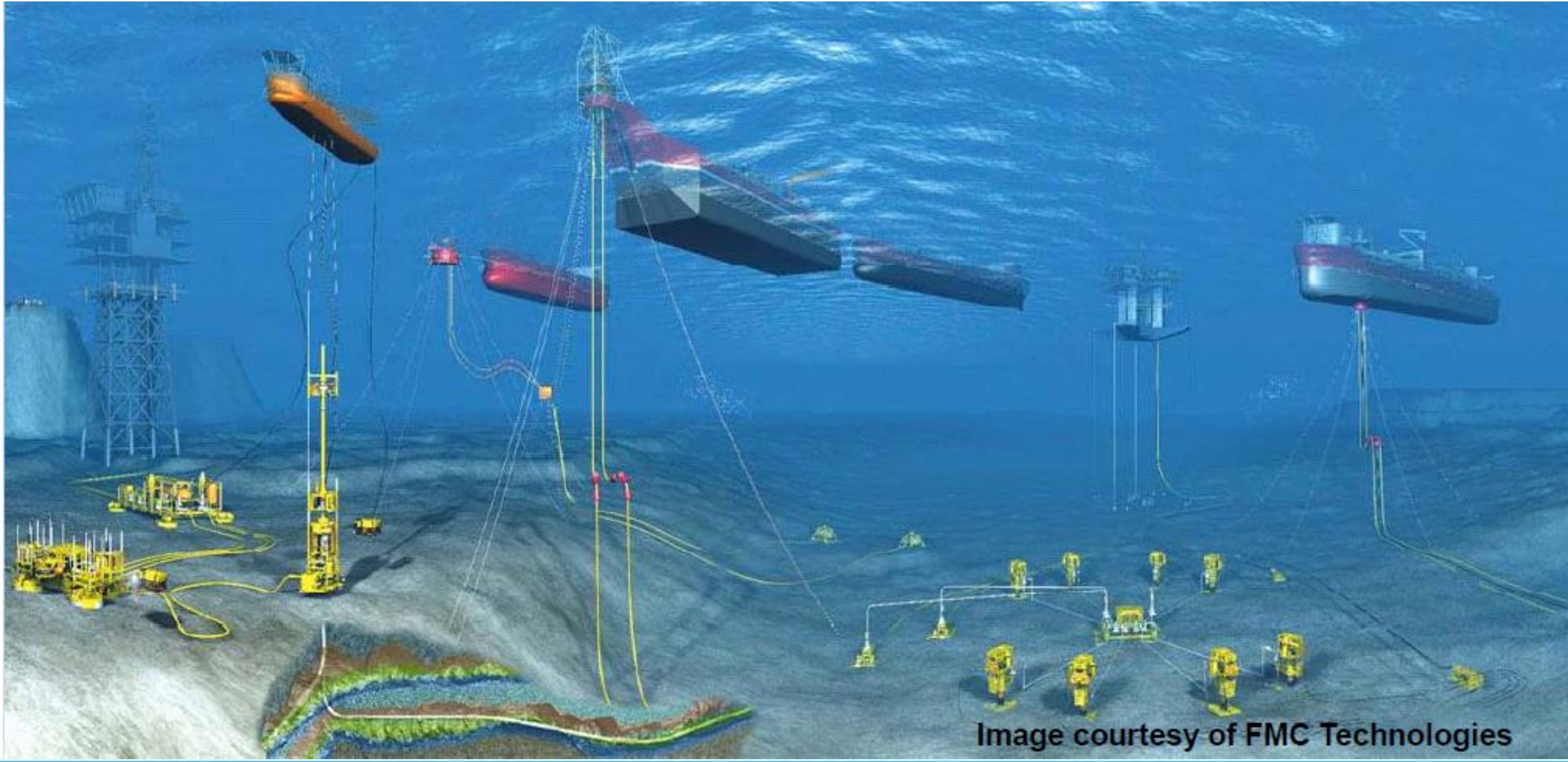
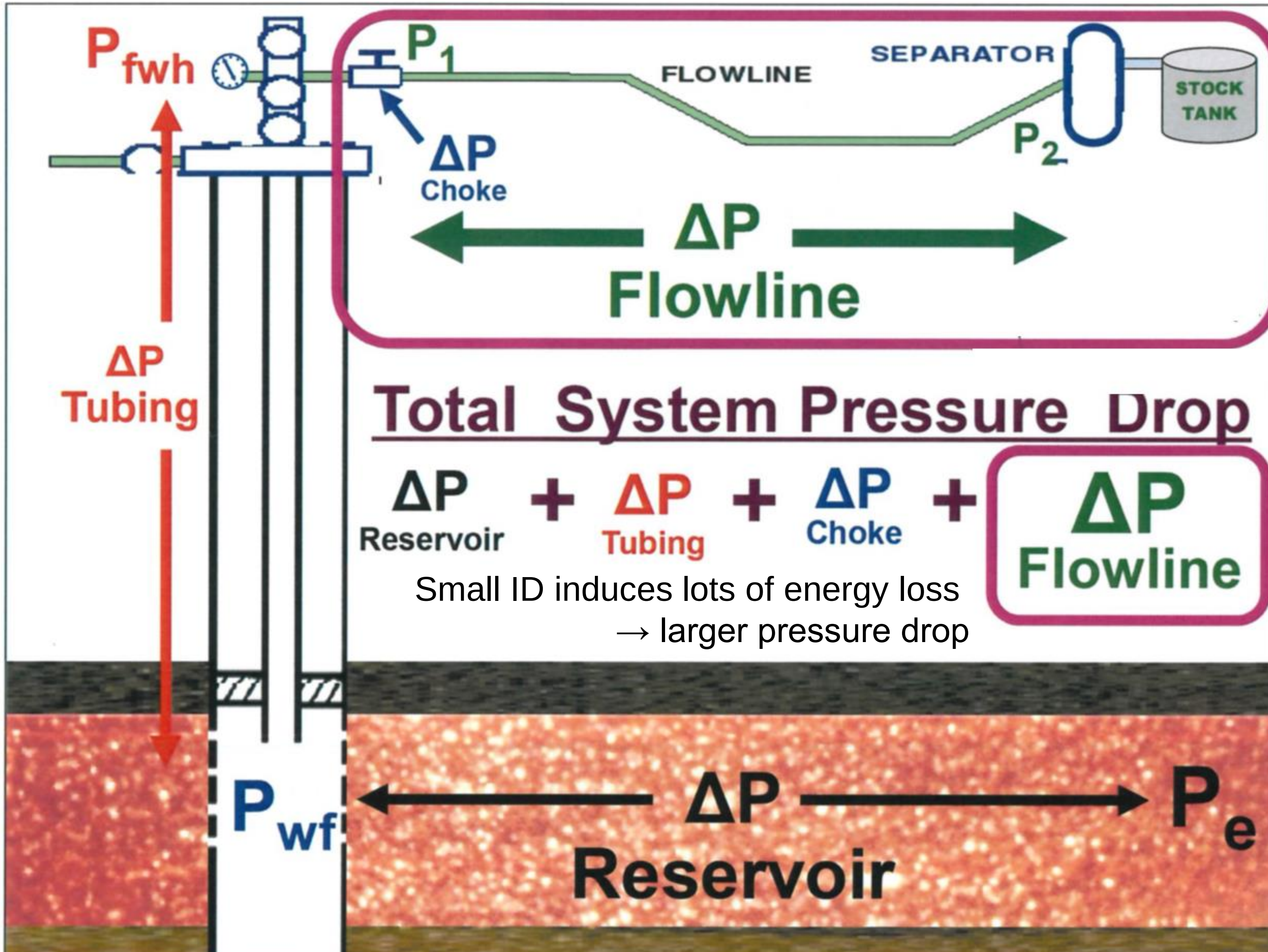


Flow Assurance

서유택

Gathering system

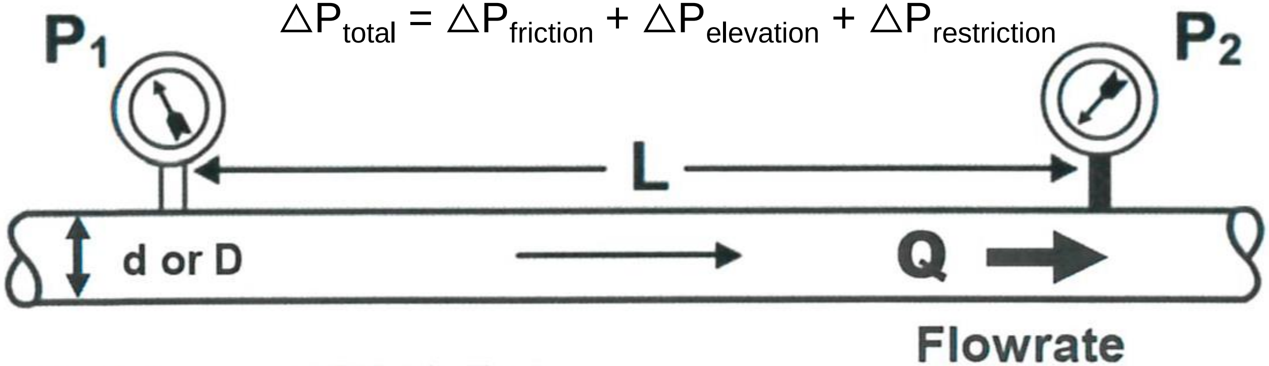


Small ID induces lots of energy loss
→ larger pressure drop

Pressure drop vs. Flowrate in oil field flowlines

$$\Delta P = P_1 - P_2$$

$$\triangle P_{total} = \triangle P_{friction} + \triangle P_{elevation} + \triangle P_{restriction}$$



D = Internal Diameter in Feet

d = Internal Diameter in Inches

Darcy – Weisbach Formula

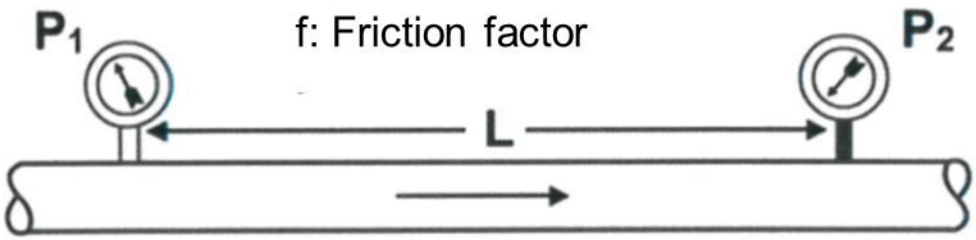
- Pressure drop expressed in feet of fluid head

$$h_{ft} = \frac{f\ L\ v^2}{D\ 2g}$$

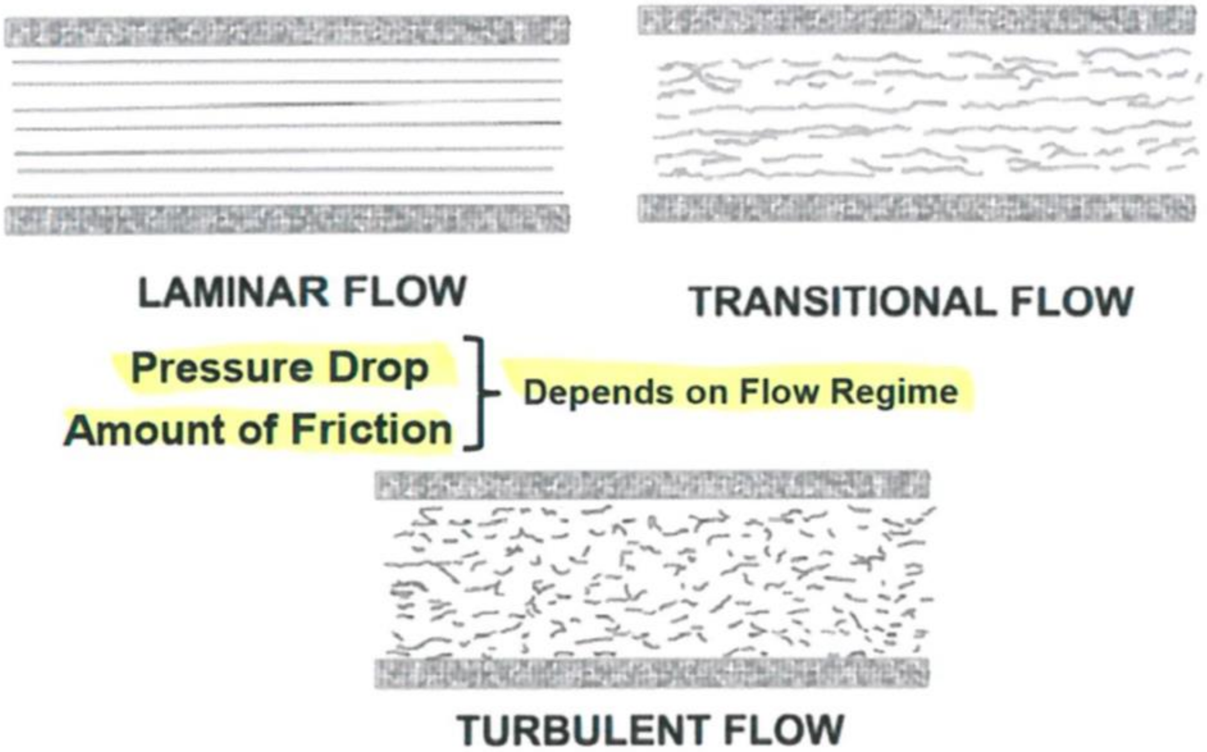
- Pressure drop expressed in psi

$$\triangle P = \frac{\rho\ f\ L\ v^2}{144\ D\ 2g}$$

g: correction factor
not gravity acceleration
(= 32.2 ft/s² = 9.81 m/s²)



Flow regime in pipe



- Gas dominant stream is mostly turbulent
- Flow regime determined by Reynolds number

Reynolds number

- Dimensionless parameter

  : Ratio of Inertia forces to Viscous forces

$$R_e = \frac{\rho D v}{\mu_e}$$

ρ : lb/ft^3 D : ft v : ft/sec μ_e : lb/ft - sec

- Re < 2000 = Laminar flow

$$Liquid: Re = 92.1 \frac{SG_L Q_{BPD}}{d\ \mu}$$

$$Gas: Re = 20100 \frac{SG_G Q_{MMCFD}}{d\ \mu}$$

d: inches, μ: centipoise

Friction factor

- f = Dimensionless factor of proportionality

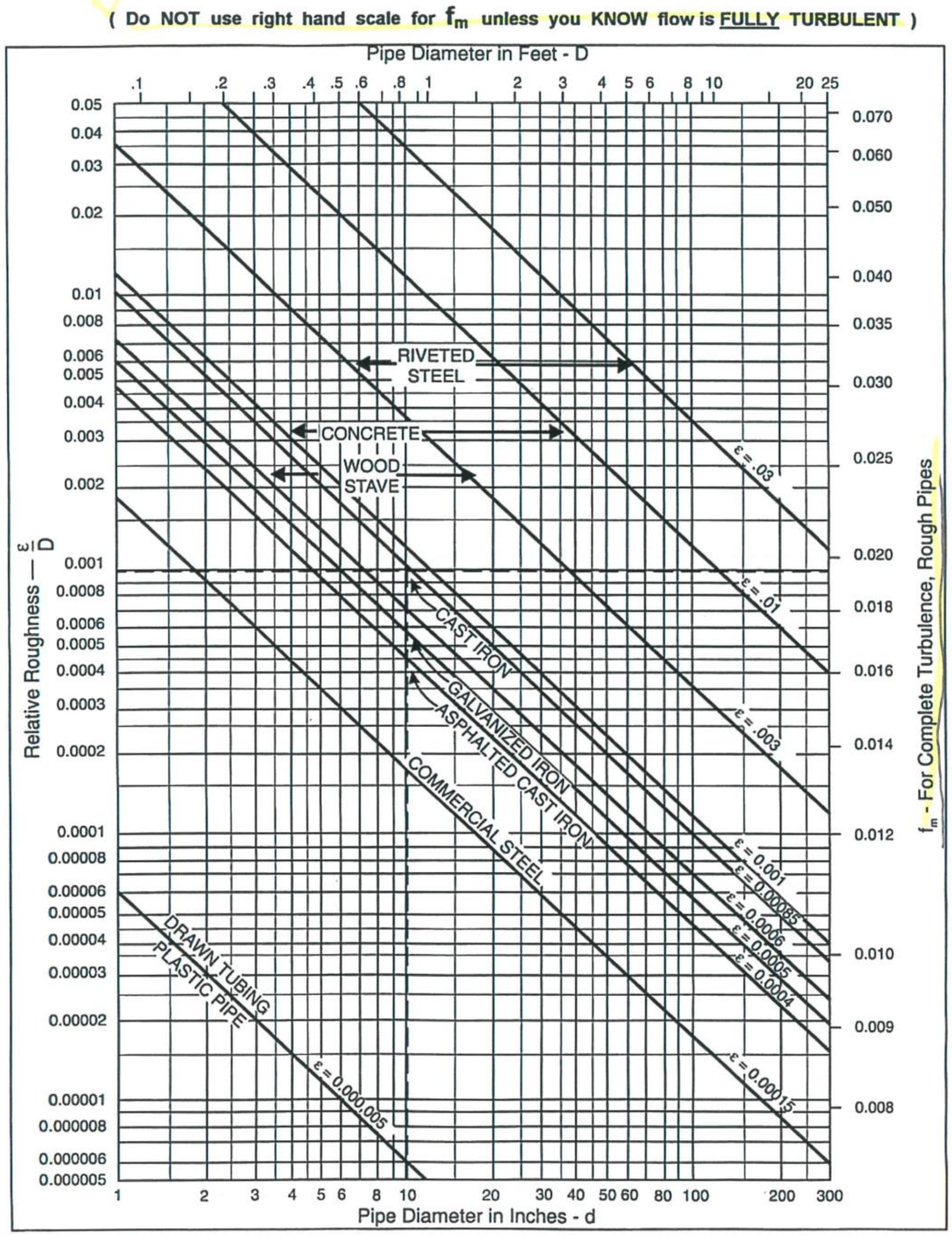
  f_m = Moddy friction factor

  f_f = Fanning fraction factor (f_f =1/4 f_m)

- Laminar flow: $f_m = 64 / Re$

- For transitional and turbulent flow
  - f_m a function of Re
  - Relative roughness: ε / D

- For complete turbulence
  - f_m a function of ε / D only



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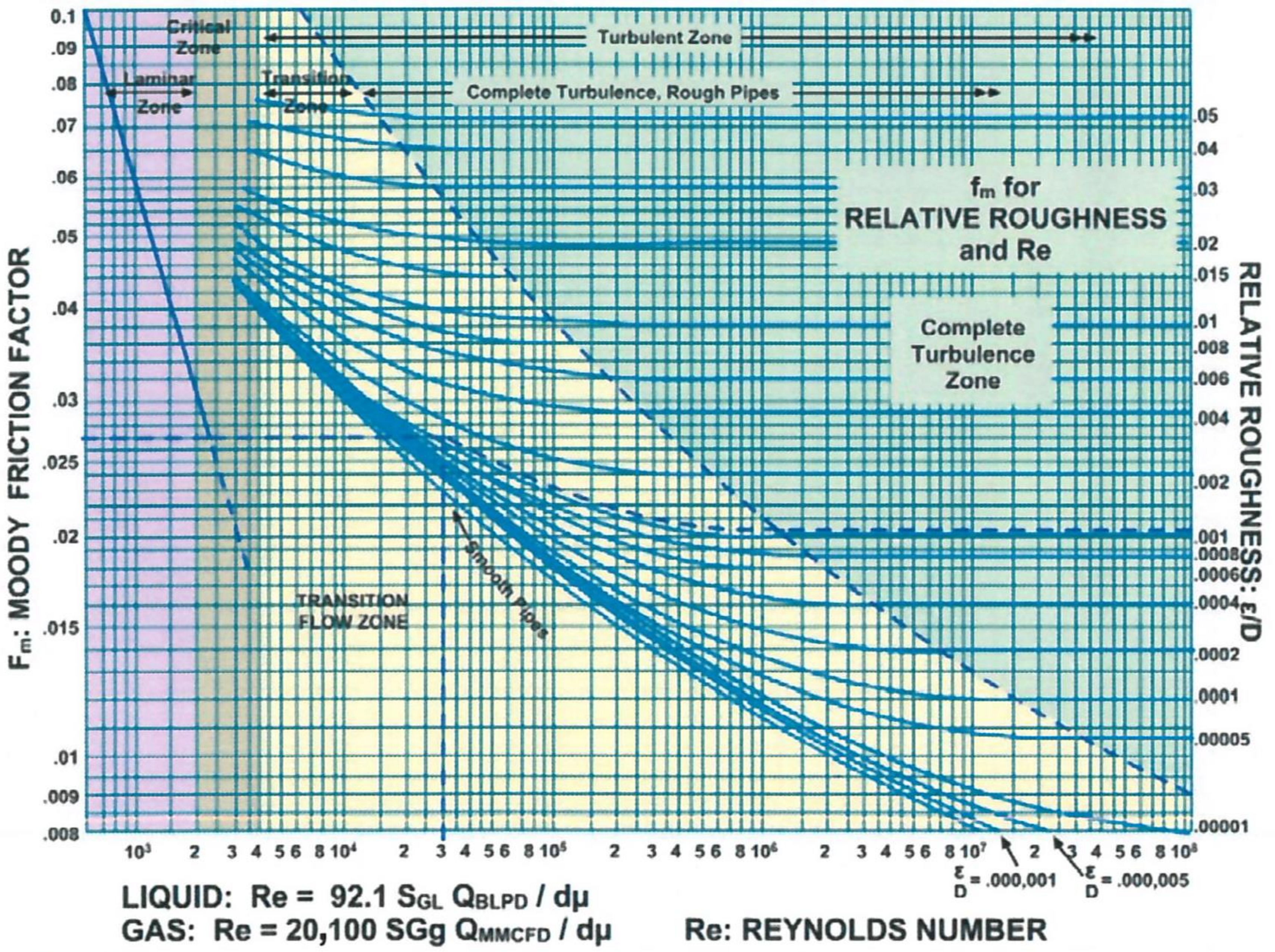
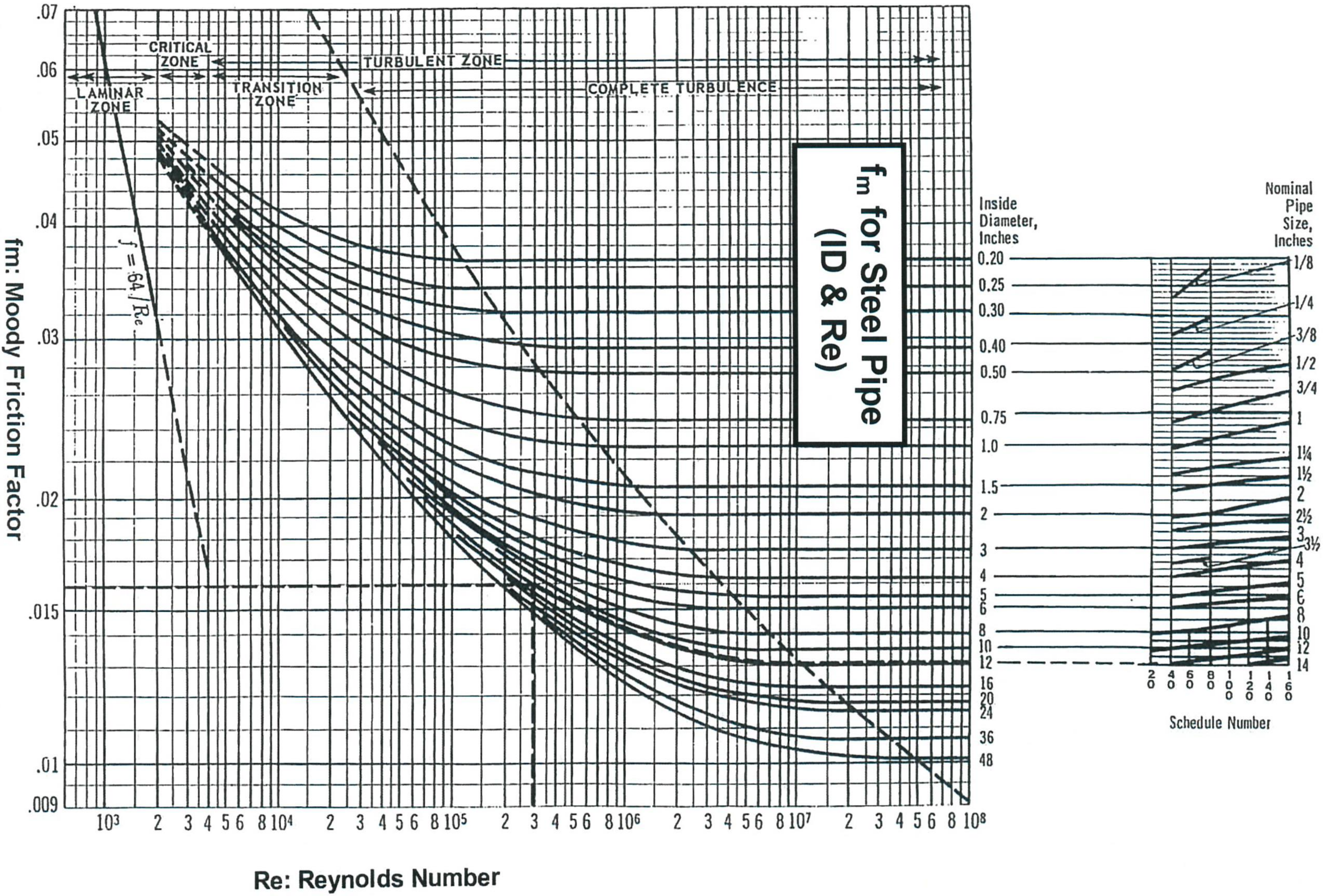
Note: Absolute Roughness units are in feet.
Relative Roughness is Dimensionless.

ε for Steel Pipe = 0. 00015 feet



Turbulent Zone
Critical Zone
Laminar Zone
Transition Zone
Complete Turbulence, Rough Pipes
fm for RELATIVE ROUGHNESS and Re
Complete Turbulence Zone
TRANSITION FLOW ZONE
Smooth Pipes
Fm: MOODY FRICTION FACTOR
RELATIVE ROUGHNESS: ε/D
ε/D = .000,001
ε/D = .000,005
LIQUID: Re = 92.1 SGL QBLPD / dμ
GAS: Re = 20,100 SGg QMMCFD / dμ
Re: REYNOLDS NUMBER



fm: Moody Friction Factor
.07
.06
.05
.04
.03
.02
.015
.01
.009
CRITICAL ZONE
LAMINAR ZONE
TRANSITION ZONE
TURBULENT ZONE
COMPLETE TURBULENCE
f = 64 / Re
fm for Steel Pipe (ID & Re)
Inside Diameter, Inches
0.20
0.25
0.30
0.40
0.50
0.75
1.0
1.5
2
3
4
5
6
8
10
12
16
20
24
36
48
Nominal Pipe Size, Inches
1/8
1/4
3/8
1/2
3/4
1
1¼
1½
2
2½
3
3½
4
5
6
8
10
12
14
20
40
60
80
100
120
140
160
Schedule Number
10³ 2 3 4 5 6 8 10⁴ 2 3 4 5 6 8 10⁵ 2 3 4 5 6 8 10⁶ 2 3 4 5 6 8 10⁷ 2 3 4 5 6 8 10⁸
Re: Reynolds Number

Pressure drop: Laminar flow (Re < 2000)

- Liquid

$$\Delta P_{psi} = 0.00068 \frac{\mu_{cp} L_{ft} V_{ft/sec}}{d_{in}^2}$$

$$\Delta P_{psi} = 7.95 \times 10^{-6} \frac{\mu_{cp} L_{ft} Q_{BPD}}{d_{in}^4}$$

- Gas

$$\Delta P_{psi} = \frac{0.040\ \mu_{cp} L_{ft} T_{^\circ R} Z Q_{MMCFD}}{P_{psi} d_{in}^4}$$

No "f_m" since f_m = 64/Re and Re = SG_L Q / d μ

Pressure drop: Transitional and Turbulent

- Liquid

$$\Delta P_{psi} = 11.5 \times 10^{-6} \frac{f_m L_{ft} Q_{BPD}^2 SG_L}{d_{in}^5}$$

- Gas

$$P_1^2 - P_2^2 = 25.1 \frac{f_m L_{ft} Q_{MMCFD}^2 SG_G Z T_R}{d_{in}^5}$$

Exercise ΔP: Liquid flow in Pipe

- What is the friction pressure drop in 10,000 ft of 2 inch ID pipe flowing 50 BPD of 35 ^{o}API crude oil (μ=1.2 cp and SG_L=0.85) ?

1. First calculate Reynold's number to determine flow regime

   :

2. Use the equation for

   $\Delta P_{psi} =$

Exercise: Increasing flow rate 3000 BPD

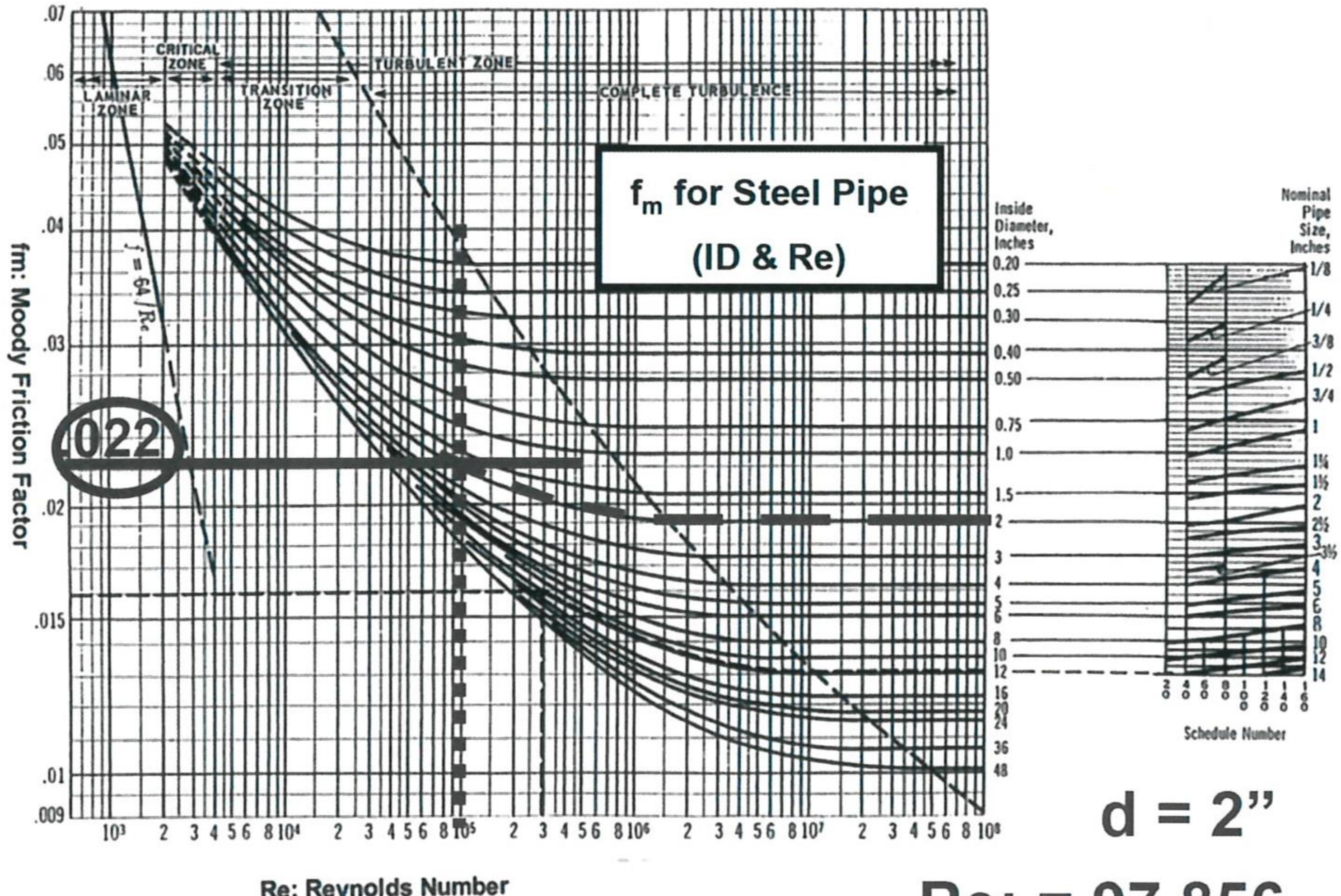
1. First calculate Reynold's number to determine flow regime

   :

2. Use the equation for

3. Determine f_m using chart

$\Delta P_{psi}=$



d = 2”

Re: = 97,856

LIQUID: Re = 92.1 SG_L Q_{BLPD} / d μ

GAS: Re = 20,100 SG_g Q_{MMCFD} / d μ

Pipeline sizing Summary

- **Consider Fluid Velocity**
  - Noise / Corrosion / Erosion
  - Liquid / Solids Build-Up
- **Contain Internal Pressure**

$$P = 2\,S\,t\,F\,E\,T\,/\,d$$

- **Pressure Drop: Horizontal Pipeline**

Laminar

$$\text{Liquid}: \Delta P_{psi} = 7.95 \times 10^{-6}\, \mu_{cp}\, L_{ft}\, Q_{BLPD} \,/\, d^4_{inch}$$

$$\text{Gas}: \Delta P_{psi} = 0.40\, \mu_g\, L_{ft}\, T\, Z\, Q_{MMCFD} \,/\, P_{psi}\, d^4_{inch}$$

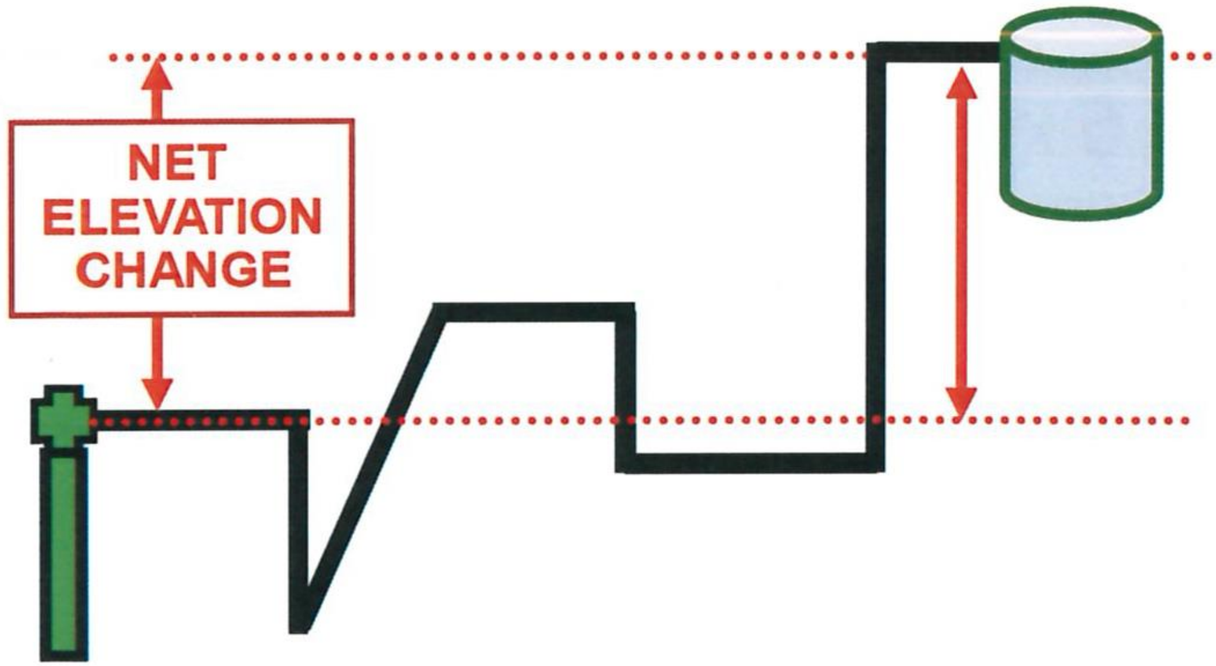
Non-Laminar

$$\text{Liquid}: \Delta P_{psi} = 11.5 \times 10^{-6}\, f_m\, L\, Q^2_{BLPD}\, SG_L \,/\, d^5$$

$$\text{Gas}: (P_1)^2 - (P_2)^2 = 25.1\, f_m\, L\, Q^2_{MMSCFD}\, SG_g\, Z\, T \,/\, d^5$$

Pipeline installation

What if pipeline is not horizontal?



Pressure drop due to Elevation

- Liquid: ΔP due to Elevation

$$\Delta P_{E(psi)} = \frac{\rho_{L(lb/ft^2)} H_{E(ft)}}{144} = 62.4 \frac{SG_L H_{E(ft)}}{144}$$

$$\Delta P_{E(psi)} = 0.433\, SG_L H_{E(ft)}$$

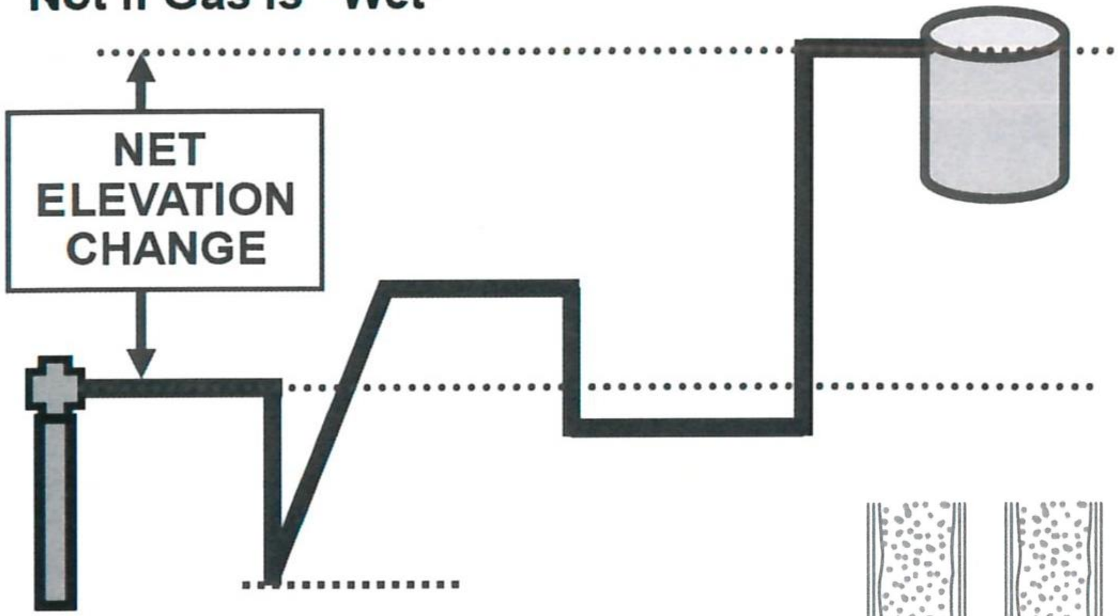
- Gas: ΔP due to Elevation

$$\Delta P_{E(psi)} = \frac{\rho_{G(lb/ft^2)} H_{E(ft)}}{144} = 2.70\, \frac{SG_G P_{psi} / T_{^oR} Z H_{E(ft)}}{144}$$

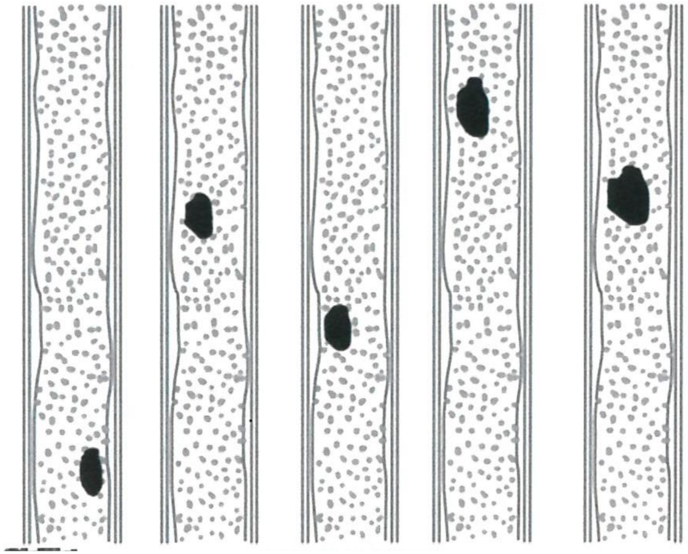
$$\Delta P_{E(psi)} = 0.188\, \frac{SG_G\, P_{psi}}{T_{^oR}\, Z\, H_{E(ft)}}$$

Not always true for gas flow

- Not if Gas is "Wet"

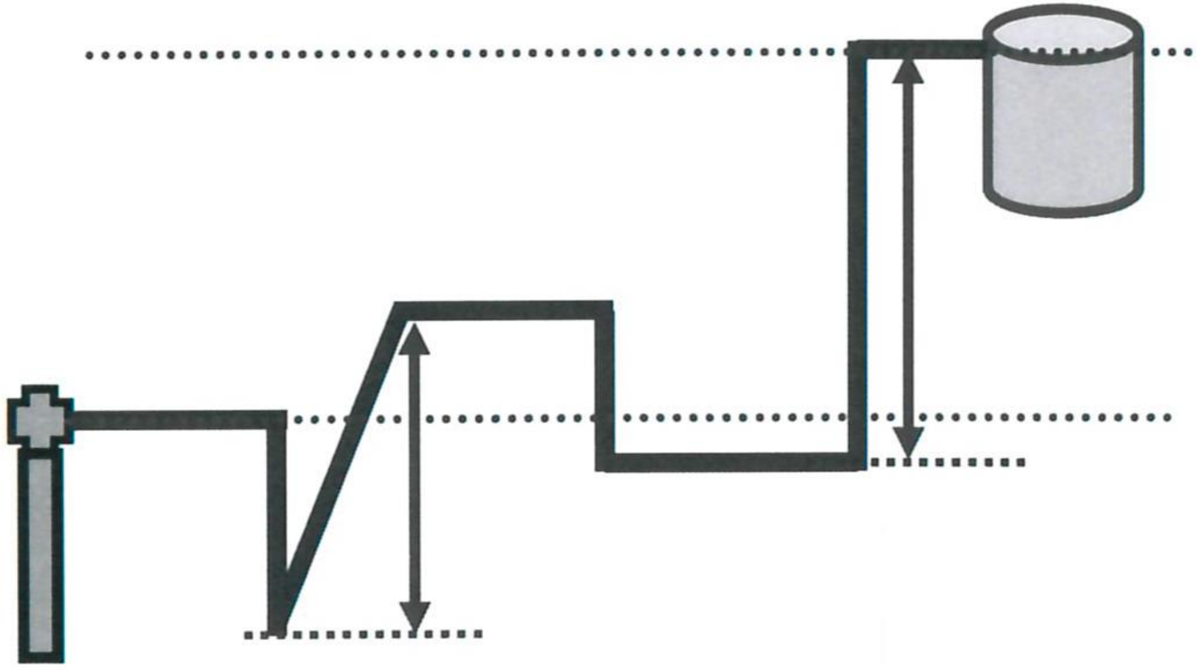


- Big liquid droplets for annular flow



Pressure drop for Wet gas

- Sum the “Ups”



Estimating ΔP without using Friction Factor

- Empirical equations
  - Useful for quick calculation before use of PCs
  - Commonly accepted empirical equations

: Hazen-Williams empirical equation (Liquid flow)

$$\Delta P \quad = 0.7 \times 10^{-6} \frac{Q^{1.85} L \, SG_L}{d^{4.87}}$$

$$(\Delta P \; in \; psi, Q \; in \; BLPD, L \; in \; feet, d = ID \; in \; inches)$$

: Weymouth formula (gas flow)

$$P_2^2 = P_1^2 \quad - \left[\frac{0.8 \, L_{ft} T_R Z \, SG_G Q_{MMCFD}^2}{d_{in}^{5.334}} \right]$$

- most common for oil field use
- good for IDs between 0.75 inch & 16 inch
- at Laminar rates, calculated ΔP is too low

: Panhandle empirical equation (gas flow)

Panhandle: A & B Empirical equation

- For estimating ΔP without friction factor

A: $$Q_{MMCFD} = \left[\frac{0.020\,E\,\left(P_1^2 - P_2^2\right)^{0.51} d^{2.62}}{\left(SG_G^{0.853} z T^{o}{}_R L_{mi}\right)^{0.539}}\right]$$

- For IDs between 6 inch and 24 inch

- Re between $5*10^6$ and $15*10^6$

B: $$Q_{MMCFD} = \left[\frac{0.028\,E\,\left(P_1^2 - P_2^2\right)^{0.51} d^{2.53}}{\left(SG_G^{0.961} z T^{o}{}_R L_{mi}\right)^{0.51}}\right]$$

- For IDs between 6 inch and 24 inch

- Re > $15*10^6$

ΔP in psi, Q in MMCFD, L_{mi} in miles, d = ID in inches

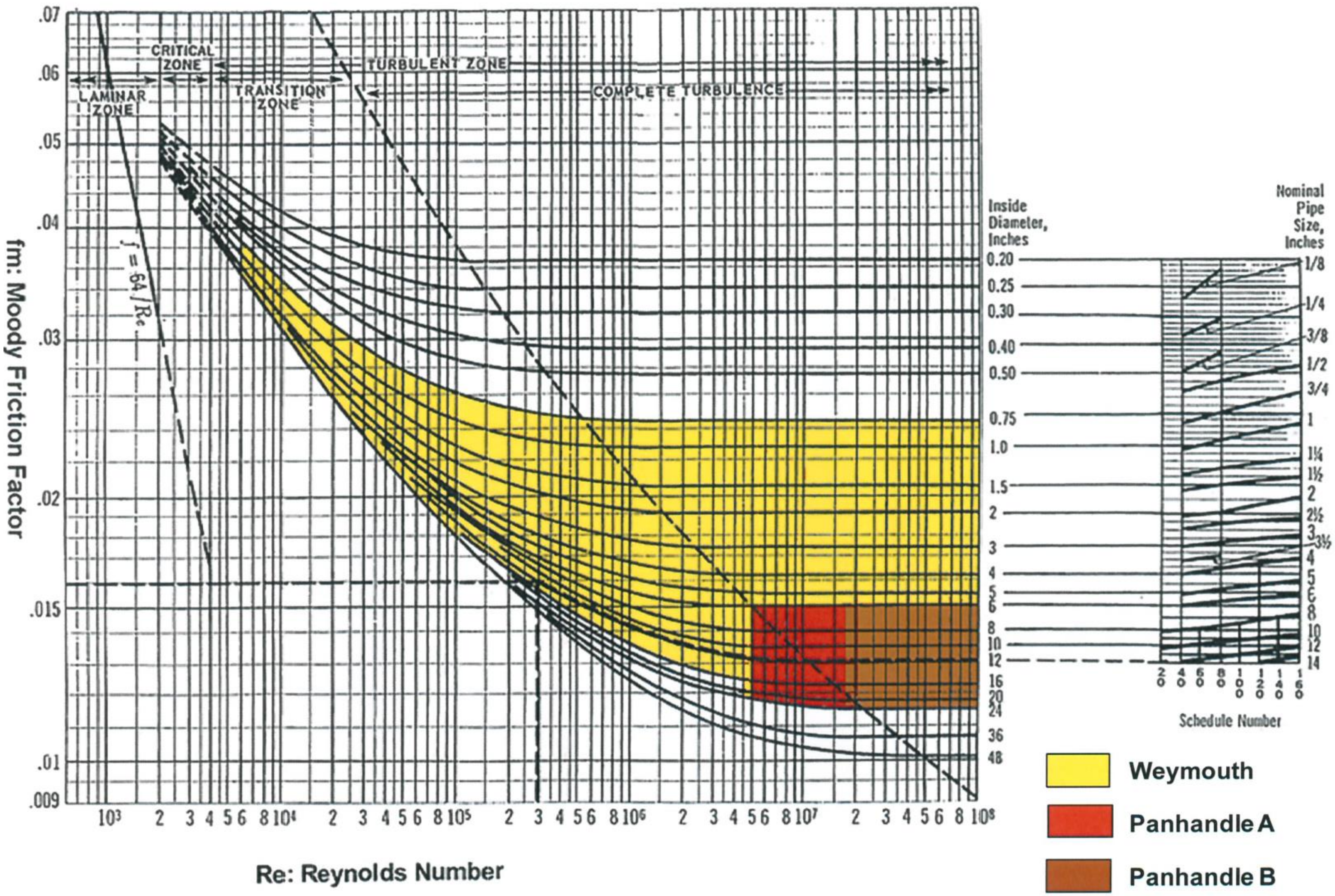
E factor : E = 1.00 for new pipe

= 0.95 for good condition

= 0.92 for average condition

= 0.85 for old pipe

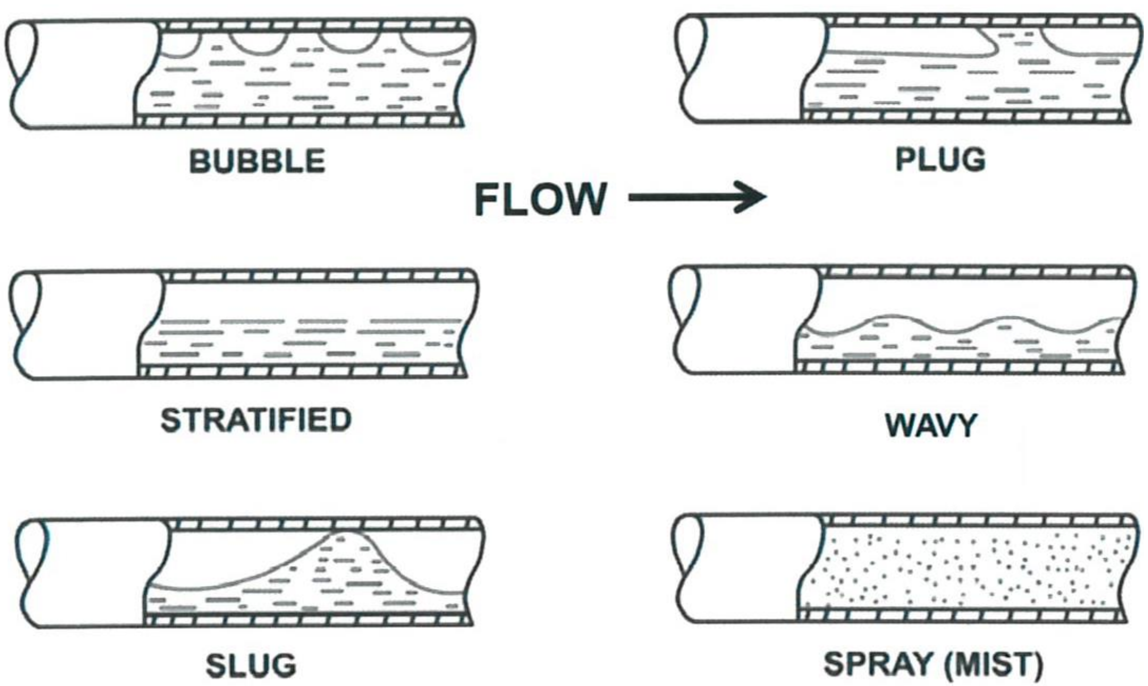
= 0.75 for corroded pipe



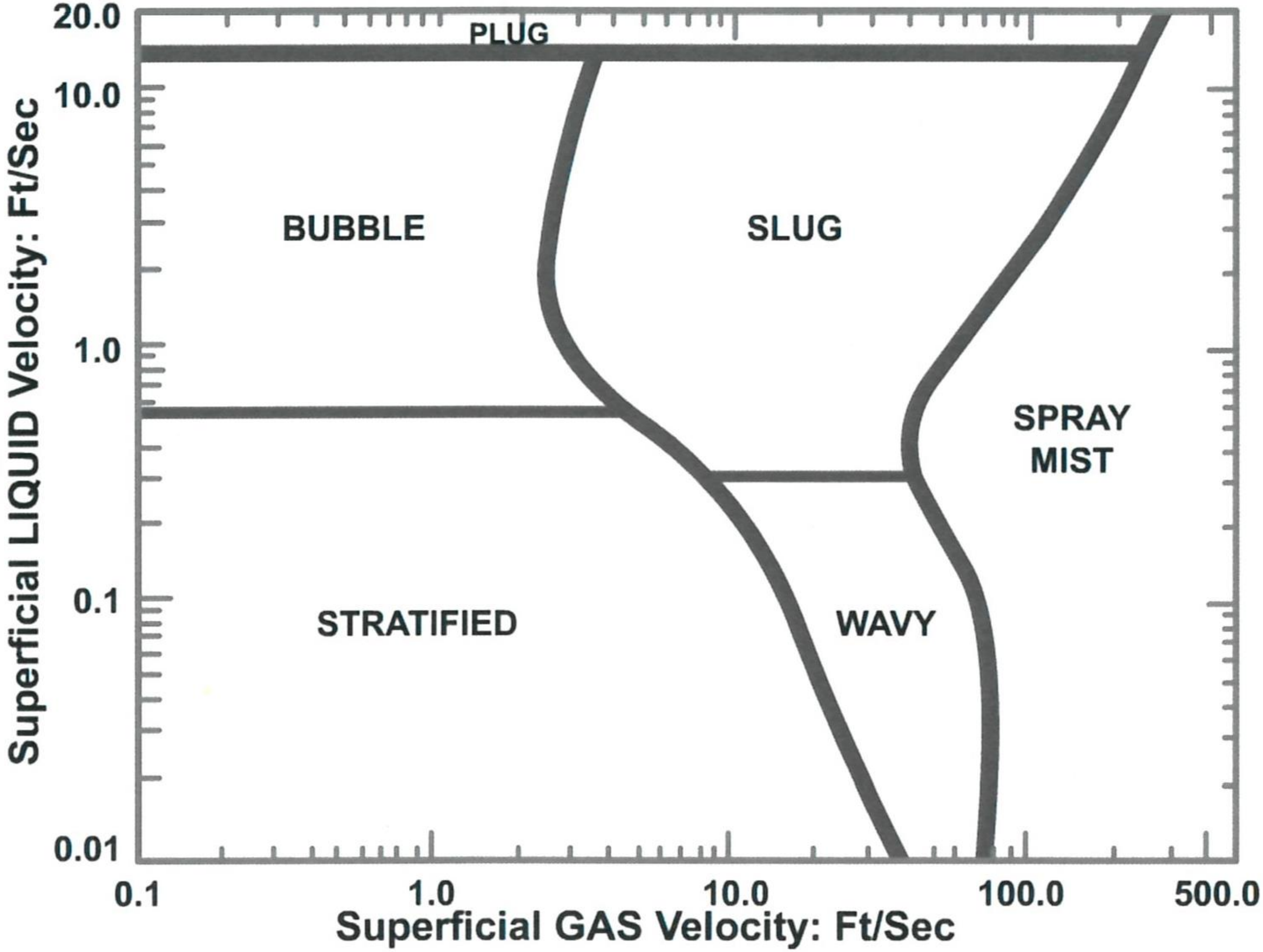
fm: Moody Friction Factor
Re: Reynolds Number
LAMINAR ZONE
CRITICAL ZONE
TRANSITION ZONE
TURBULENT ZONE
COMPLETE TURBULENCE
f = 64/Re
Inside Diameter, Inches
Nominal Pipe Size, Inches
Schedule Number
Weymouth
Panhandle A
Panhandle B

Pressure drop in pipe: Two phase flow

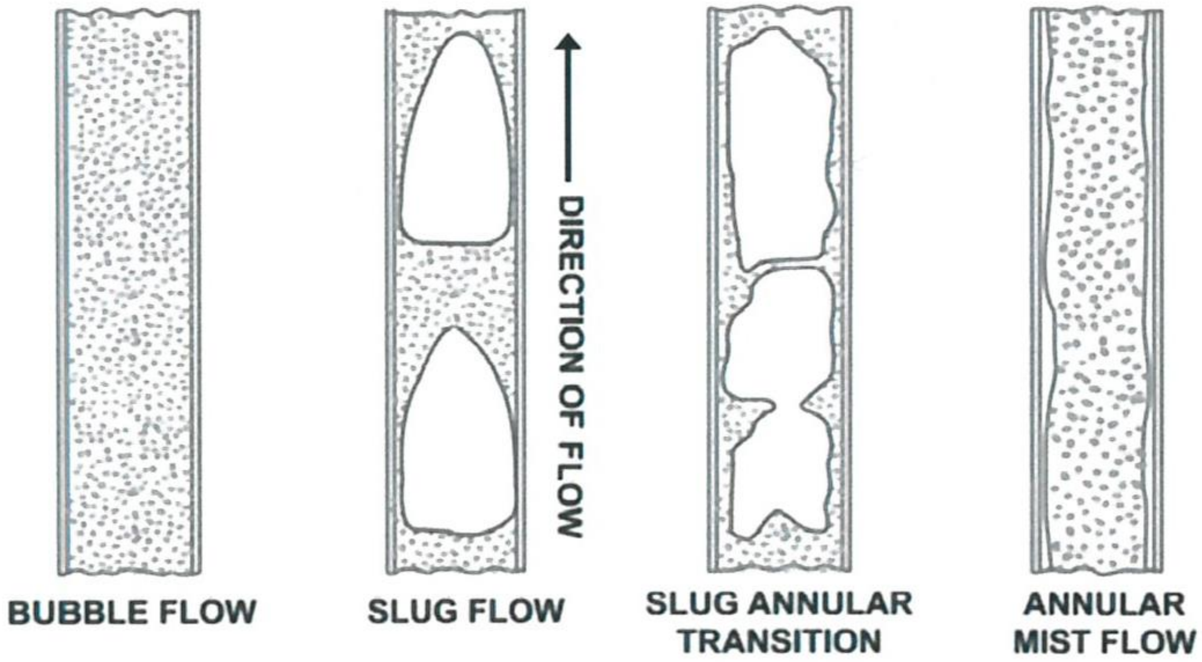
- With liquid and gas both flowing
  - Two phase flow
  - Three phase flow
- Horizontal flow patterns
  - Noise produced with bubbles
  - Using superficial velocities for gas and liquid



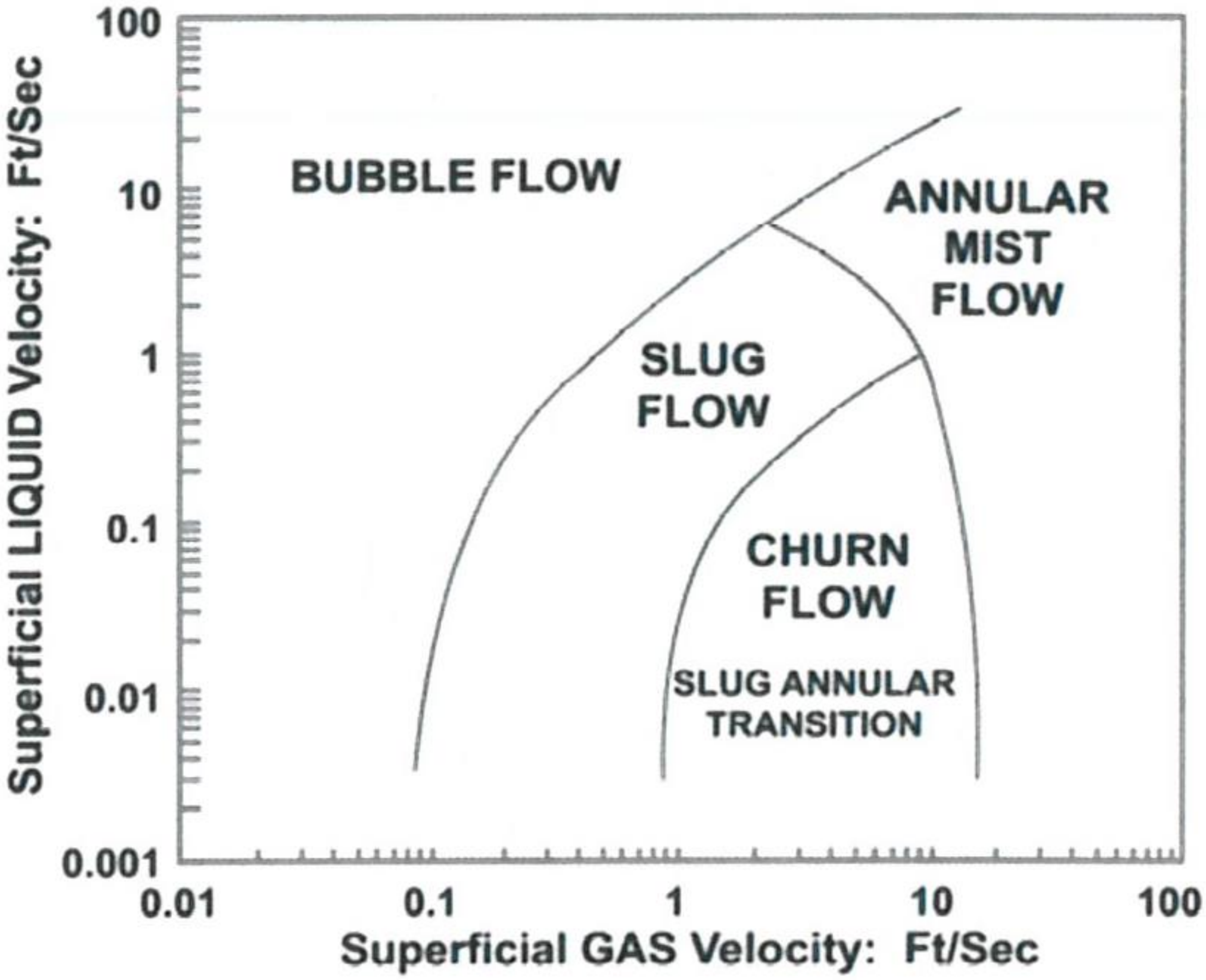
Two-phase horizontal flow regime



Vertical two-phase flow regimes



Two-phase vertical flow regimes



Pressure drop for two-phase flow

- Very complex: errors ≈ 20% common
  - Use simulation software and experience
- API RP 14 E gives following simplified method
  - Assumes: $\Delta P < 10\%$, bubble / mist flow, f=0.015

$$\Delta P = \frac{5 \times 10^{-8}\, L\, W^2}{d^5\ \rho_{mix}}$$

where, W= 3180 $Q_{MMCFD} SG_G + 14.6\, Q_{BPD} SG_L$

$$and\ \rho_{mix} = \frac{12409\, SG_L P + 2.7\, R_{scf/bbl} SG_G P}{198.7\, P + R_{scf/bbl}\, T\, z}$$

Two phase flow: High GOR > 10,000 ft^3/bbl

- Use gas equations but change SG_G to :

$$SG_{mix} = \frac{SG_G + \frac{4591\ SG_L}{R_{scf/bbl}}}{1 + \frac{1123}{R_{scf/bbl}}}$$

If GOR < 10,000 scf/bbl, use two-phase correlations

AGA: Recommended multiphase ΔP calculations

HAND CALCULATION METHODS

- Frictional ΔP: Dukler, A.E., Moye Wicks, III, and R.G. Cleveland. "Frictional Pressure Drop in Two-Phase Flow: B. An Approach through Similarity Analysis" AIChE Journal, Vol 10, No. 1, January 1964, pp. 44-51.
- Elevation ΔP: Flanigan, Orin. "Effect of Uphill Flow on Pressure Drop in Design of Two-Phase Gathering Systems" Oil and Gas Journal, March 10, 1958, pp. 132-141.
- Liquid Hold-up: Eaton, Ben A., et al. "The Prediction of Flow Patterns, Liquid Holdup and Pressure Losses Occurring During Continues Two-Phase Flow in Horizontal Pipelines" J. Pet. Tech. AIME, JUNE 1967, pp.815-828.

For examples using these Methods : see AGA ENGINEERING DATA BOOK

Gas Processors Association. 1998

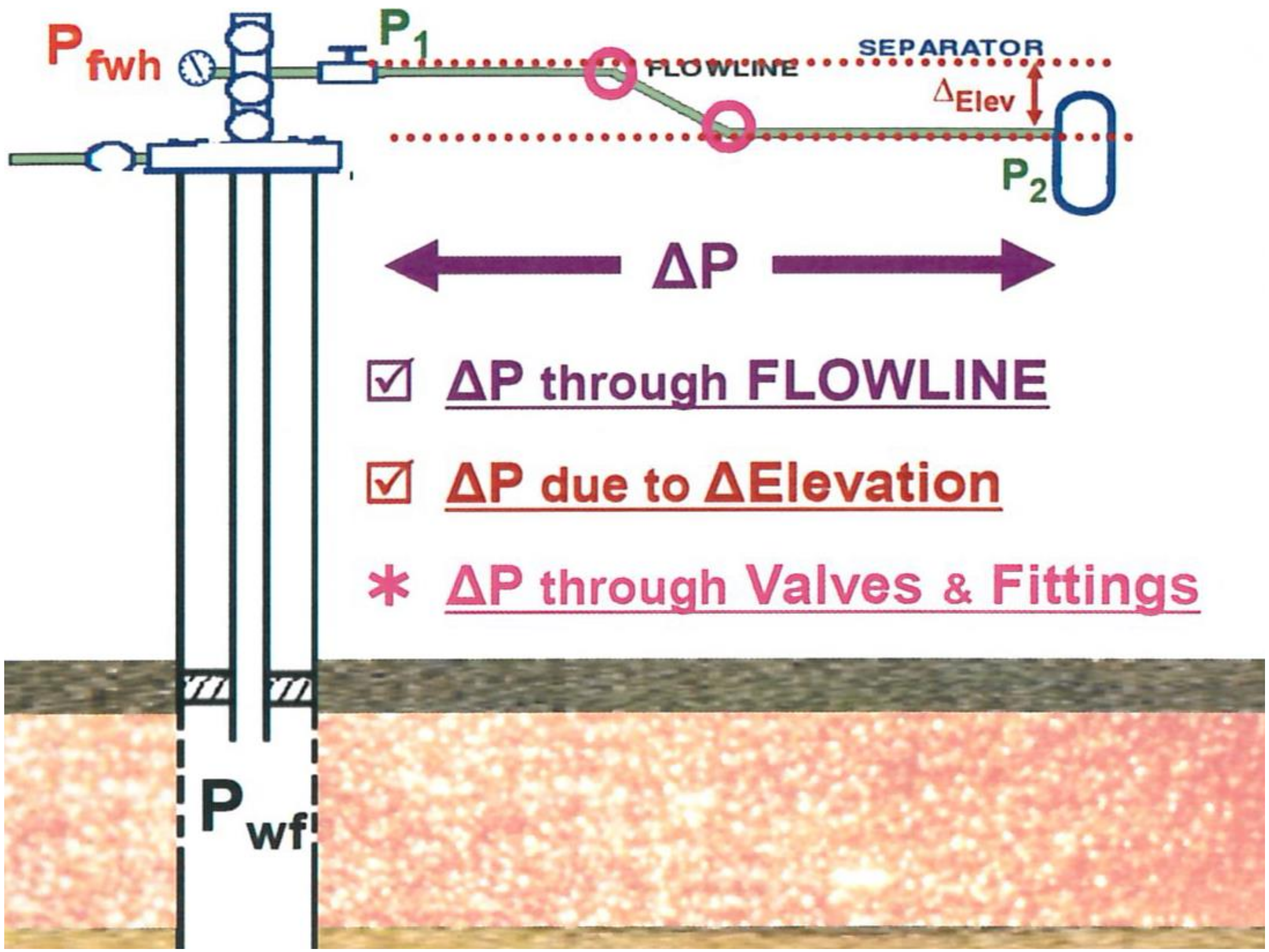
gpsa@gasprocessors.com

COMPUTER CALCULATION METHODS

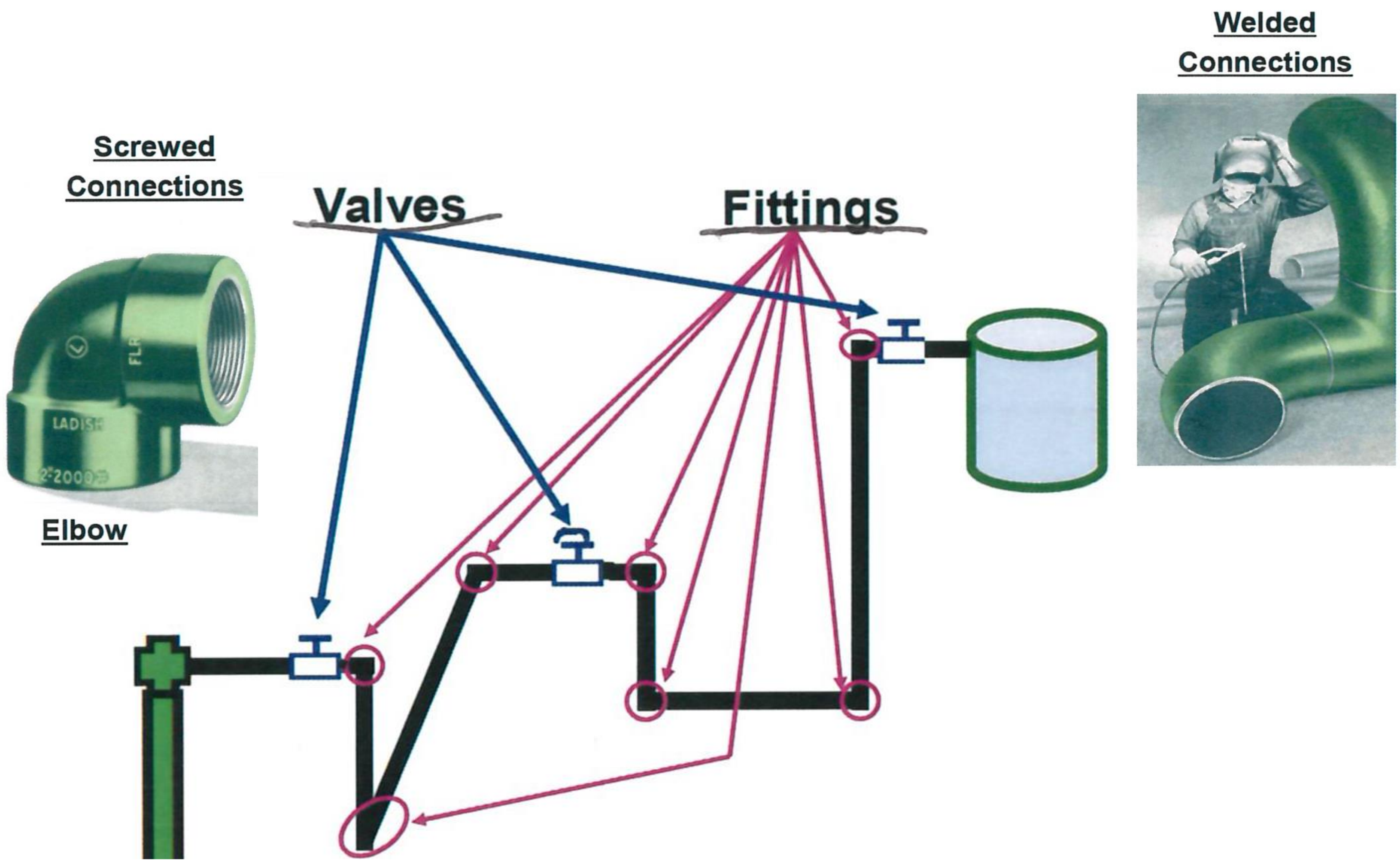
- Beggs, H. Dale, and James P. Brill. "A Study of Two-Phase Flow in Inclined Pipes" Trans. AIME, May 1973, pp. 606 – 617.
- Orkiszewski, J. "Predicting Two-Phase Pressure Drops in Vertical Pipe" Pet. Tech, AIME, 6/67 pp 829 – 838.
- Baker, O. , et al. "Gas-Liquid Flow in Pipelines, II. Design Manual" AGA - API Project NX-28, 10/ 70
- Brill & Mukherjee "Multiphase Flow in Wells" Monograph Vol 17 SPE Henry L Doherty Series

Ansari and Olga-S Transient Multiphase Simulator: OLGA

Pressure drop through valves and fittings



Pressure drop through valves and fittings



Pressure drop through valves and fittings

- Resistance coefficients: K_r
- Flow coefficients: liquid – C_v, Gas – C_g
- Equivalent length: L_E

Darcy's Law for valves and fittings

- Resistance coefficient: K_r

$$\Delta H = K_r \frac{v^2}{2\,g}, where\ K_r = \frac{f\,L}{D}$$

Larger K_r ⇨ Larger ΔP

- Liquid

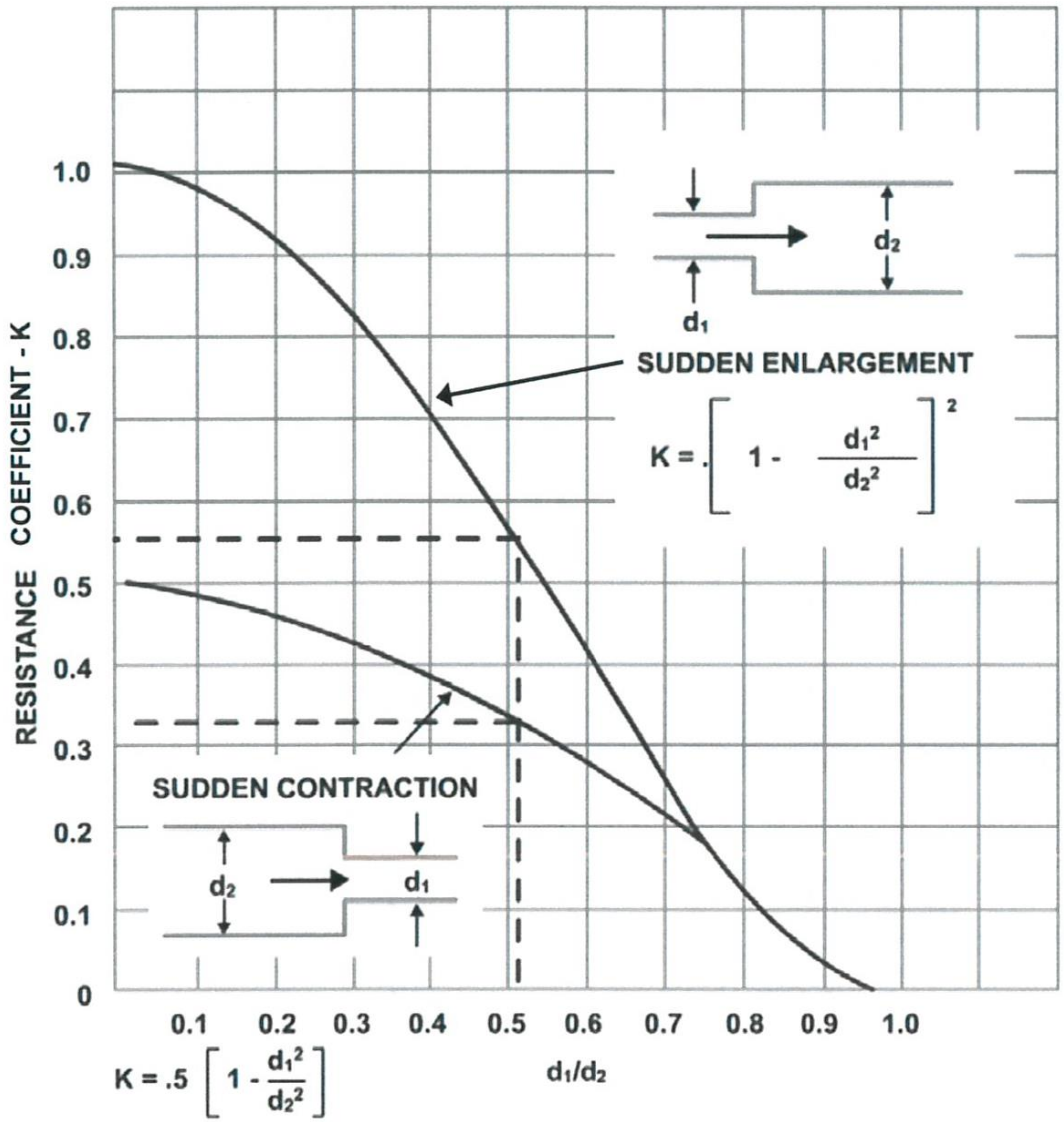
$$\Delta P_{psi} = 0.958 \times 10^{-6} \frac{K_r Q_{BPD}^2 SG_L}{d^4}$$

- Gas

$$P_1^2 - P_2^2 = 2.09 \frac{K_r Q_{MMCFD}^2 SG_G z\, T_{^oR}}{d^4}$$

Resistance coefficients

Global Valve, wide open	10.0
Angle Valve, wide open	5.0
Gate Valve, wide open	0.2
Tee	1.8
90° Elbow	0.9
45° Elbow	0.4



Darcy's law for valves and fittings

- Flow coefficient: C_v and C_g

  : a relative measure of its efficiency at allowing fluid flow

Larger C_v (liquids) or C_g (gases) ⇨ Smaller ΔP

- Liquid

$$\Delta P_{psi} = 8.5 \times 10^{-4} \frac{Q_{BPD}^2 SG_L}{C_v^2}$$

- Gas

$$P_1^2 - P_2^2 = 1.869 \frac{Q_{MMCFD}^2 SG_G z\, T_{°R}}{C_g^2}$$

Relationship between K_r and C_v

$$C_v = 29.9 \frac{d^2}{\sqrt{K_r}}$$

$$K_r = 894 \frac{d^4}{C_v^2}$$

Equivalent lengths

- The pressure drop in a system component such as valve and fittings can be converted to the **"equivalent length"** of a pipe or tube that would give the same pressure loss.

$$L_E = \frac{K_r\, d}{12\, f_m}$$

$$L_E = 74.5\, \frac{d^5}{f_m C_v^2}$$

L_E: Equivalent Length of Valves and Fittings, in Feet

Nominal Pipe size in.	Globe valve or ball check valve	Angle valve	Swing check valve	Plug cock	Gate or ball valve	45° ell Welded	45° ell Threaded	Short rad. ell Welded	Short rad. ell Threaded	Long rad. ell Welded	Long rad. ell Threaded	Hard T Welded	Hard T Threaded	Soft T Welded	Soft T Threaded	90° miter bends 2 miter	90° miter bends 3 miter	90° miter bends 4 miter
1½	55	26	13	7	1	1	2	3	5	2	3	8	9	2	3			
2	70	33	17	14	2	2	3	4	5	3	4	10	11	3	4			
2½	80	40	20	11	2	2	-	5	-	3	-	12	-	3	-			
3	100	50	25	17	2	2		6		4		14		4				
4	130	65	32	30	3	3		7		5		19		5				
6	200	100	48	70	4	4		11		8		28		8				
8	260	125	64	120	6	6		15		9		37		9				
10	330	160	80	170	7	7		18		12		47		12				
12	400	190	95	170	9	9		22		14		55		14		28	21	20
14	450	210	105	80	10	10		26		16		62		16		32	24	22
16	500	240	120	145	11	11		29		18		72		18		38	27	24
18	550	280	140	160	12	12		33		20		82		20		42	30	28
20	650	300	155	210	14	14		35		23		90		23		46	33	32
22	688	335	170	225	15	15		40		25		100		25		52	36	34
24	750	370	185	254	16	16		44		27		110		27		56	39	36
30	-	-	-	312	21	21		55		40		140		40		70	51	44
36	-	-	-		25	25		66		47		[illegible]		47		84	[illegible]	52
42	-	-	-		30	30		77		55		200		55		98	69	64
48	-	-	-		35	35		88		55		220		65		112	81	72
54	-				40	40		99		70		250		70		126	90	80
60	-				45	[illegible]		110		80		[illegible]		80		190	99	92

Enlargement and contraction (equiv. L in terms of small d):

Nominal Pipe size in.	Enlargement Sudden d/D = 1/4	Enlargement Sudden d/D = 1/2	Enlargement Sudden d/D = 3/4	Enlargement Std. red. d/D = 1/2	Enlargement Std. red. d/D = 3/4	Contraction Sudden d/D = 1/4	Contraction Sudden d/D = 1/2	Contraction Sudden d/D = 3/4	Contraction Std. red. d/D = 1/2	Contraction Std. red. d/D = 3/4
1½	5	3	1	4	1	3	2	1	1	-
2	7	4	1	5	1	3	3	1	1	-
2½	8	5	2	6	2	4	3	2	2	-
3	10	6	2	8	2	5	4	2	2	-
4	12	8	3	10	3	6	5	3	3	-
6	18	12	4	14	4	9	7	4	4	1
8	25	16	5	19	5	12	9	5	5	2
10	31	20	7	24	7	15	12	6	6	2
12	37	24	8	28	8	18	14	7	7	2
14	42	25	9	-	-	20	16	8	-	-
16	47	30	10	-	-	24	18	9	-	-
18	53	35	11	-	-	26	20	10	-	-
20	60	38	13	-	-	30	23	11	-	-
22	65	42	14	-	-	32	25	12	-	-
24	70	46	15	-	-	35	27	13	-	-

Full Opening - Small L_E

Reduced Opening - Large L_E

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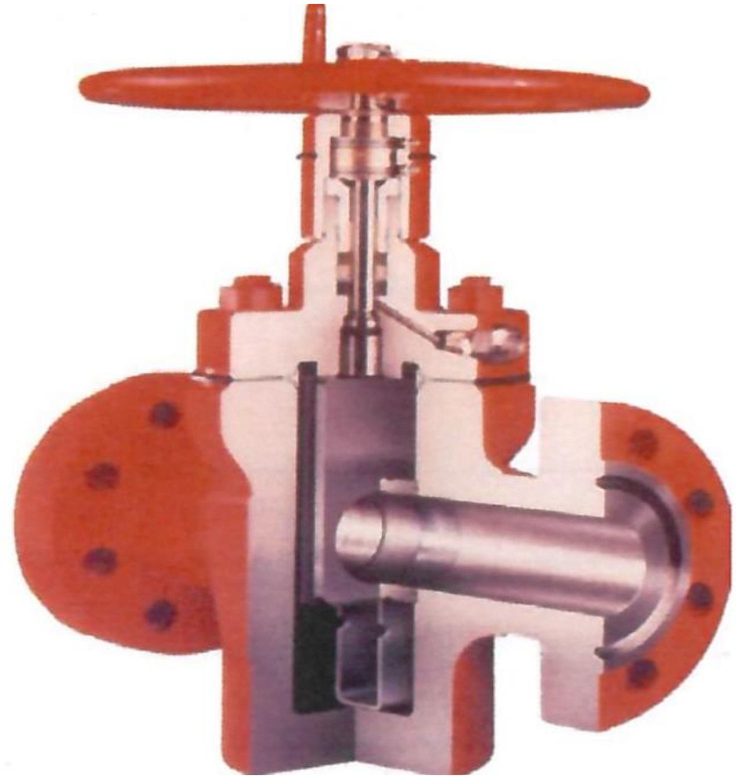
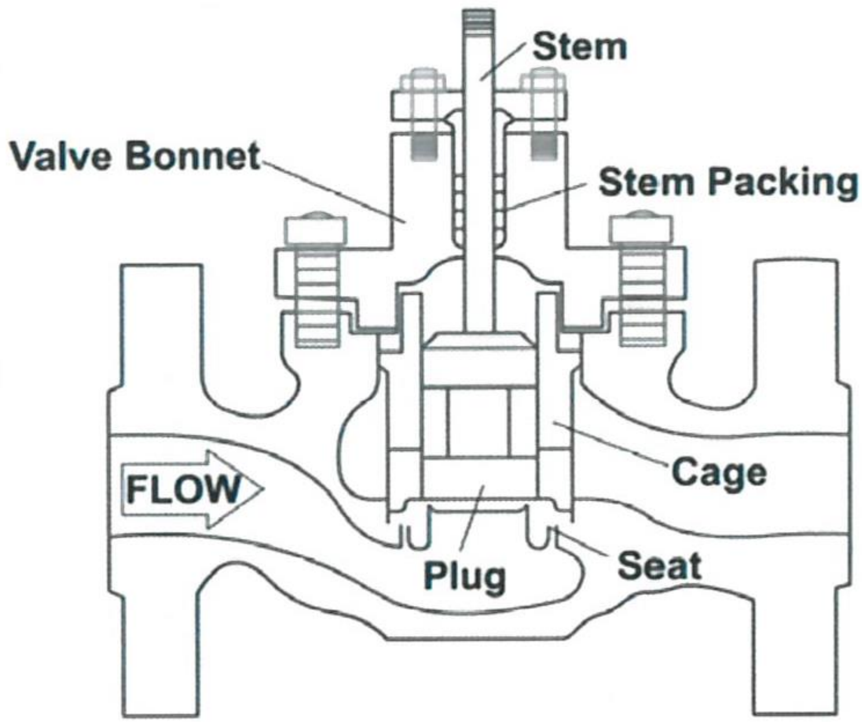
Gate valve



- Full Opening Throughput
- Not Much ΔP
- Small L_E

Globe valve



- Reduced Opening Throughput
- Larger ΔP
- Larger L_E

Thank you