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.

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

Red designates course emphasis; Gray designates minor emphasis

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 …

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- 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.

Red designates course emphasis; Gray designates minor emphasis

Redbook

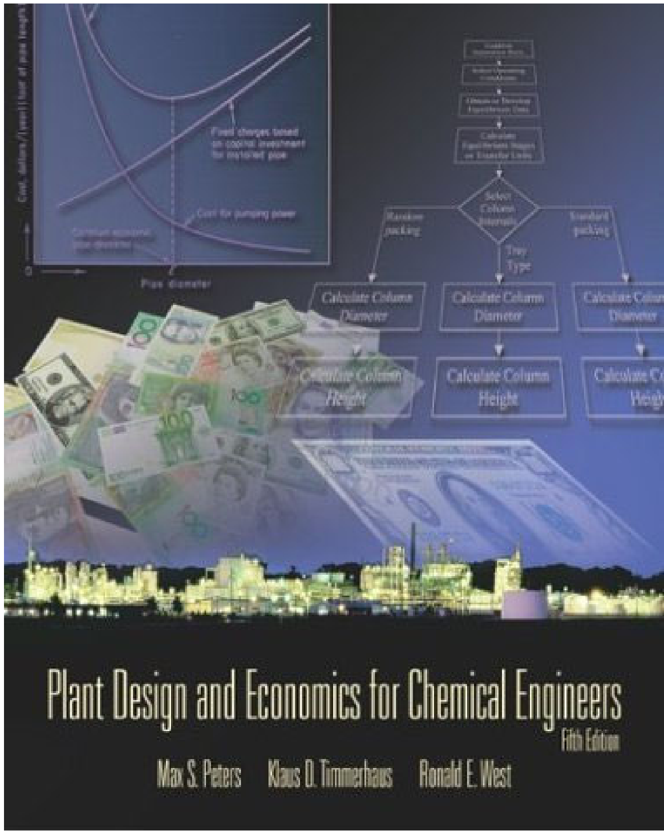
Credit Hours: 3.5 (BS=0, ET=3.5, MA=0)

Prerequisites: CH459, CH485, CH365

Co-requisite: None

Lessons: 40 @ 55 min, 7 @ 120 min

Special Requirements: None



Chapter Coverage

Introduction
Chapter 1

Heat Exchangers
Chapters 14

Fluid Handling
Chapter 12

Design Reports
Chapter 11

Flowsheet Synthesis
Chapter 4

Cost Estimation
Chapter 6

Interest
Chapter 7

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. Cadets are responsible for reviewing the approved solutions and finding mistakes.
3. Cadets may resubmit problem sets after grades have been posted. The instructor will email the class when the assignment has been graded and the grades posted. Corrections must be under separate cover with a new title (e.g., PS10 Corrections). The instructor will find your resubmissions in SharePoint. You are not required to email the instructor.
4. Your resubmission must identify what your error was and what you should have done. You must also repair the error and verify the correction.
5. Solutions will be posted by the instructor, and you may use those to identify mistakes in your work. However, simply copying the instructor solution for the resubmission will not change your grade. You must make corrections to your work.
6. Resubmissions must be posted in SharePoint within 24 hours of notification of posting (weekends and holidays included). Beyond that time, resubmissions will not be allowed.
7. 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, ΔU=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

$$W_o = \underbrace{g\Delta z}_{\text{potential energy change}} + \underbrace{\Delta\left(\frac{V^2}{2\alpha}\right)}_{\text{kinetic energy change}} + \underbrace{\Delta(pv)}_{\text{external pressure change}} + \underbrace{\sum F}_{\text{frictional losses inside piping}}$$

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

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

Correction factor:
α = 1.0 (turbulent)
α = 0.5 (viscous)

specific volume, m³/kg

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

equivalent length (straight pipe + fittings)

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

$f = friction\ factor$

$f = f(R_n)$
(slide 12)

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

---

compressible:

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

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

not shown in eq 12-13

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

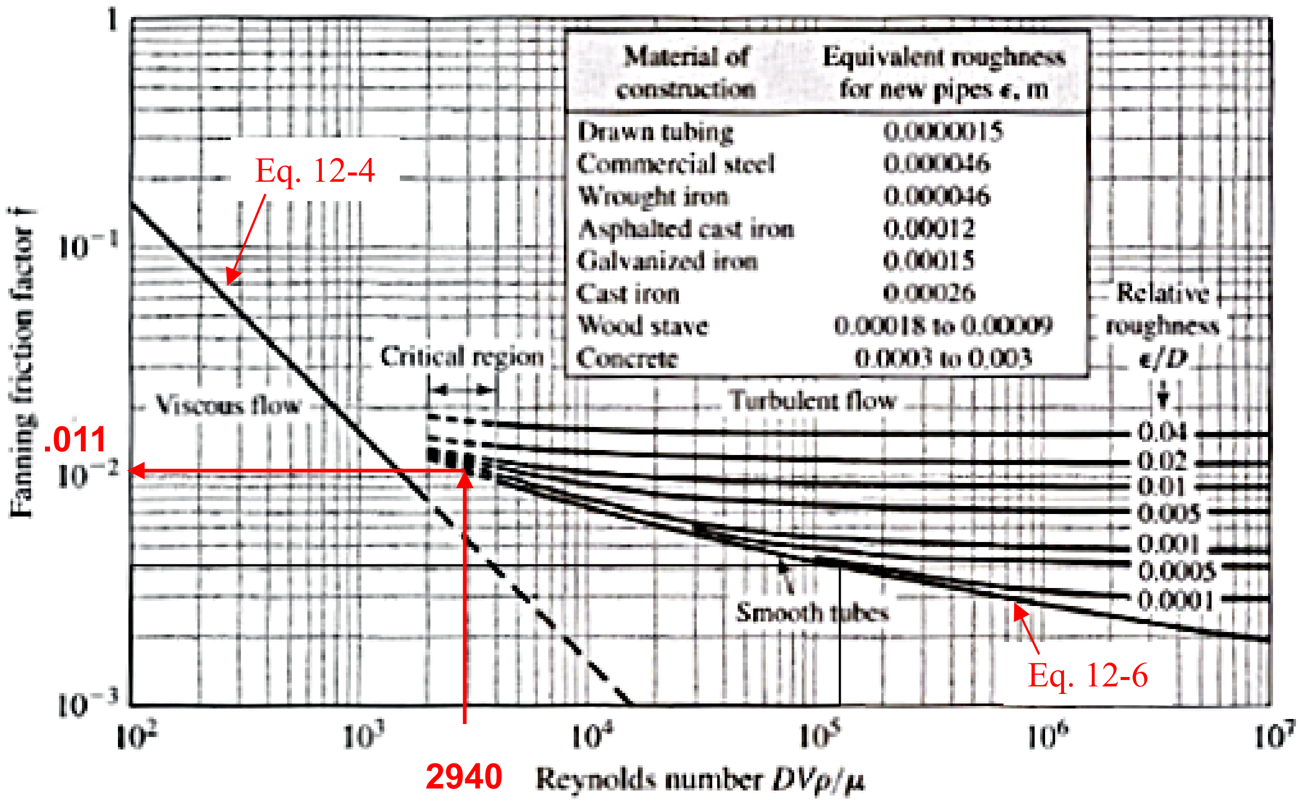
"shaft" work

Best handled in CHEMCAD

Friction Factors – Straight Pipe

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

f=0.011



Material of construction	Equivalent roughness for new pipes ε, m
Drawn tubing	0.0000015
Commercial steel	0.000046
Wrought iron	0.000046
Asphalted cast iron	0.00012
Galvanized iron	0.00015
Cast iron	0.00026
Wood stave	0.00018 to 0.00009
Concrete	0.0003 to 0.003

Figure 12-1
Fanning friction factors for long, straight pipes. [Based on L. F. Moody, *Trans. ASME.* **66:** 671–684 (1944).]

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

Eq. 12-3b, page 486

Re ≤ 2100

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

Eq. 12-4, page 487

4000 < Re < 100,000

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

Eq. 12-5, page 487

Re > 4,000

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

Eq. 12-6, page 487

Frictional Losses in Fittings

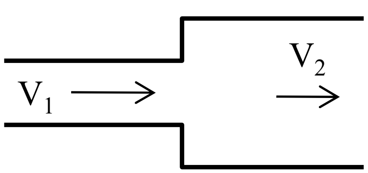
Table 12-1 on page 490 is more comprehensive

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

5 x 32 x 0.078 m = 12.48 m of pipe

$F = \dfrac{2fV^2(L_{straight} + L_e)}{D}$	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

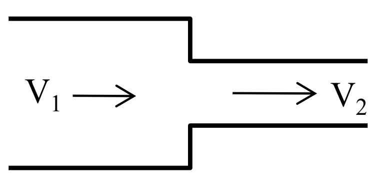
enlargement



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

α=1.0 for turbulent flow
α=0.5 for laminar flow

constriction



units are m^2/s^2

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

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

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

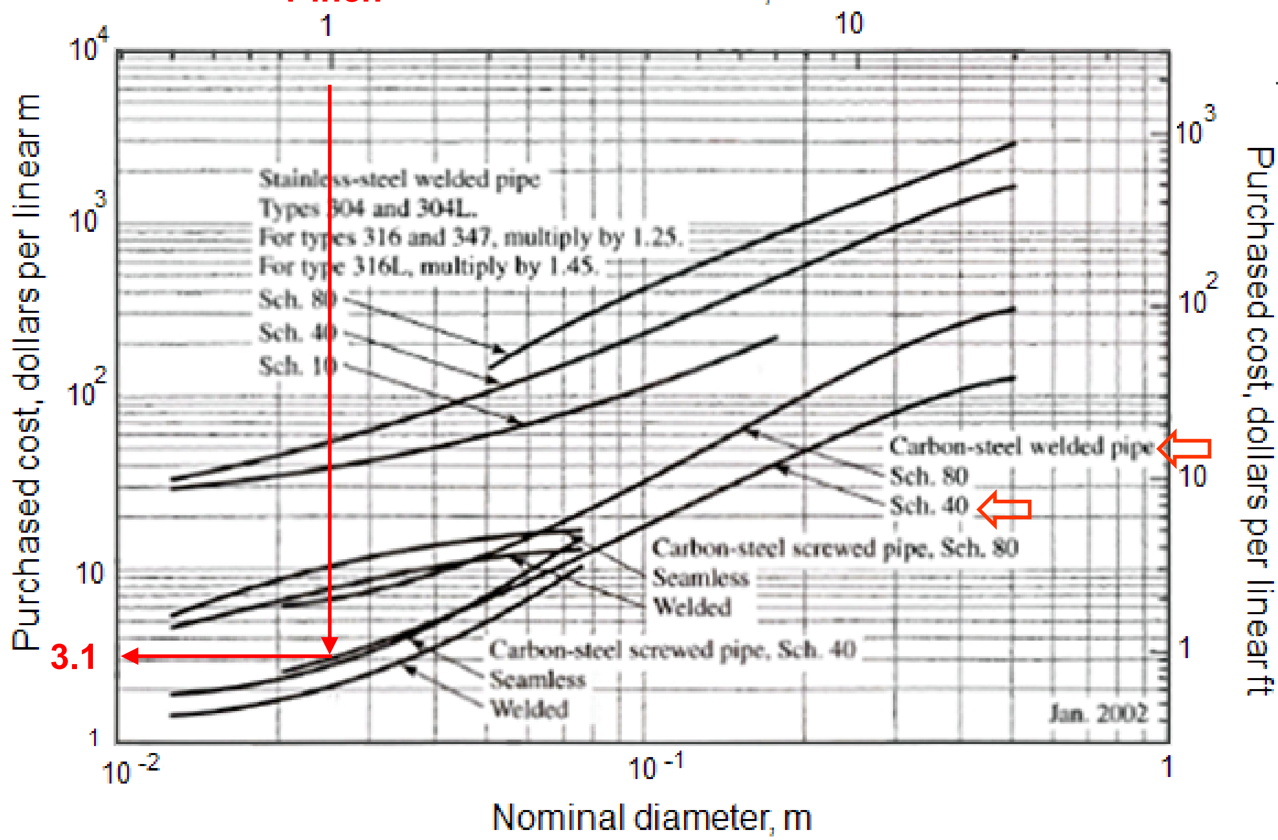
$$for \quad A_2/A_1 > 0.715, \quad K_c = 0.75(1.00 - A_2/A_1)$$

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

Additional Charts and Data:

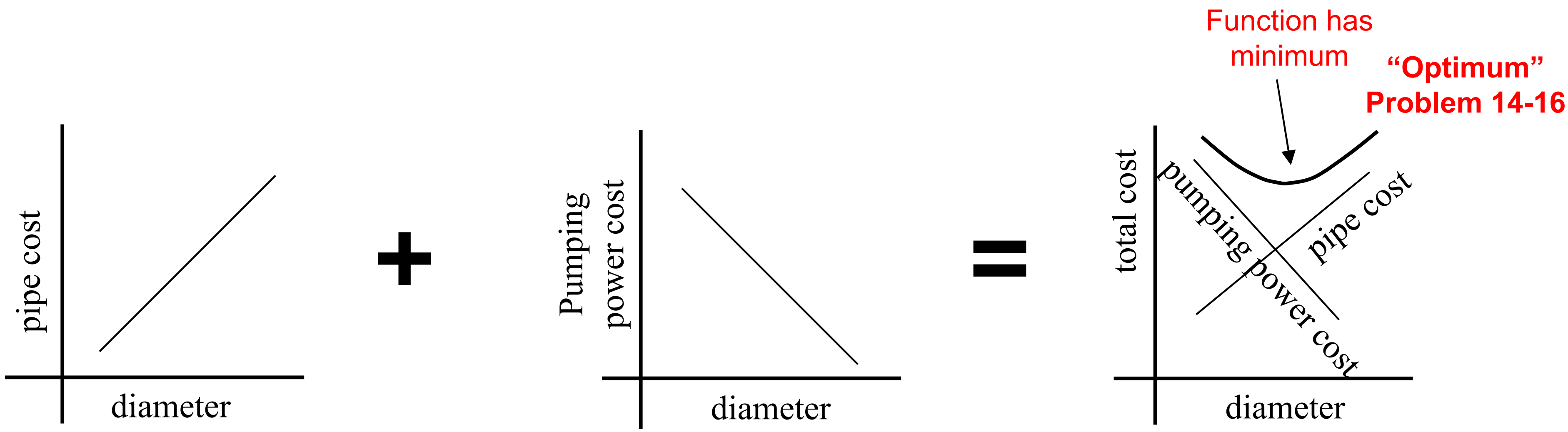
Pipes	pp 503-504	(figs. 12-4 to 12-6)
Valves	pp 505-507	(figs. 12-7 to 12-11)
Insulation, paint	p 507	(fig 12-12)
Additional Fittings	See Link to Pipe Fitting Prices – 1979 Edition	

Factors for Determining Cost:

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

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 $D_i \geq 0.0254$m

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

Re < 2100 and $D_i < 0.0254$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 $D_i \geq 0.0254$m

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

Re > 2100 and $D_i < 0.0254$m

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

Re < 2100 and $D_i \geq 0.0254$m

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

Re < 2100 and $D_i < 0.0254$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, ft² Outside	Surface per linear ft, ft² Inside	Weight per lin ft, lb steel
1/8	0.405	40‡	0.269	0.058	0.106	0.070	0.25
		80§	0.215	0.036	0.106	0.056	0.32
1/4	0.540	40	0.364	0.104	0.141	0.095	0.43
		80	0.302	0.072	0.141	0.079	0.54
3/8	0.675	40	0.493	0.192	0.177	0.129	0.57
		80	0.423	0.141	0.177	0.111	0.74
1/2	0.840	40	0.622	0.304	0.220	0.163	0.85
		80	0.546	0.235	0.220	0.143	1.09
3/4	1.05	40	0.824	0.534	0.275	0.216	1.13
		80	0.742	0.432	0.275	0.194	1.48
1	1.32	40	1.049	0.864	0.344	0.274	1.68
		80	0.957	0.718	0.344	0.250	2.17
1 1/4	1.66	40	1.380	1.50	0.435	0.362	2.28
		80	1.278	1.28	0.435	0.335	3.00
1 1/2	1.90	40	1.610	2.04	0.498	0.422	2.72
		80	1.500	1.76	0.498	0.393	3.64
2	2.38	40	2.067	3.35	0.622	0.542	3.66
		80	1.939	2.95	0.622	0.508	5.03
2 1/2	2.88	40	2.469	4.79	0.753	0.627	5.80
		80	2.323	4.23	0.753	0.609	7.67
3	3.50	40	3.068	7.38	0.917	0.804	7.58
		80	2.900	6.61	0.917	0.760	10.3
4	4.50	40	4.026	12.7	1.178	1.055	10.8
		80	3.826	11.5	1.178	1.002	15.0
6	6.625	40	6.065	28.9	1.734	1.590	19.0
		80	5.761	26.1	1.734	1.510	28.6
8	8.625	40	7.981	50.0	2.258	2.090	28.6
		80	7.625	45.7	2.258	2.000	43.4
10	10.75	40	10.02	78.8	2.814	2.62	40.5
		60	9.75	74.6	2.814	2.55	54.8
12	12.75	30	12.09	115	3.338	3.17	43.8
16	16.0	30	15.25	183	4.189	4.00	62.6
20	20.0	20	19.25	291	5.236	5.05	78.6
24	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.
§Schedule 80 designates former "extra-strong" pipe.

5, 5S, 10, 10S, 20, 30, 40, 40S, 60, 80, 80S, 100, 120, 140, 160, STD, XS, and XXS

Pipe Schedule No.

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

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

$$P_s = \frac{2 S_s t_m}{D_m}$$

Thickness, Lesson 5

P_s = safe working pressure, kPa

S_s = safe working stress, kPa

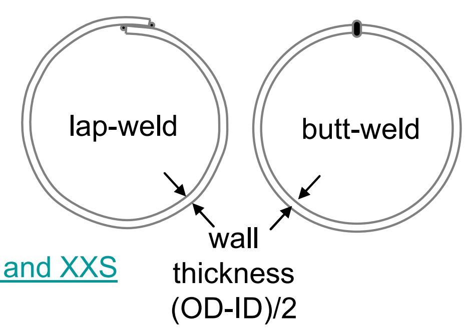
S_s = 49,000 kPa for butt-welded steel

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/m^3. 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/m^3., and the viscosity at 40°C is $5x10^{-4}$ Pa·s.

“pressure loss” is internal frictional pressure losses ΣF.