CHART

- For turbulent flow
- Same as Figure 17.4: Plot of R_e (x-axis) against f for different relative roughness (ε/D) values
- Error prone; Appendix 17.B (based on Colebrook Eq. is a better alternative)



■ **FIGURE 8.23** Friction factor as a function of Reynolds number and relative roughness for round pipes—the Moody chart (Data from Ref. 7 with permission).

EXAMPLE 17.2: FRICTION FACTOR

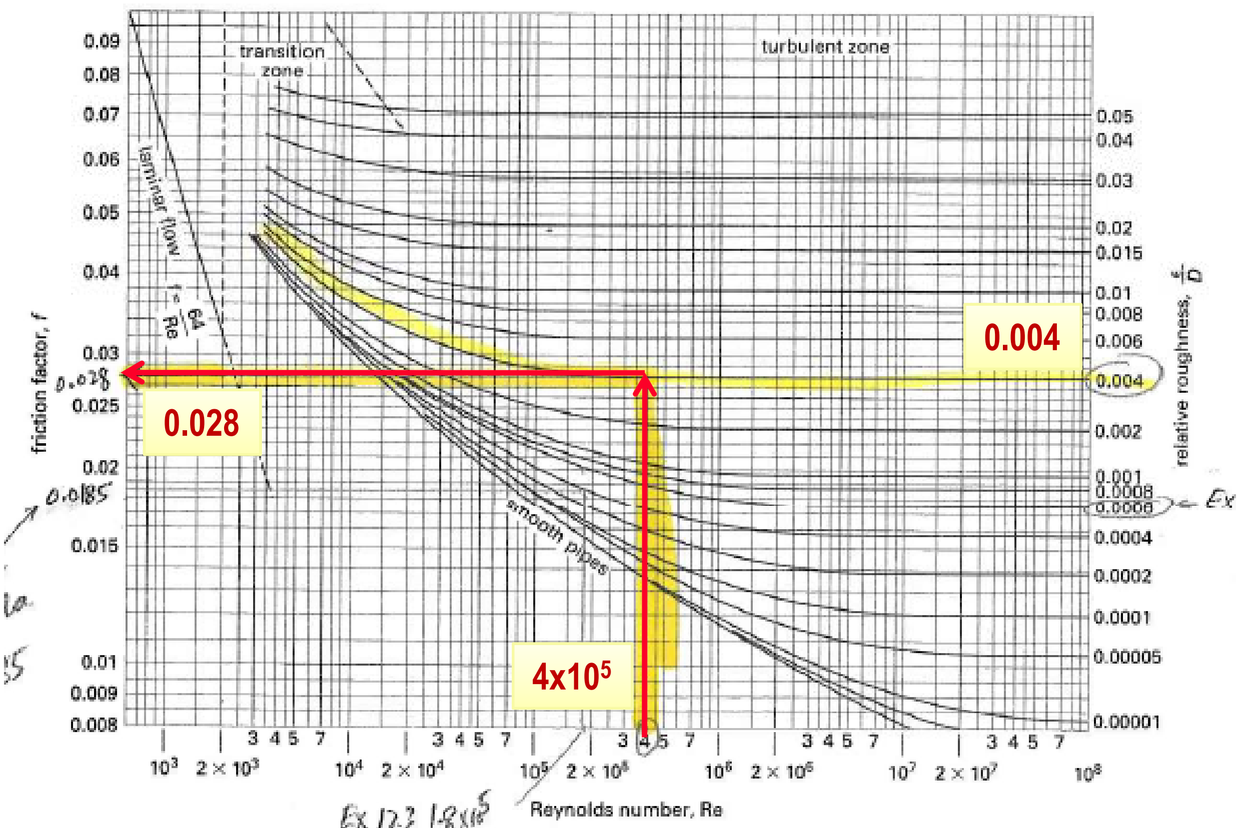
- Determine the friction factor for a Reynolds number of Re = 400,000 and a relative roughness of $\varepsilon / D = 0.004$ using
  a) the Moody diagram
  b) Appendix 17.B
  c) the Swamee-Jain approximation
  d) Check the table value of f with the Colebrook equation.

- **Given Data:**
  $Re = 400{,}000 = 40 \times 10^5$
  $\varepsilon / D = 0.004$

- **Calculate (?):**
  - f (from Moody diagram)
  - f (from Appendix 17.B)

EXAMPLE 17.2: FRICTION FACTOR

- **Solution:**
  From Figure 17.4
  - Select curve for ε/D = 0.004
  - Select 4×10^5 on x-axis and move up to meet ε/D curve
  - Move left to cross y-axis at **f = 0.028** ANSWER 1



Reprinted with permission from L. F. Moody, "Friction Factor for Pipe Flow," *ASME Transactions*, Vol. 66, published by the American Society of Mechanical Engineers, copyright © 1944.

Figure 17.4 *Moody Friction Factor Chart*

EXAMPLE 17.2: FRICTION FACTOR

- **Solution:**
  From Appendix 17.B, f = 0.0287 ANSWER 2

APPENDIX 17.B *(continued)*
Darcy Friction Factors
(turbulent flow)

Ex. 17.2

relative roughness (ϵ/D)

Reynolds no.	0.001	0.0015	0.002	0.0025	0.003	0.0035	0.004	0.006	0.008
2×10^3	0.0502	0.0506	0.0510	0.0513	0.0517	0.0521	0.0525	0.0539	0.0554
2.5×10^3	0.0469	0.0473	0.0477	0.0481	0.0485	0.0489	0.0493	0.0509	0.0524
3×10^3	0.0444	0.0449	0.0453	0.0457	0.0462	0.0466	0.0470	0.0487	0.0503
4×10^3	0.0409	0.0414	0.0419	0.0424	0.0429	0.0433	0.0438	0.0456	0.0474
5×10^3	0.0385	0.0390	0.0396	0.0401	0.0406	0.0411	0.0416	0.0436	0.0455
6×10^3	0.0367	0.0373	0.0378	0.0384	0.0390	0.0395	0.0400	0.0421	0.0441
7×10^3	0.0353	0.0359	0.0365	0.0371	0.0377	0.0383	0.0388	0.0410	0.0430
8×10^3	0.0341	0.0348	0.0354	0.0361	0.0367	0.0373	0.0379	0.0401	0.0422
9×10^3	0.0332	0.0339	0.0345	0.0352	0.0358	0.0365	0.0371	0.0394	0.0416
1×10^4	0.0324	0.0331	0.0338	0.0345	0.0351	0.0358	0.0364	0.0388	0.0410
1.5×10^4	0.0296	0.0305	0.0313	0.0320	0.0328	0.0335	0.0342	0.0369	0.0393
2×10^4	0.0279	0.0289	0.0298	0.0306	0.0315	0.0323	0.0330	0.0358	0.0384
2.5×10^4	0.0268	0.0278	0.0288	0.0297	0.0306	0.0314	0.0322	0.0352	0.0378
3×10^4	0.0260	0.0271	0.0281	0.0291	0.0300	0.0308	0.0317	0.0347	0.0374
4×10^4	0.0248	0.0260	0.0271	0.0282	0.0291	0.0301	0.0309	0.0341	0.0369
5×10^4	0.0240	0.0253	0.0265	0.0276	0.0286	0.0296	0.0305	0.0337	0.0365
6×10^4	0.0235	0.0248	0.0261	0.0272	0.0283	0.0292	0.0302	0.0335	0.0363
7×10^4	0.0230	0.0245	0.0257	0.0269	0.0280	0.0290	0.0299	0.0333	0.0362
8×10^4	0.0227	0.0242	0.0255	0.0267	0.0278	0.0288	0.0298	0.0331	0.0361
9×10^4	0.0224	0.0239	0.0253	0.0265	0.0276	0.0286	0.0296	0.0330	0.0360
1×10^5	0.0222	0.0237	0.0251	0.0263	0.0275	0.0285	0.0295	0.0329	0.0359
1.5×10^5	0.0214	0.0231	0.0246	0.0259	0.0271	0.0281	0.0292	0.0327	0.0357
2×10^5	0.0210	0.0228	0.0243	0.0256	0.0268	0.0279	0.0290	0.0325	0.0355
2.5×10^5	0.0208	0.0226	0.0241	0.0255	0.0267	0.0278	0.0289	0.0325	0.0355
3×10^5	0.0206	0.0225	0.0240	0.0254	0.0266	0.0277	0.0288	0.0324	0.0354
4×10^5	0.0204	0.0223	0.0239	0.0253	0.0265	[illegible]	0.0287	0.0323	0.0354
5×10^5	0.0202	0.0222	0.0238	0.0252	0.0264	0.0276	0.0286	0.0323	0.0353
6×10^5	0.0201	0.0221	0.0237	0.0251	0.0264	0.0275	0.0286	0.0323	0.0353
7×10^5	0.0201	0.0221	0.0237	0.0251	[illegible]	[illegible]	[illegible]		

DARCY FORMULA

- Also known as: Darcy-Weisback equation
- Valid for both laminar and turbulent flow

$$h_f = \frac{f\,L\,v^2}{2Dg} \qquad \cdots\ 17.22$$

h_f = head loss due to friction

L = pipe length

D = pipe diameter

v = velocity

f = Darcy friction factor

- f does not depend on pipe material
- f depends on pipe roughness

$$f = \frac{64}{R_e} \quad \text{for laminar flow } (R_e < 2{,}100) \qquad \cdots\ 17.16$$

Re = Reynolds number

$$f = \frac{0.316}{R_e^{0.25}} \quad \text{for turbulent flow } (3{,}000 < R_e < 100{,}000) \qquad \cdots\ 17.17$$

EXAMPLE 17.3: HEAD LOSS BY DARCY EQ.

50°F water is pumped through 1000 ft of 4 in. scheduled-40 welded steel pipe at the rate of 300 gpm. What friction loss (in ft-lbf/lbm) is predicted by the Darcy equation?

- **Given Data:**
  - T = 50°F
  - Material = Schedule-40 welded steel
  - L = 1000 ft
  - D = 4 in (nominal diameter)
  - Q = 300 gpm x 0.002228 = 0.6684 cfs

- **Calculate (?):**
  - h_f

EXAMPLE 17.3: HEAD LOSS BY DARCY EQ.

- **Solution:**

  ν (nu) = kinematic viscosity = 1.41 x 10^{-5} ft^2/sec (From Appendix 14.A)
  ε (epsilon) = specific roughness = 0.0002 ft (From Appendix 17.A)
  D = Internal diameter = 0.3355 ft (From Appendix 16.B)
  A = internal area = 0.0884 ft^2 (From Appendix 16.B)

  - v = Q/A = 0.6684 / 0.0884 = 7.56 ft/sec

$$\text{From Eq. 16.23, } R_e = \frac{D_e v}{\nu} = \frac{0.3355 \times 7.56}{1.41 \times 10^{-5}} = 1.8 \times 10^5$$

- Relative roughness = ε / D = 0.0002/0.335 = 0.0006
- Using calculated R_e and ε / D values, from Appendix 17.B, f = 0.0195

$$\text{From Eq. 17.22, } h_f = \frac{f L v^2}{2Dg} = \frac{0.0195 \times 1000 \times 7.56^2}{2 \times 0.3355 \times 32.2} = \boxed{51.6 \text{ ft}}$$ ANSWER

EXAMPLE 17.3

APPENDIX 17.A

Specific Roughness and Hazen-Williams Constants for Various Water Pipe Materials[b]

type of pipe or surface	ϵ (ft) range	ϵ (ft) design	C range	C clean	C design[a]
steel					
welded and seamless	0.0001–0.0003	0.0002	150–80	140	100
interior riveted, no projecting rivets				139	100
projecting girth rivets				130	100
projecting girth and horizontal rivets				115	100
vitrified, spiral-riveted, flow with lap				110	100
vitrified, spiral-riveted, flow against lap				100	90
corrugated				60	60

EXAMPLE 17.3

APPENDIX 16.B
Dimensions of Welded and Seamless Steel Pipe[a,b]
(selected sizes)[c]
(English units)

nominal diameter (in)	schedule	outside diameter (in)	wall thickness (in)	internal diameter (in)	internal area (in^2)	internal diameter (ft)	internal area (ft^2)
$\frac{1}{8}$	40 (S)	0.405	0.068	0.269	0.0568	0.0224	0.00039
	80 (X)		0.095	0.215	0.0363	0.0179	0.00025
$\frac{1}{4}$	40 (S)	0.540	0.088	0.364	0.1041	0.0303	0.00072
	80 (X)		0.119	0.302	0.0716	0.0252	0.00050
$\frac{3}{8}$	40 (S)	0.675	0.091	0.493	0.1909	0.0411	0.00133
	80 (X)		0.126	0.423	0.1405	0.0353	0.00098
$\frac{1}{2}$	40 (S)	0.840	0.109	0.622	0.3039	0.0518	0.00211
	80 (X)		0.147	0.546	0.2341	0.0455	0.00163
	160		0.187	0.466	0.1706	0.0388	0.00118
	(XX)		0.294	0.252	0.0499	0.0210	0.00035
$\frac{3}{4}$	40 (S)	1.050	0.113	0.824	0.5333	0.0687	0.00370
	80 (X)		0.154	0.742	0.4324	0.0618	0.00300
	160		0.218	0.614	0.2961	0.0512	0.00206
	(XX)		0.308	0.434	0.1479	0.0362	0.00103
1	40 (S)	1.315	0.133	1.049	0.8643	0.0874	0.00600
	80 (X)		0.179	0.957	0.7193	0.0798	0.00500
	160		0.250	0.815	0.5217	0.0679	0.00362
	(XX)		0.358	0.599	0.2818	0.0499	0.00196
$1\frac{1}{4}$	40 (S)	1.660	0.140	1.380	1.496	0.1150	0.01039
	80 (X)		0.191	1.278	1.283	0.1065	0.00890
	160		0.250	1.160	1.057	0.0967	0.00734
	(XX)		0.382	0.896	0.6305	0.0747	0.00438
$1\frac{1}{2}$	40 (S)	1.900	0.145	1.610	2.036	0.1342	0.01414
	80 (X)		0.200	1.500	1.767	0.1250	0.01227
	160		0.281	1.338	1.406	0.1115	0.00976
	(XX)		0.400	1.100	0.9503	0.0917	0.00660
2	40 (S)	2.375	0.154	2.067	3.356	0.1723	0.02330
	80 (X)		0.218	1.939	2.953	0.1616	0.02051
	160		0.343	1.689	2.240	0.1408	0.01556
	(XX)		0.436	1.503	1.774	0.1253	0.01232
$2\frac{1}{2}$	40 (S)	2.875	0.203	2.469	4.788	0.2058	0.03325
	80 (X)		0.276	2.323	4.238	0.1936	0.02943
	160		0.375	2.125	3.547	0.1771	0.02463
	(XX)		0.552	1.771	2.464	0.1476	0.01711
3	40 (S)	3.500	0.216	3.068	7.393	0.2557	0.05134
	80 (X)		0.300	2.900	6.605	0.2417	0.04587
	160		0.437	2.626	5.416	0.2188	0.03761
	(XX)		0.600	2.300	4.155	0.1917	0.02885
$3\frac{1}{2}$	40 (S)	4.000	0.226	3.548	9.887	0.2957	0.06866
	80 (X)		0.318	3.364	8.888	0.2803	0.06172
4	40 (S)	4.500	0.237	4.026	12.73	0.3355	0.08841
	80 (X)		0.337	3.826	11.50	0.3188	0.07984
	120		0.437	3.626	10.33	0.3022	0.07171
	160		0.531	3.438	9.283	0.2865	0.06447
	(XX)		0.674	3.152	7.803	0.2627	0.05419

EXAMPLE 17.3: f FROM MOODY DIAGRAM

- From Appendix 17.B, f = 0.0195
- From Moody diagram, f = 0.0185
- 5% difference ⇒ use the method specified in the problem or your answer might be different from the 4 multiple-choice answers.

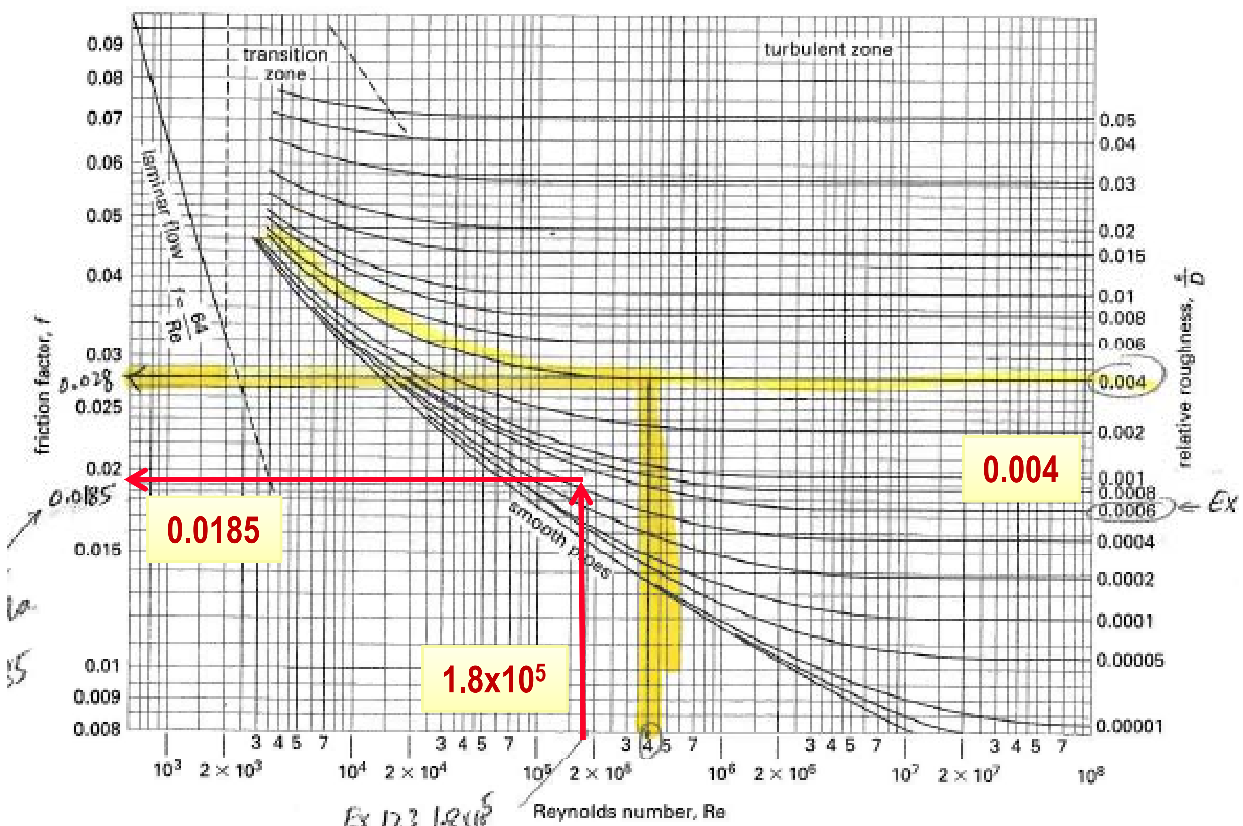


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Figure 17.4 *Moody Friction Factor Chart*

HAZEN-WILLIAMS FORMULA

- Does not depend on Reynolds number
- Depends on Hazen-Williams roughness coefficient "C"
- Valid for turbulent flow only

$$h_f = \frac{3.022\ v^{1.85}\ L}{C^{1.85}\ D^{1.17}} \quad (U.S.) \qquad \cdots\ 17.30$$

EXAMPLE 17.4: HEAD LOSS BY HAZEN-WILLIAMS EQ.

50°F water is pumped through 1000 ft of 4 in. scheduled-40 welded steel pipe at the rate of 300 gpm. What friction loss (in ft-lbf/lbm) is predicted by the Hazen-Williams formula? Assume C = 100. (Given data is the same as Example 17.3)

- **Given Data:**
  - T = 50°F
  - Material = Schedule-40 welded steel
  - L = 1000 ft
  - D = 4 in (nominal diameter)
  - Q = 300 gpm x 0.002228 = 0.6684 cfs
  - C = 100

- **Calculate (?):**
  - h_f

- **Solution:**

From Eqn. 17.30,

$$h_f = \frac{3.022 \times 7.56^{1.85} \times 1000}{100^{1.85} \times 0.3355^{1.17}} = \boxed{90.3 \text{ ft}}$$

ANSWER

SUGGESTED READING: CHAPTER 17

- 15. Minor losses and Example 17.7
- 21. Discharge from tanks and Example 17.8
- 26. Culverts
- 28. Series pipe systems
- 29. Parallel pipe systems and Example 17.9
- 58. Similarity