

CH402 Chemical Engineering Process Design

Class Notes L1

Course Admin and Piping Design

USMA Chemical Engineering Mission

To prepare commissioned leaders of character who are proficient in applying chemical and engineering principles to solve problems in a complex operational environment.

Published in the USMA Redbook (Part 2 – Disciplinary Offerings)

Chemical Engineering Program Educational Objectives

During a career as commissioned officers in the United States Army and beyond, program graduates:

- Demonstrate effective leadership and chemical engineering expertise.
- Contribute to the solution of infrastructure or operational problems (in a complex operational environment).
- Succeed in graduate school or other advanced study programs.
- Advance their careers through clear and precise technical communication.

Published in the USMA Redbook (Part 2 – Disciplinary Offerings)

(Today)

Firsties provide input to development of PEOs during the program briefing in January.

Chemical Engineering Student Outcomes

Student Outcome 8

The chemical engineering curriculum closely tracks the topics in the Fundamentals of Engineering Exam

On completion of the chemical engineering program, our graduates demonstrate an ability to understand ...

- Chemistry
- Material and energy balances
- Safety and environmental factors.**
- Thermodynamics of physical and chemical equilibria
- Heat, mass, and momentum transfer
- Chemical reaction engineering
- Continuous and staged separation processes
- Process dynamics and control
- Modern experimental and computing techniques**
- Process design.**

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Student Outcomes, cont.

Student Outcomes 1-7

The Chemical Engineering Major contains the student outcomes recommended by ABET.

On completion of the chemical engineering program, our graduates demonstrate an ability to ...

- Identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.
- Apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.
- Communicate effectively with a range of audiences.
- Recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts.
- Function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.
- Design and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.
- Acquire and apply new knowledge as needed, using appropriate learning strategies.

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Redbook

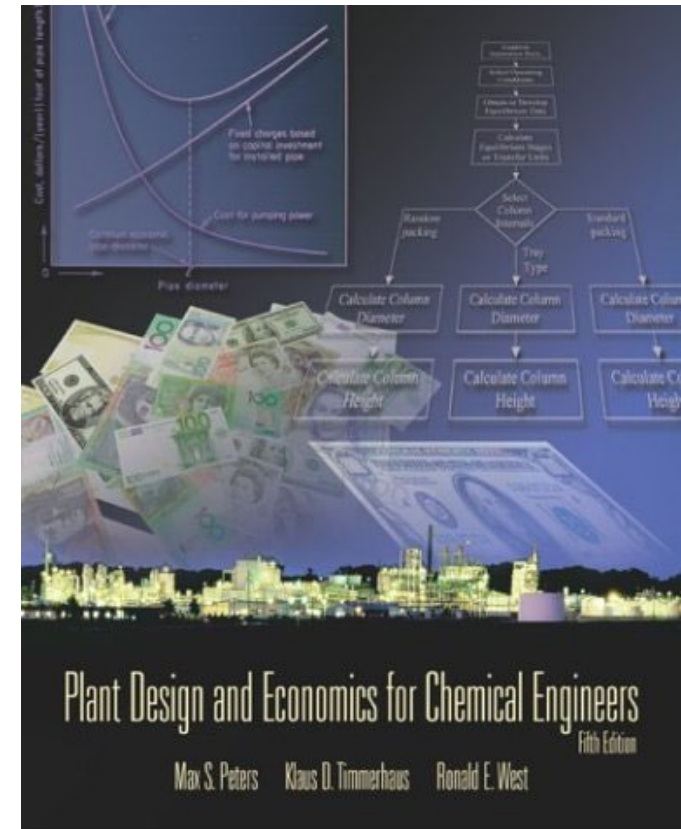
Credit Hours: 3.5 (BS=0, ET=3.5, MA=0)

Prerequisites: CH459, CH485, CH365

Co-requisite: None

Lessons: 40 @ 55 min, 7 @ 120 min

Special Requirements: None



Chapter Coverage

Introduction
Chapter 1

Flowsheet Synthesis
Chapter 4

Heat Exchangers
Chapters 14

Cost Estimation
Chapter 6

Fluid Handling
Chapter 12

Interest
Chapter 7

Design Reports
Chapter 11

Profitability
Chapter 8

Design Project
Independent Study

Assessment

| | | |
|--------------------------------------|------|--------|
| 29 Problem @ 6 pts each: | 174 | 9.43% |
| 5 Small Design Probs. @ 50 pts each: | 250 | 13.55% |
| 2 WPRs @ 200 pts each: | 400 | 21.68% |
| 1 Design Report @ 400 pts: | 400 | 21.68% |
| 2 IPRs @ 100 pts each: | 200 | 10.84% |
| 5 Quizzes @ 24 or 25 pts: | 121 | 6.56% |
| 1 Term End Exam @ 300 pts: | 300 | 16.26% |
| Total: | 1845 | |

All assignments are required.

| Grade | Attributes |
|-------|---|
| 6 | Cadets present complete solution and answers are correct. |
| | |
| 2 | Cadets present solution but answer is incorrect. |
| 1 | Cadet presents minimal work and answer is incorrect. |
| 0 | Answers shown with no work. |

Procedure:

1. Detailed grading comments will not be provided by the instructor.
2. The instructor will notify the class when the assignment has been graded and the approved solution posted.
3. Cadets are responsible for reviewing the approved solutions and finding mistakes.
4. Cadets may then resubmit problem sets after grades have been posted.
5. Resubmissions must be submitted in Canvas within the suspense, generally 48 hours after notification of posting (weekends and holidays included). Beyond that time, resubmissions will not be graded.
6. Corrections must include a single pdf document with a cover page and a new title (e.g., PS10 Corrections). The instructor will find your resubmissions in Canvas. You are not required to email the instructor. Other documents such as Mathematica or Excel files may also be submitted to support your work, but the pdf is required.
7. Your resubmission must identify what your error was in the initial submission. You must also repair the error and verify the correction.
8. You may use the posted solutions to identify mistakes in your work. However, simply copying the instructor solution for the resubmission without correcting the initial submission will not change your grade.
9. Initial grade must be greater than 1/6 to be eligible for a resubmission.
10. The maximum score for a resubmission is 5/6.

Piping Design



Piping can range from 15 to 70% of the total delivered equipment cost.

This does not include instrumentation (control valves, sensors, actuators, IT.)



Piping Design Equations

Mechanical Energy Balance – 1st Law of Thermodynamics

Determines energy for pumping fluid through pipe network.

BLUF – why do this? – energy has cost (\$/kWh).

(Equation partially derived in CH365 L7, Chapter 2 of Smith, van Ness, Abbott, & Swihart, page 50, assuming steady state, $\Delta U=0$, and $Q=0$)

incompressible:

Eq. 12-12, page 492
reduced form of 12-2

1st Law, steady state, one entrance, one exit, constant T

“mechanical” work

potential energy change

kinetic energy change

external pressure change

frictional losses inside piping

new term not used in eq 12-1 or in CH365

equivalent length (straight pipe + fittings)

$$W_o = g\Delta z + \Delta\left(\frac{V^2}{2\alpha}\right) + \Delta(pv) + \sum F$$

$g = 9.8 \frac{m}{s^2}$

Correction factor:
 $\alpha = 1.0$ (turbulent)
 $\alpha = 0.5$ (viscous)

specific volume, m³/kg

$$\Delta(pv) = \frac{p_2 - p_1}{\rho}$$

$$F = \frac{2fV^2L_{eq}}{D}$$

$f = \text{friction factor}$

$$f = f(R_n)$$

(slide 12)

$$R_n = \frac{DV\rho}{\mu}$$

compressible:

Eq. 12-13, page 493
(example 12-2)

“shaft” work

$$W + Q = g\Delta Z + \Delta\left(\frac{V^2}{2\alpha}\right) + \Delta h + \sum F$$

not shown in eq 12-13

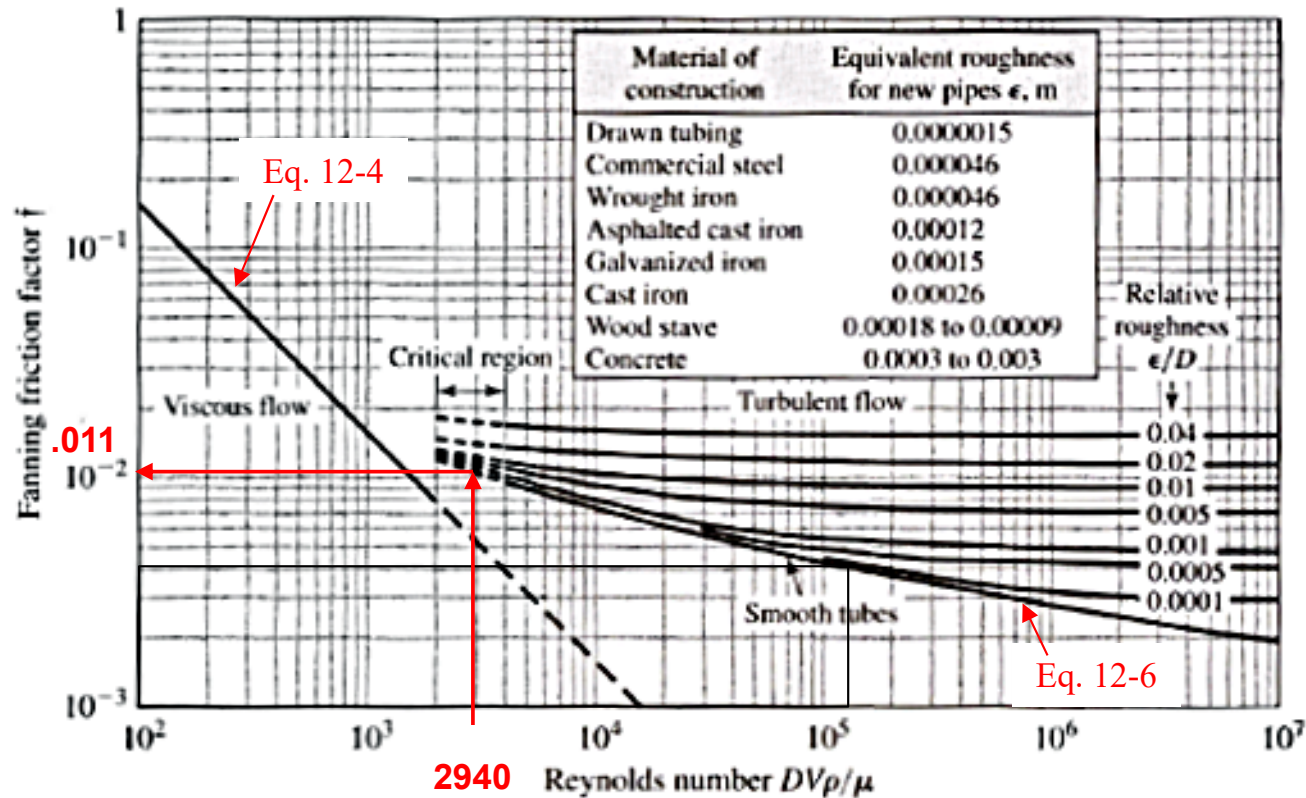
$$\Delta h = R \cdot \int_{T_1}^{T_2} \left(C_{P_{298}}^{ig} / R \right) dT$$

Best handled in CHEMCAD

Friction Factors – Straight Pipe

Example:
Determine f for
commercial
“carbon” steel
when Reynolds
number is 2940.

$$f=0.011$$



$$R_n = \frac{DV\rho}{\mu}$$

Eq. 12-3b,
page 486

Figure 12-1

Fanning friction factors for long, straight pipes. [Based on L. F. Moody, *Trans. ASME*, 66: 671–684 (1944).]

$$Re \leq 2100$$

$$f = \frac{16}{Re}$$

Eq. 12-4,
page 487

$$4000 < Re < 100,000$$

$$f = \frac{.079}{Re^{0.25}}$$

Eq. 12-5,
page 487

$$Re > 4,000$$

$$\frac{1}{f^{1/2}} = -4 \log \left[\frac{\epsilon}{3.7D} + \frac{1.256}{(Re)(f)^{1/2}} \right]$$

Eq. 12-6,
page 487

Frictional Losses in Fittings

Table 12-1 on page 490 is more comprehensive

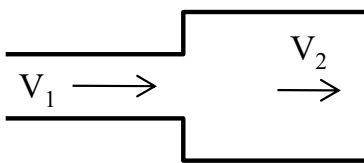
| $F = \frac{2fV^2(L_{\text{straight}} + L_e)}{D}$ | L_e/D per fitting (dimensionless) |
|--|--|
| 45-degree elbows | 15 |
| 90-degree elbows, std. radius | 32 |
| 90-degree elbows, med. Radius | 26 |
| 90-degree elbows, long radius | 20 |
| 90-degree elbows, square | 60 |
| 180-degree close-return bend | 75 |
| 180-degree medium-radius return bend | 50 |
| Tee, used as elbow, entering run | 60 |
| Tee, used as elbow, entering branch | 90 |
| couplings | 0 |
| unions | 0 |
| gate valves, open | 7 |
| globe valves, open | 300 |

Example:
Determine the
equivalent length of
5 90-degree elbows
when the diameter
is 0.078 m

$5 \times 32 \times 0.078 \text{ m} =$
12.48 m of pipe

units are
 m^2/s^2

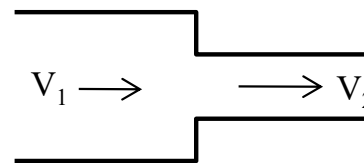
enlargement



$$F_{\text{expansion}} = \frac{(V_1 - V_2)^2}{2\alpha}$$

$\alpha=1.0$ for turbulent flow
 $\alpha=0.5$ for laminar flow

constriction



$$F_{\text{constriction}} = \frac{K_c V_2^2}{2\alpha}$$

$\alpha = 1$ (turbulent)
 $\alpha = 1$ (laminar)

for $A_2 / A_1 < 0.715$, $K_c = 0.4(1.25 - A_2 / A_1)$

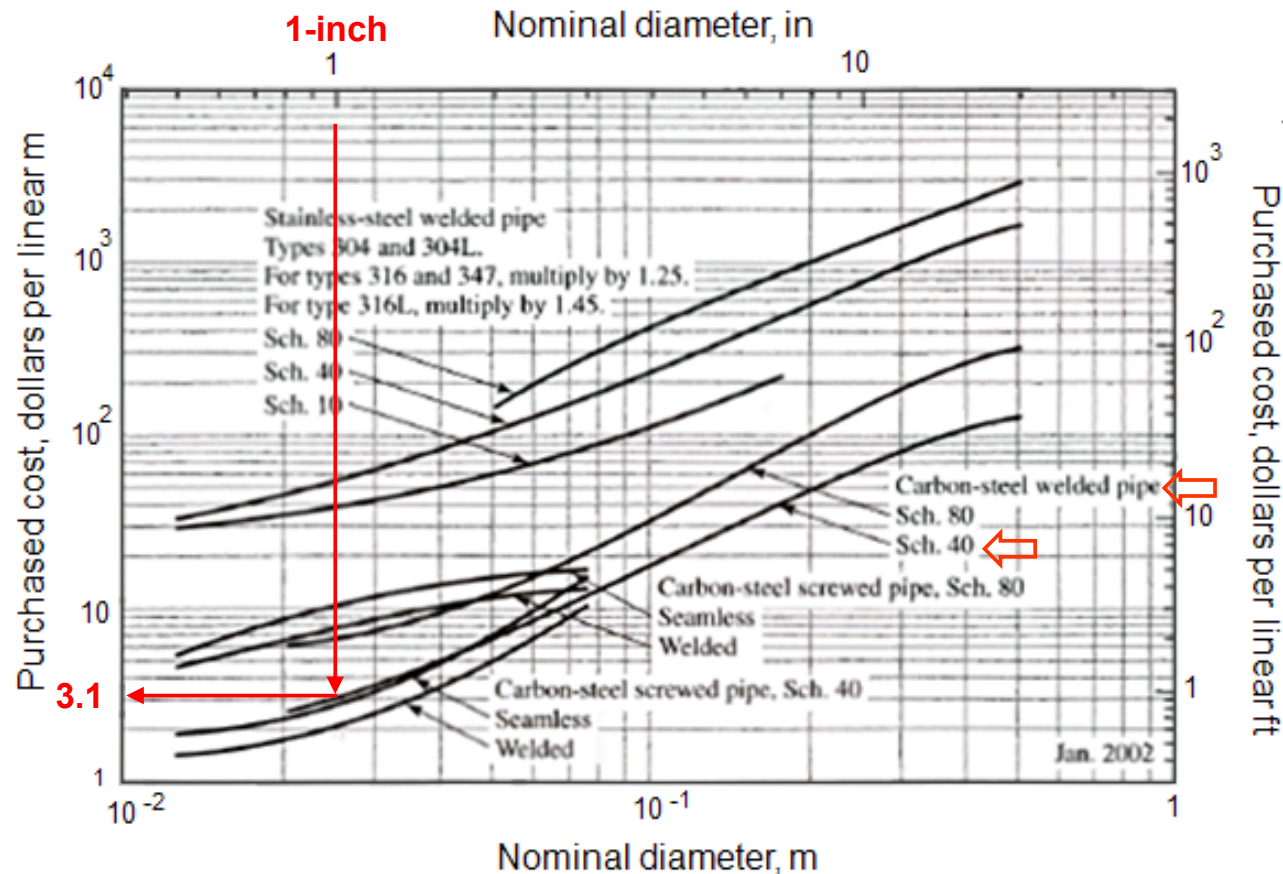
for $A_2 / A_1 > 0.715$, $K_c = 0.75(1.00 - A_2 / A_1)$

for conical and rounded shapes, $K_c=0.05$

Cost of Piping

<http://www.mhhe.com/engcs/chemical/peters/data/ce.html>

Nominal diameter defined,
Slide 16



Example:
1-inch Sch 40
carbon-steel
welded pipe

Cost is \$3.1/m in
January of 2002

Figure 12-4
Purchased cost of pipe per unit length

Factors for Determining Cost:

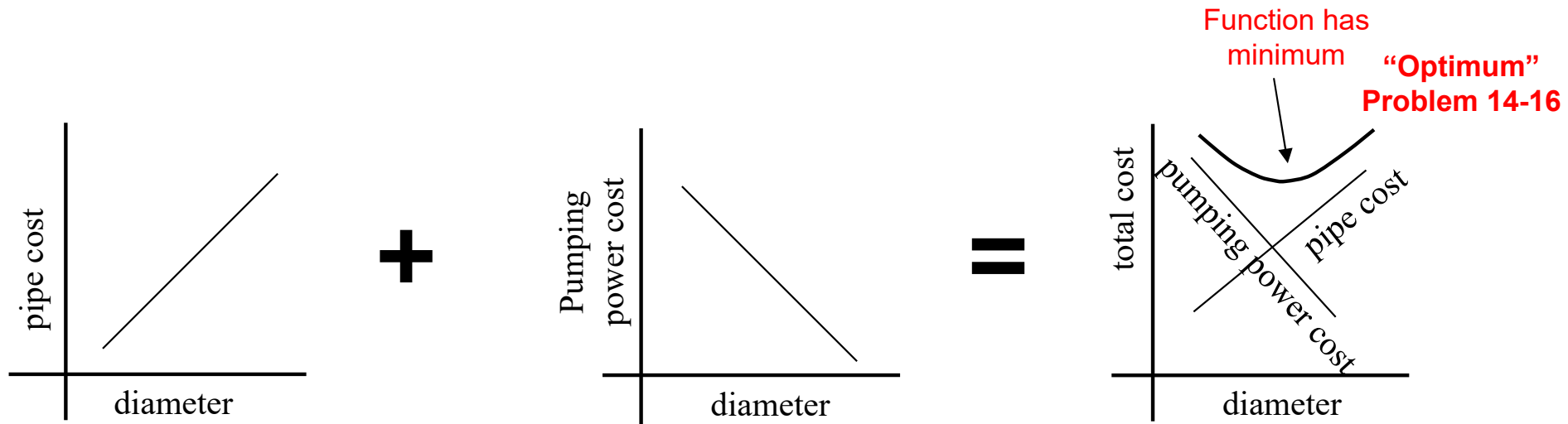
- Length
- Diameter and thickness
- Material of construction
- Mounting and support hardware
- Insulation and paint

Additional Charts and Data:

| | |
|---------------------|--|
| Pipes | pp 503-504 (figs. 12-4 to 12-6) |
| Valves | pp 505-507 (figs. 12-7 to 12-11) |
| Insulation, paint | p 507 (fig 12-12) |
| Additional Fittings | See Link to Pipe Fitting Prices – 1979 Edition |

How to Find the Pipe Diameter

Optimization of Combined Pipe Cost and Pumping Power Cost



Chapter 12: Eqns. 12-15,16 page 501
(abbreviated)

$$D_{i,opt} = 0.363 \dot{m}_v^{0.45} \rho^{0.13}$$

$Re > 2100$ and $D_i \geq 0.0254\text{m}$

$$D_{i,opt} = 1.33 \dot{m}_v^{0.40} \mu^{0.20}$$

$Re < 2100$ and $D_i < 0.0254\text{m}$

book has .133
(typo)

\dot{m}_v = volumetric flowrate, $\frac{m^3}{s}$

μ = viscosity, $Pa \cdot s$

Chapter 9: Eqns. 9-76 to 9-79 page 404
(complete set of equations)

$$D_{i,opt} = 0.363 \dot{m}_v^{0.45} \rho^{0.13} \mu^{0.025}$$

$Re > 2100$ and $D_i \geq 0.0254\text{m}$

$$D_{i,opt} = 0.49 \dot{m}_v^{0.49} \rho^{0.14} \mu^{0.027}$$

$Re > 2100$ and $D_i < 0.0254\text{m}$

$$D_{i,opt} = 0.863 \dot{m}_v^{0.36} \mu^{0.18}$$

$Re < 2100$ and $D_i \geq 0.0254\text{m}$

$$D_{i,opt} = 1.33 \dot{m}_v^{0.40} \mu^{0.20}$$

$Re < 2100$ and $D_i < 0.0254\text{m}$

(To learn more, there is an excellent tutorial hyperlinked to figure, or copy and paste this link into your browser:
<https://hardhatengineer.com/pipe-class-piping-specifications-pipeend/pipe-schedule-chart-nominal-pipe-sizes/>)

Table D-13 Steel pipe dimensions†

| Nominal pipe size, in. | OD, in. | Schedule no. | ID, in. | Flow area per pipe, in. ² | Surface per linear ft, ft ² | | Weight per lin ft, lb steel |
|------------------------------|---------|-----------------|---------|---|---|--------|-----------------------------------|
| | | | | | Outside | Inside | |
| ¼ | 0.405 | 40 [§] | 0.269 | 0.058 | 0.106 | 0.070 | 0.25 |
| | | 80 [‡] | 0.215 | 0.036 | 0.106 | 0.056 | 0.32 |
| ½ | 0.540 | 40 | 0.364 | 0.104 | 0.141 | 0.095 | 0.43 |
| | | 80 | 0.302 | 0.072 | 0.141 | 0.079 | 0.54 |
| ¾ | 0.675 | 40 | 0.493 | 0.192 | 0.177 | 0.129 | 0.57 |
| | | 80 | 0.423 | 0.141 | 0.177 | 0.111 | 0.74 |
| 1 | 0.840 | 40 | 0.622 | 0.304 | 0.220 | 0.163 | 0.85 |
| | | 80 | 0.546 | 0.235 | 0.220 | 0.143 | 1.09 |
| 1½ | 1.05 | 40 | 0.824 | 0.534 | 0.275 | 0.216 | 1.13 |
| | | 80 | 0.742 | 0.432 | 0.275 | 0.194 | 1.48 |
| 2 | 1.32 | 40 | 1.049 | 0.864 | 0.344 | 0.274 | 1.68 |
| | | 80 | 0.957 | 0.718 | 0.344 | 0.250 | 2.17 |
| 2½ | 1.66 | 40 | 1.380 | 1.50 | 0.435 | 0.362 | 2.28 |
| | | 80 | 1.278 | 1.28 | 0.435 | 0.335 | 3.00 |
| 3 | 1.90 | 40 | 1.610 | 2.04 | 0.498 | 0.422 | 2.72 |
| | | 80 | 1.500 | 1.76 | 0.498 | 0.393 | 3.64 |
| 4 | 2.38 | 40 | 2.067 | 3.35 | 0.622 | 0.542 | 3.66 |
| | | 80 | 1.939 | 2.95 | 0.622 | 0.508 | 5.03 |
| 5 | 2.88 | 40 | 2.469 | 4.79 | 0.753 | 0.627 | 5.80 |
| | | 80 | 2.323 | 4.23 | 0.753 | 0.609 | 7.67 |
| 6 | 3.50 | 40 | 3.068 | 7.38 | 0.917 | 0.804 | 7.58 |
| | | 80 | 2.900 | 6.61 | 0.917 | 0.760 | 10.3 |
| 8 | 4.50 | 40 | 4.026 | 12.7 | 1.178 | 1.055 | 10.8 |
| | | 80 | 3.826 | 11.5 | 1.178 | 1.002 | 15.0 |
| 10 | 6.625 | 40 | 6.065 | 28.9 | 1.734 | 1.590 | 19.0 |
| | | 80 | 5.761 | 26.1 | 1.734 | 1.510 | 28.6 |
| 12 | 8.625 | 40 | 7.981 | 50.0 | 2.258 | 2.090 | 28.6 |
| | | 80 | 7.625 | 45.7 | 2.258 | 2.000 | 43.4 |
| 16 | 10.75 | 40 | 10.02 | 78.8 | 2.814 | 2.62 | 40.5 |
| | | 60 | 9.75 | 74.6 | 2.814 | 2.55 | 54.8 |
| 20 | 12.75 | 30 | 12.09 | 115 | 3.338 | 3.17 | 43.8 |
| 24 | 16.0 | 30 | 15.25 | 183 | 4.189 | 4.00 | 62.6 |
| 30 | 20.0 | 20 | 19.25 | 291 | 5.236 | 5.05 | 78.6 |
| 36 | 24.0 | 20 | 23.25 | 425 | 6.283 | 6.09 | 94.7 |

†The data provided in this table are in the USCS units used by the pipe manufacturers in the United States.

§Schedule 40 designates former "standard" pipe. 5, 5S, 10, 10S, 20, 30, 40, 40S, 60, 80, 80S, 100, 120, 140, 160, STD, XS, and XXS

‡Schedule 80 designates former "extra-strong" pipe.

Pipe Schedule No.

Eqs. 12-14 and 12-14a page 499

$$schedule = \frac{1000P_s}{S_s}$$

$$P_s = \frac{2S_s t_m}{D_m} \quad \begin{array}{l} \text{Thickness,} \\ \text{Lesson 5} \end{array}$$

P_s = safe working pressure, kPa

S_s = safe working stress, kPa

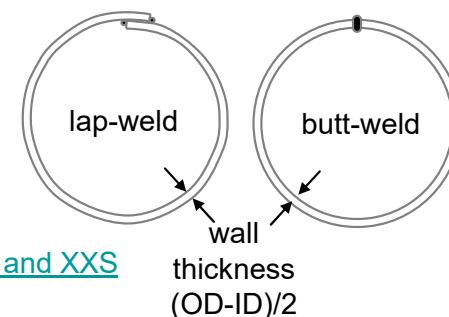
S_s = 49,000 kPa for butt-welded steel

S_s = 62,000 kPa for lap-welded steel

Stresses are in Table 12-10 page 555

t_m = wall thickness

D_m = mean diameter, m



Homework

Problem 12-1

Estimate the size of the motor necessary to pump a lean oil to the top of an absorption tower operating at a pressure of 445 kPa. The oil is to be pumped from an open tank with a liquid level 3 m above the floor through 46 m of pipe with an inside diameter of 0.078 m. There are five 90° elbows in the line, and the top of the tower is 9.1 m above the floor level. A flow of 2.7 kg/s of lean oil is required. The viscosity of the oil is 15 cP, and its density is 857 kg/m³. Assume that the efficiency of the pumping system including the motor is 40%.

Problem 12-2

What is the pressure loss when 2.14 kg/s of pure benzene at 40°C flows through a 21-m length of straight pipe with an inside diameter of .0409 m? The pipeline contains six 90° elbows, one tee used as an elbow (equivalent resistance equal to 60 pipe diameters), one globe valve, and one gate valve. The density of the benzene is 849 kg/m³., and the viscosity at 40°C is 5x10⁻⁴ Pa·s.

“pressure loss” is internal frictional pressure losses ΣF .