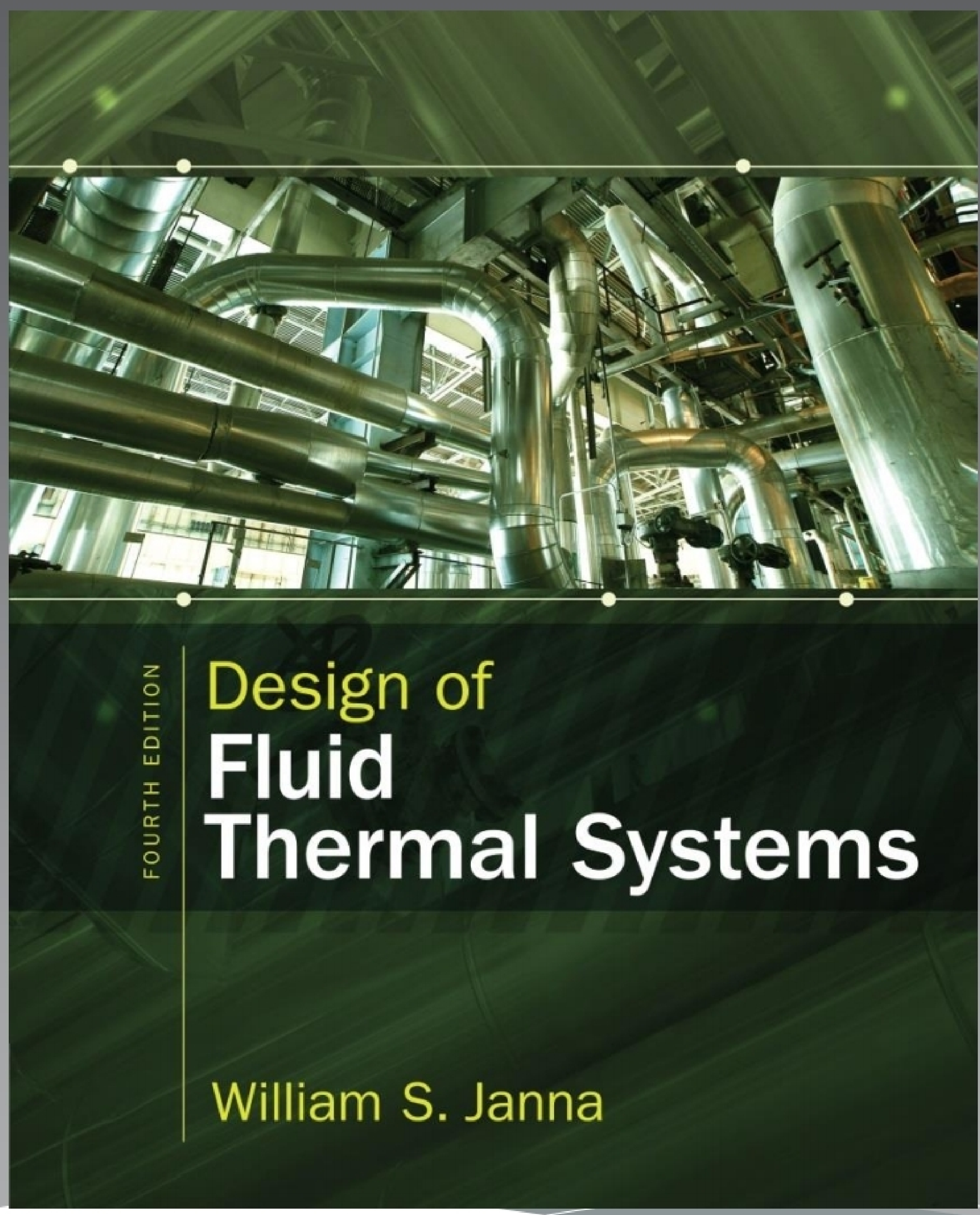


Chapter 3

Piping Systems I

CENGAGE Learning

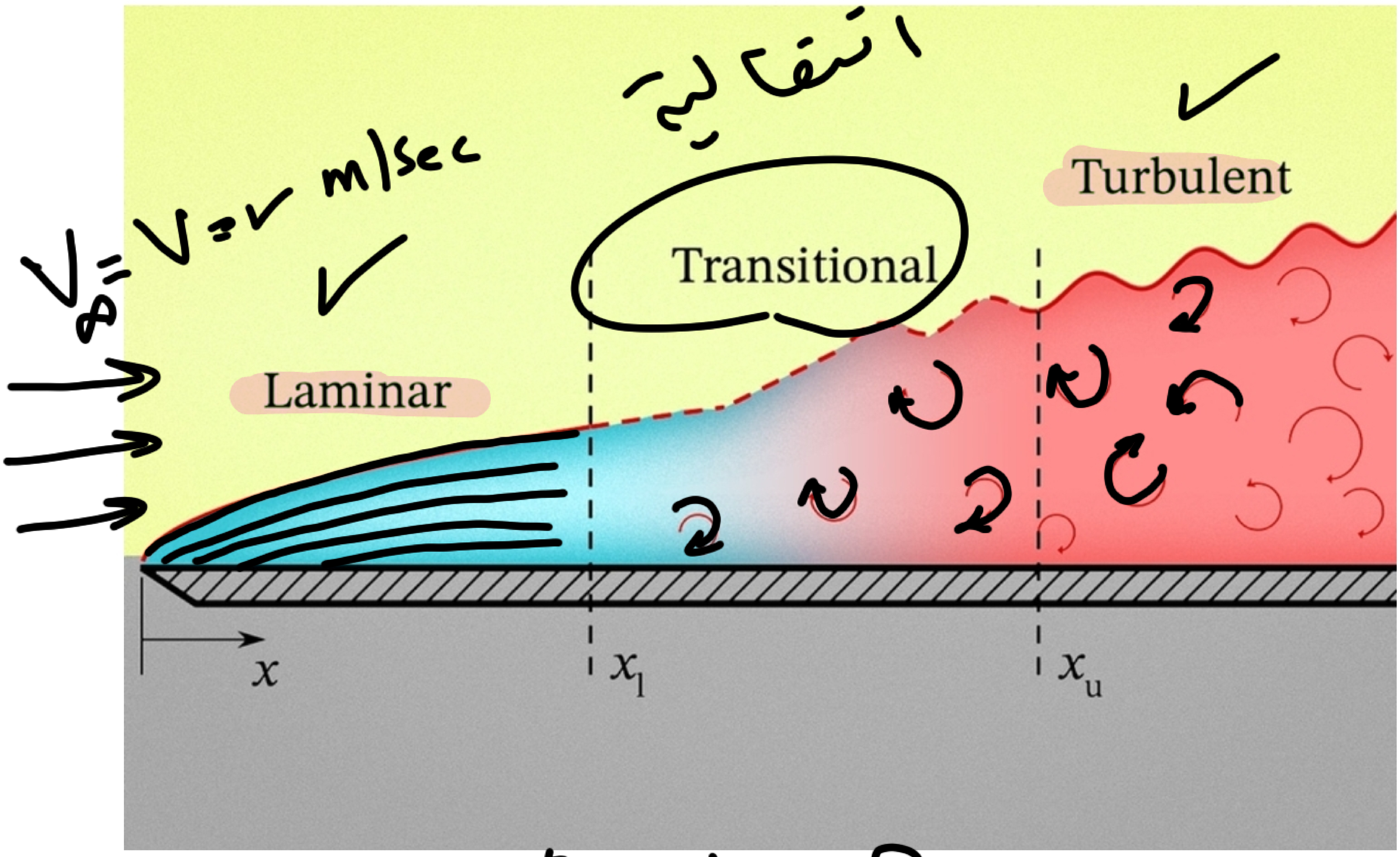
3.0 – Reynolds number

Flow can be characterized as:

- **Laminar flow** → $\boxed{\mathrm{Re} = \dfrac{\rho V D}{\mu g_c} = \dfrac{VD}{\nu} < 2\,100}$
- **Turbulent flow** → **Re > 4000**
- **V : is the average velocity of the flow**
- **D : is a characteristics dimension the duct cross section**

A quick warning:

- This concept, under whatever terms and nomenclature you learned it ($\rho VD/\mu$, VD/ν, ratio of inertial to viscous forces), MUST be completely familiar in all aspects to you.
- *This course will not be passable if you don't remember fluid mechanics and dynamics.*



$$Re = \frac{\text{Inertia Force}}{\text{Viscous Force}}$$

$$\boxed{Re = \frac{\rho V l_c}{\mu}} \quad (1)$$

نيو $\nu = \frac{\mu}{\rho}$ $\frac{m^2}{sec}$

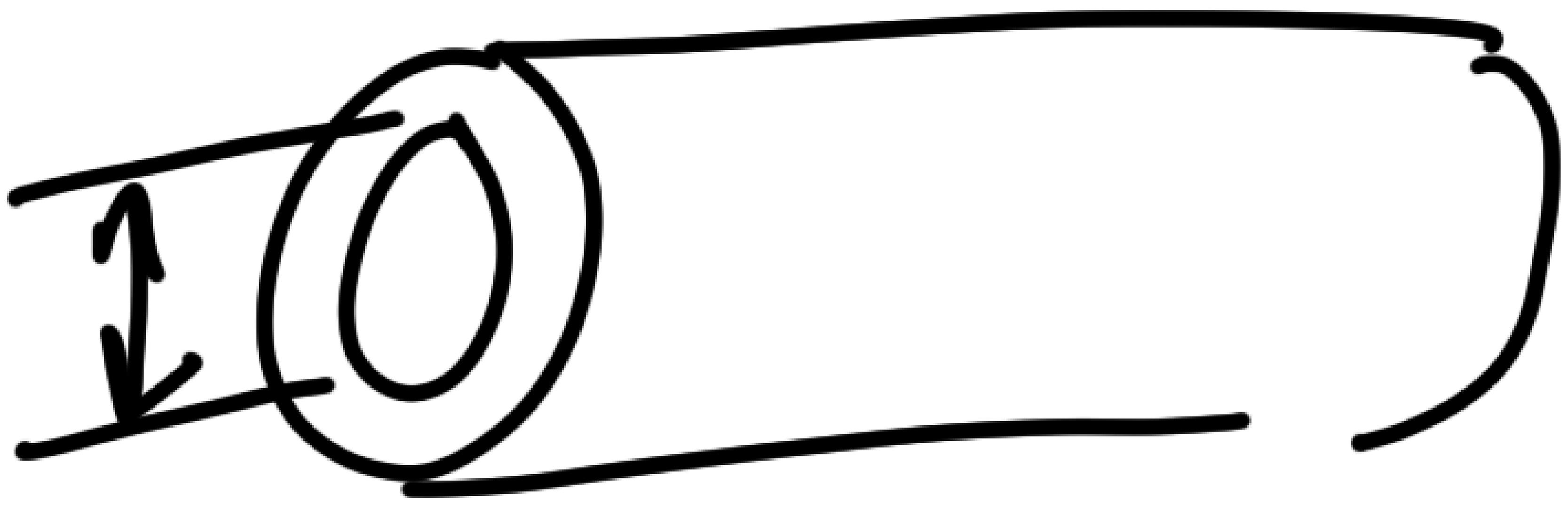
$\nu \rightarrow$ kinematic viscosity

$\rho \rightarrow$ density kg/m^3

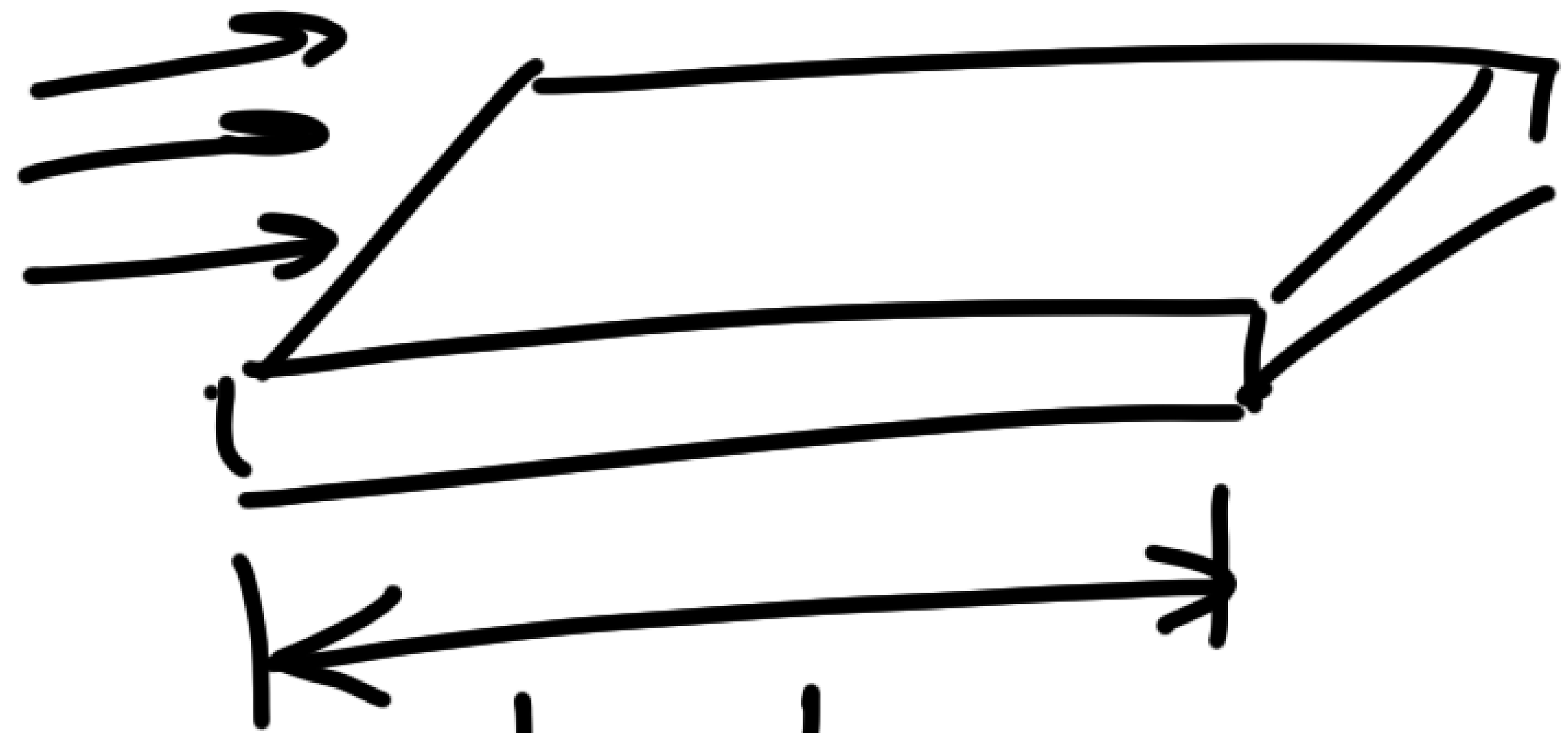
$V \rightarrow$ velocity m/sec

$\mu \rightarrow$ dynamic viscosity $\frac{kg}{m\cdot sec} \equiv \frac{N}{m^2}\cdot sec$ Pa.sec

$$Re = \frac{\rho V l_c}{\mu} = \frac{V l_c}{\nu}$$

D 

$l_c = D$



$L = L_c$

$Re < 2100$

the flow is laminar

f = friction factor = $\dfrac{64}{Re}$

$f >> 4000$ ✓

the flow is Turbulent.

$$f = \frac{0.25}{\left(\log\left[\frac{\varepsilon/D}{3.7} + \frac{5.74}{Re^{0.9}}\right]\right)^2}$$

ابسلون

او

$\dfrac{\varepsilon}{D}$ relative roughness

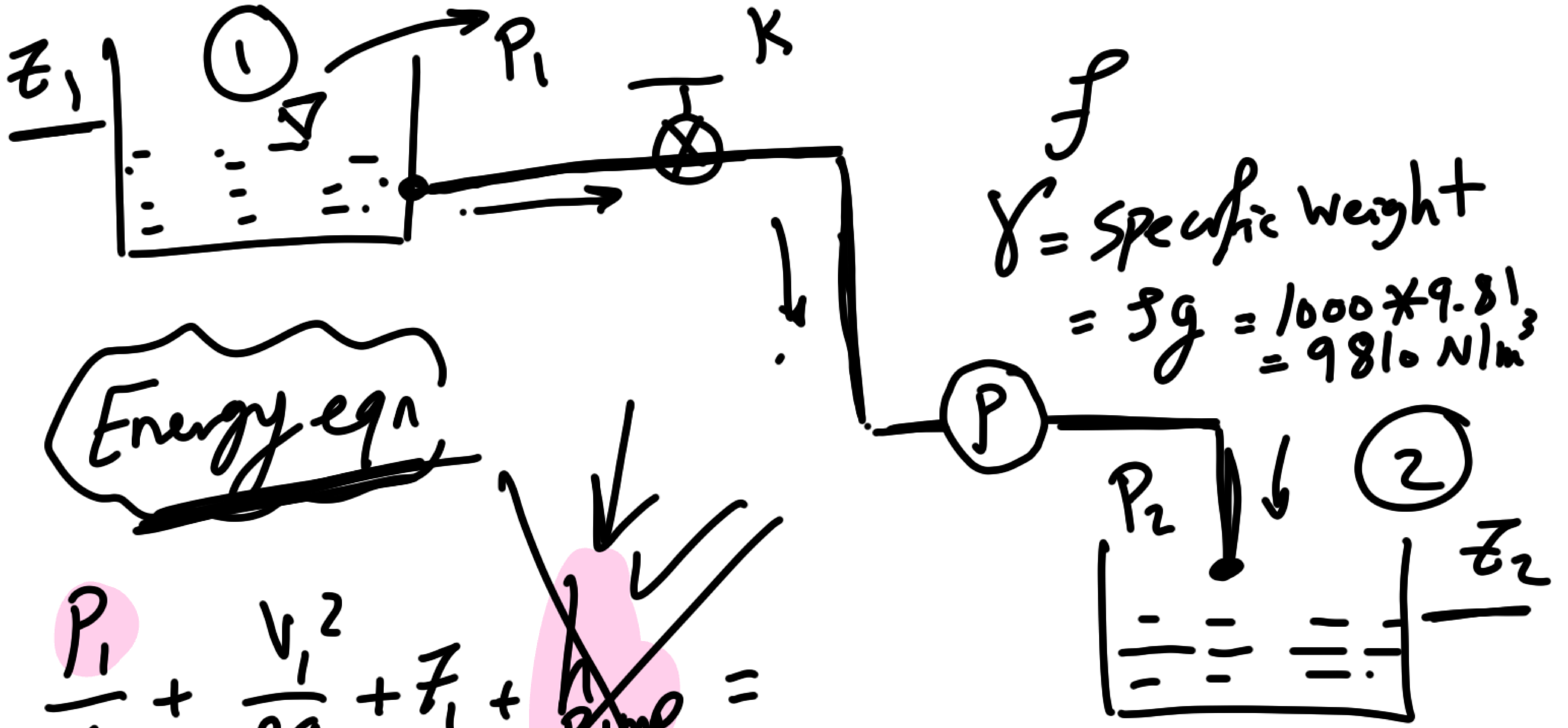
moody chart

$\varepsilon \rightarrow$ absolute roughness

الخشونة

Tables mm

$D \rightarrow$ diameter. (mm)



γ = specific weight

$= \rho g = 1000 * 9.81$

$= 9810\ N/m^3$

Energy eqn

$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + Z_1 + \cancel{h_{pump}} =$$

$$\frac{P_2}{\gamma} + \frac{V_2^2}{2g} + Z_2 + \cancel{h_{Turbine}}^{\,0} + h_{Losses}$$

h_{losses} = major loss + minor loss

$$= f\,\underbrace{\frac{L}{D}\,\frac{V^2}{2g}} + \underbrace{\sum K\,\frac{V^2}{2g}}$$

friction factor

Tables.

$$\boxed{\frac{A_1}{A_2} = \frac{V_2}{V_1}}$$

$$\boxed{A_1 V_1 = A_2 V_2}$$ Continuity eqn.

$$\dot{W}_{pump} = \frac{\gamma Q h_{pump}}{\eta_{pump}}$$

$\eta_{pump} \rightarrow 0.8 \sim 0.9$

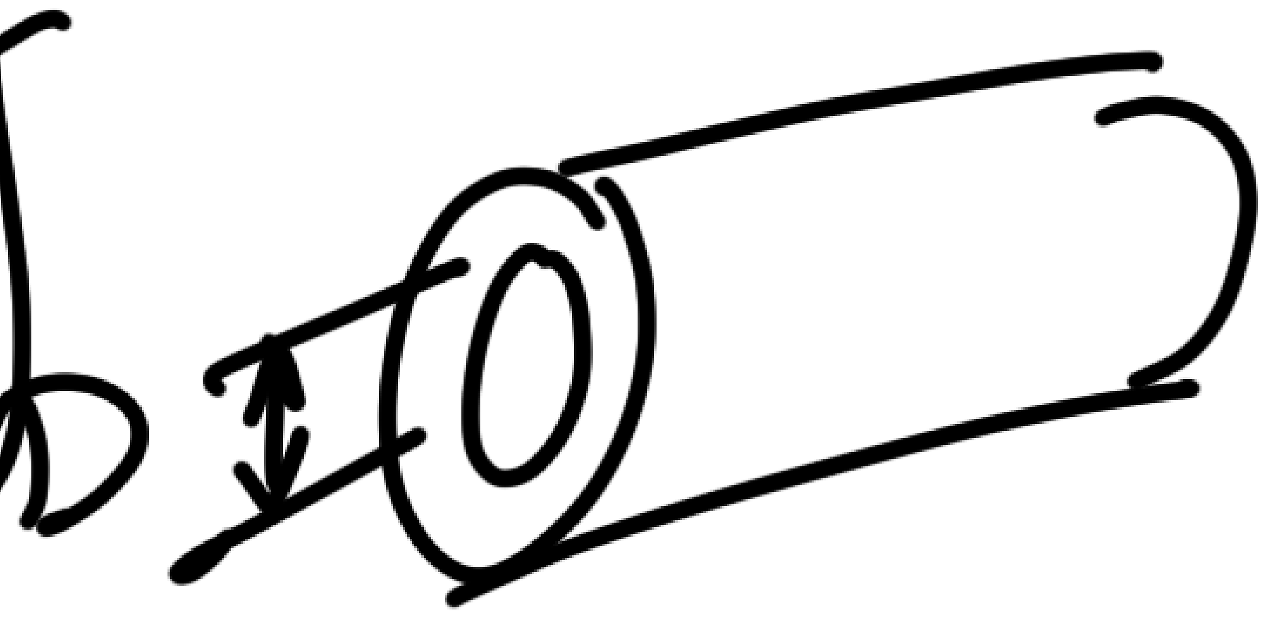
$\gamma = 9810$ W

$Q = \checkmark$ m^3/sec

$\boxed{h_{pump} = \checkmark}$

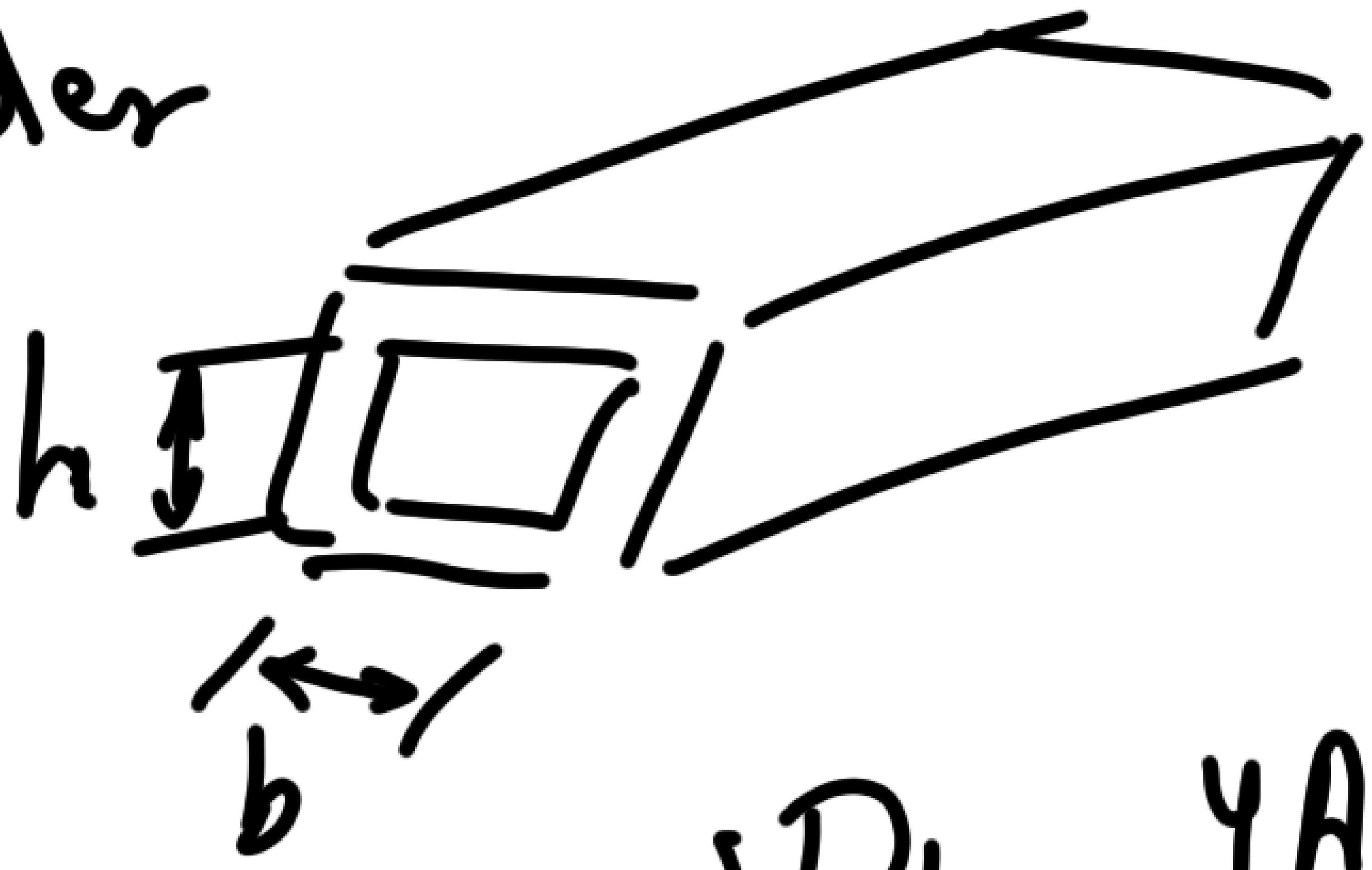
$$Re = \frac{\rho V L_c}{\mu} = \frac{V L_c}{\nu}$$

$$\boxed{Re = \frac{\rho V D_h}{\mu}}$$



D_h = hydraulic diameter

$$\boxed{D_h = D}$$



$$D_h = \frac{4A_c}{P} \rightarrow \text{perimeter}$$

$$D_h = \frac{\cancel{4}\left[\frac{\cancel{\pi}}{\cancel{4}} D^{\cancel{2}}\right]}{\cancel{\pi} \cancel{D}} = D$$

$$D_h = \frac{4A_c}{P} = \frac{\cancel{4}^{2}[bh]}{\cancel{2}^{1}[b+h]}$$

$$D_h = \frac{2bh}{b+h} \checkmark$$

R_h : is the hydraulic radius and widely used for flow in open channels.
D_{eff} : is the diameter of a circular duct that has the same area as the noncircular duct of interest → Continuity equation
D_h : is the hydraulic diameter → Momentum equation (widely used).

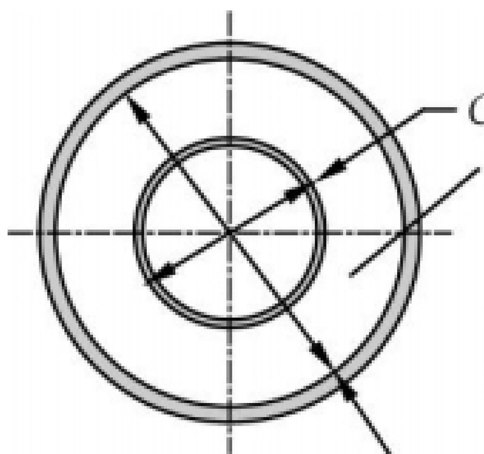


FIGURE 3.1. *Annular cross section bounded by two tubes.*

3.2 – Equivalent diameters

The flow area is not a circle (it's a donut) here, so the ID cannot be used directly in calculations. We use equivalent diameters instead.

$$R_h = \frac{\text{area of flow}}{\text{wetted perimeter}} = \frac{A}{P} \qquad R_h = \frac{A}{P} = \frac{\pi D^2/4}{\pi D} = \frac{D}{4}$$

$$\frac{\pi D_{eff}^2}{4} = A_{\substack{\text{noncirc}\\ \text{duct}}} \qquad \frac{\pi D_{eff}^2}{4} = hw \qquad D_{eff} = 2\sqrt{hw/\pi}$$

$$D_h = \frac{4 \cdot \text{area of flow}}{\text{wetted perimeter}} = \frac{4A}{P} = \frac{4\pi D^2/4}{\pi D} = D$$

For a rectangular duct of dimensions $h \times w$,

$$\boxed{D_h = \frac{4hw}{2h+2w} = \frac{2hw}{h+w}} = \frac{2bh}{b+h}$$

3.3 – Flow in a duct

$$\Sigma F_i = \iint_{cs} V_i \rho V_n dA$$

or $pA - \tau_w P dz - (p + dp)A = 0$

Pdz is perimeter times axial distance

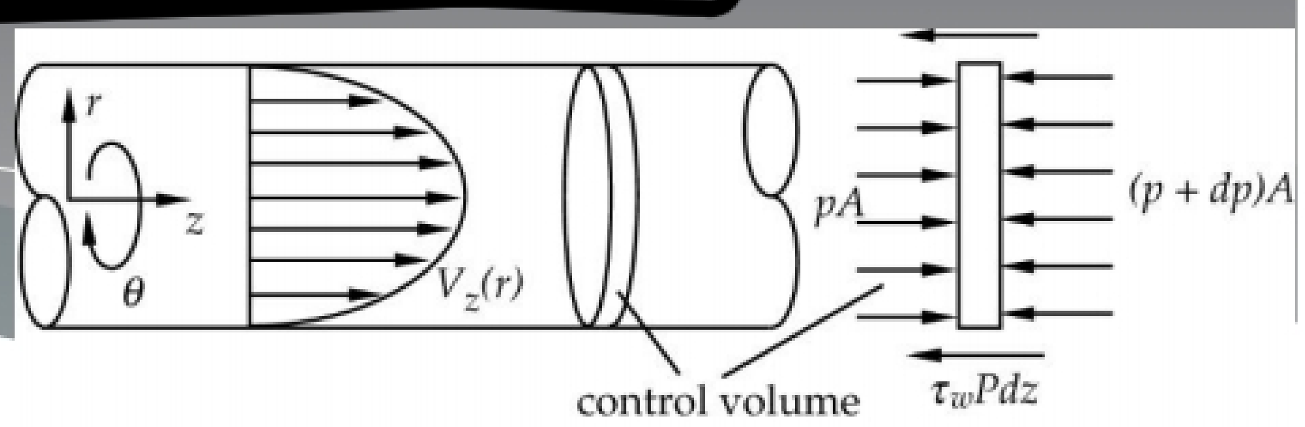


FIGURE 3.2. *Laminar flow in a circular duct.*

$$\frac{dp}{dz} = -\tau_w \frac{P}{A} = -\tau_w \frac{4P}{4A}$$

or in terms of hydraulic diameter,

$$\frac{dp}{dz} = -\frac{4\tau_w}{D_h}$$ **→ Applies for any cross section**

$$f = \frac{4\tau_w}{\rho V^2/2}$$ Darcy-Weisbach friction factor.

$$f' = \frac{\tau_w}{\rho V^2/2}$$ Fanning friction factor

$$dp = -\frac{\rho V^2}{2}\frac{f dz}{D_h}$$

$$p_2 - p_1 = -\frac{\rho V^2}{2}\frac{fL}{D_h}$$

Energy eqn

$\gamma = \rho g$

$$\boxed{\frac{p_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\rho g} + \frac{V_2^2}{2g} + z_2 + \boxed{\frac{fL}{D_h}\frac{V^2}{2g}}}$$

$$\left(\begin{matrix}\text{pressure}\\ \text{head}\end{matrix} + \text{KE} + \text{PE}\right)_1 = \left(\begin{matrix}\text{pressure}\\ \text{head}\end{matrix} + \text{KE} + \text{PE}\right)_2 + \left(\begin{matrix}\text{energy loss}\\ \text{due to friction}\end{matrix}\right)$$

3.4 – Getting the friction factor

* Note that all this applies to circular flow paths, and Newtonian fluids.
* For laminar flow, $\boxed{f = 64/Re}$ ✓
* For turbulent flow, relative roughness and the Reynolds number of a flow are used to calculate the friction factor.
* The Moody diagram is *an engineering classic*.
  * Transformations of it solve specific problems.

ε / D

3.4 Friction Factor and Pipe Roughness
Laminar Flow of a Newtonian Fluid in a Circular Duct

$$V_z = \left(-\frac{dp}{dz}\right)\left(\frac{R^2}{4\mu}\right)\left[1-\left(\frac{r}{R}\right)^2\right] \qquad \left(\frac{\text{laminar flow}}{\text{circular duct}}\right)$$

$$\boxed{Q = \iint_{CS} V_n dA}$$ Continuity eqn.

$dA = r dr d\theta$

$$Q = \int_0^{2\pi}\int_0^R \left(-\frac{dp}{dz}\right)\left(\frac{R^2}{4\mu}\right)\left[1-\left(\frac{r}{R}\right)^2\right] r dr d\theta$$

Integrating and solving, we get

$$Q = \frac{\pi R^4}{8\mu}\left(-\frac{dp}{dz}\right)$$

The average velocity is given by

$$\boxed{V = \frac{Q}{A}} = \frac{R^2}{8\mu}\left(-\frac{dp}{dz}\right) \rightarrow \quad dp = -\frac{\rho V^2}{2g_c}\frac{f dz}{D_h} \rightarrow \quad f = \frac{32\mu g_c}{\rho VR} = \frac{64\mu g_c}{\rho VD} = \frac{64}{Re}$$

μ

or $\boxed{f = \frac{64}{\text{Re}}}$ (laminar flow circular duct)

Turbulent Flow in a Circular Duct

$$f = f(\text{Re}, \varepsilon/D)$$

relative roughness ε/D

$\varepsilon \rightarrow$ absolute roughness

Table.

TABLE 3.1. *Roughness factor for various pipe materials.*

Pipe Material	ε, ft	ε, mm
Steel		
Commercial	0.00015	0.046
Corrugated	0.003–0.03	0.9–9
Riveted	0.003–0.03	0.9–9
Galvanized	0.0002–0.0008	0.06–0.25
Mineral		
Brick sewer, Cement–asbestos, Clays, Concrete	0.001–0.01	0.3–3
Wood stave	0.0006–0.003	0.18–0.9
Cast iron	0.00085	0.25
Asphalt coated	0.0004	0.12
Bituminous lined	0.000008	0.0025
Cement lined	0.000008	0.0025
Centrifugally spun	0.00001	0.0031
Drawn tubing	0.000005	0.0015
Miscellaneous		
Brass, Copper, Glass, Lead, Plastic, Tin	0.000005	0.0015
Galvanized	0.0002–0.0008	0.06–0.25
Wrought iron	0.00015	0.046
PVC	Smooth	Smooth

First Moody diagram

relative roughness ε/D

f

0.025

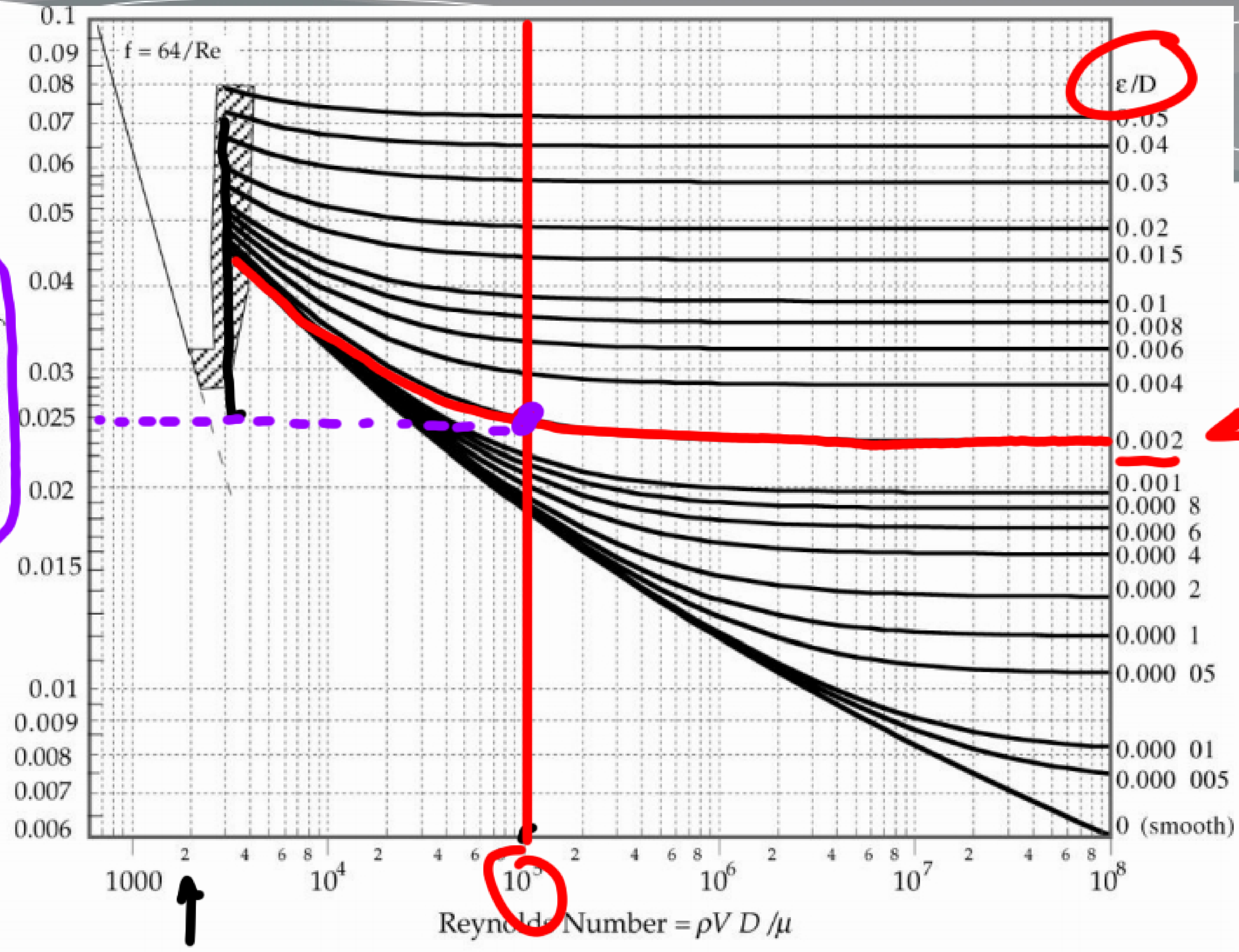
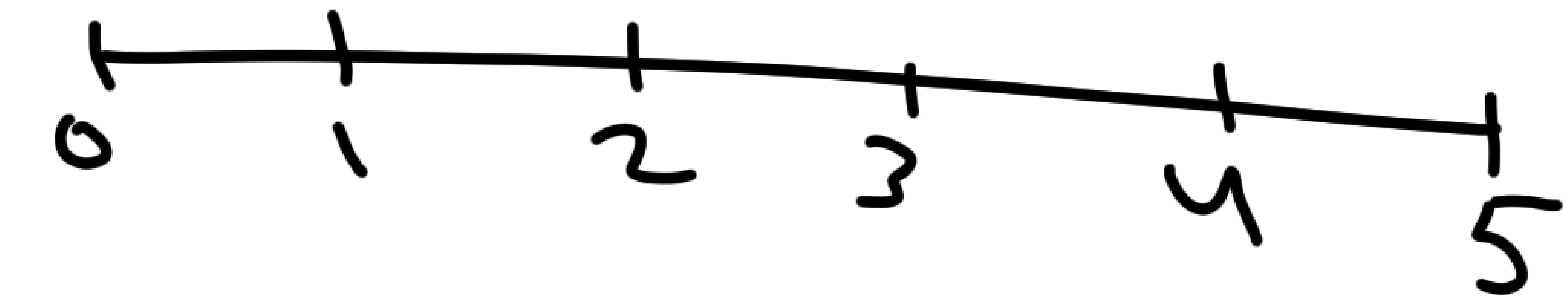
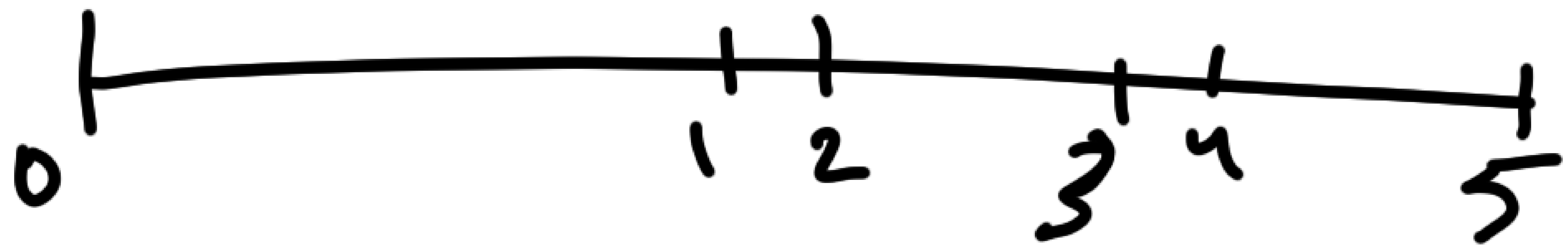


FIGURE 3.3. *Moody diagram constructed with Chen equation.*





log-log diagram.

The Chen equation is valid for Re ≥ 2 100

$$f = \left[-2.0 \log \left\{ \frac{\varepsilon}{3.7065D} - \frac{5.0452}{\mathbf{Re}} \log \left(\frac{1}{2.8257} \left[\frac{\varepsilon}{D} \right]^{1.1098} + \frac{5.8506}{\mathbf{Re}^{0.8981}} \right) \right\} \right]^{-2} \tag{3.15}$$

The Churchill Equation, also valid for **Re** ≥ 2 100, is:

$$f = 8 \left\{ \left[\frac{8}{\mathbf{Re}} \right]^{12} + \frac{1}{(B + C)^{1.5}} \right\}^{\frac{1}{12}} \tag{3.16}$$

where

$$B = \left[2.457 \ln \frac{1}{(7/\mathbf{Re})^{0.9} + (0.27\varepsilon/D)} \right]^{16}$$

and

$$C = \left(\frac{37\ 530}{\mathbf{Re}} \right)^{16}$$

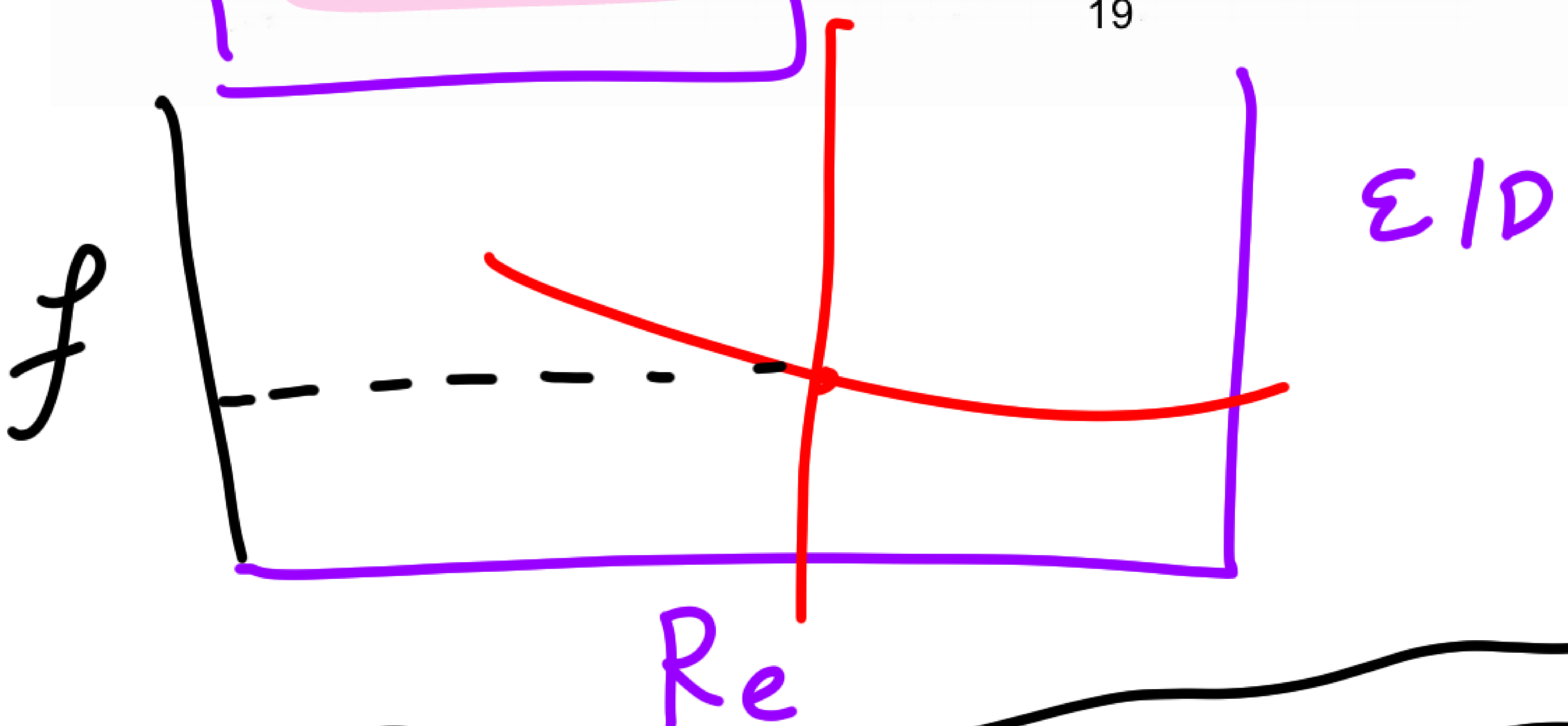
The Haaland Equation is

$$f = \left\{ -0.782\, ln \left[\frac{6.9}{\mathbf{Re}} + \left(\frac{\varepsilon}{3.7D} \right)^{1.11} \right] \right\}^{-2} \tag{3.17}$$

Another correlation is the Swamee-Jain Equation, which is

$$\boxed{f = \frac{0.250}{\left\{ \log \left[\frac{\varepsilon}{3.7D} + \frac{5.74}{\mathbf{Re}^{0.9}} \right] \right\}^2}} \tag{3.18}$$

moody chart



$$h_{losses} = \left(f \frac{L}{D} + \sum K \right) \frac{V^2}{2g}$$

3.5 – Minor losses

$$p_1 - p_2 = \sum K \frac{\rho V^2}{2}$$

$$\frac{p_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\rho g} + \frac{V_2^2}{2g} + z_2 + \frac{fL}{D_h}\frac{V^2}{2g} + \sum K \frac{V^2}{2g}$$

h_{losses}

It's refers to pressure losses encountered by a fluid as it flow through a fitting or a valve in a piping system.

* Do not disregard these because of the name – they can wreck a poorly designed process!
* These are frictional losses caused by things *other* than a straight length of pipe or tube.
* Valves, bends, inlets and outlets, and similar fittings cause "minor" losses.
* Also called "K-factor losses" because of the variable *K* used to denote them.

TABLE 3.2. *Loss coefficients for pipe fittings: inlets, exits, and elbows.*

Square edged inlet $K = 0.5$	Basket strainer $K = 1.3$
Re-entrant inlet or inward projecting pipe $K = 1.0$	Well rounded inlet or a bell mouth inlet $K = 0.05$
Foot valve $K = 0.8$	Exit $K = 1.0$
Convergent outlet or nozzle $K = 0.1(1 - D_2/D_1)$, D_2/D_1 from 0.5 to 0.9	

	threaded	flanged, welded, glued, bell & spigot
90° Elbow	regular $K = 1.4$; $K = 1.4(ID)^{-0.53}$, ID from 0.3 to 4 in	regular $K = 0.31$; $K = 0.44(ID)^{-0.23}$, ID from 1 to 25 in
	long radius $K = 0.75$; $K = 0.75(ID)^{-0.81}$, ID from 0.3 to 4 in	long radius $K = 0.22$; $K = 0.51(ID)^{-0.58}$, ID from 1 to 23 in
45° Elbow	regular $K = 0.35$; $K = 0.35(ID)^{-0.14}$, ID from 0.3 to 4 in	long radius $K = 0.17$; $K = 0.22(ID)^{-0.14}$, ID from 1 to 23 in

TABLE 3.2 continued. *Loss coefficients for pipe fittings: elbows, T-joints, and couplings*

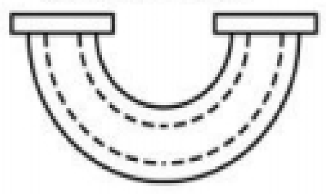
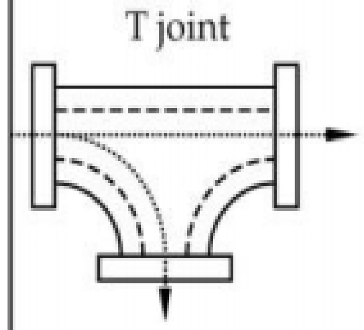
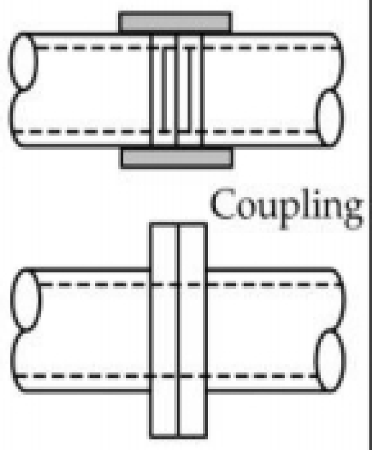
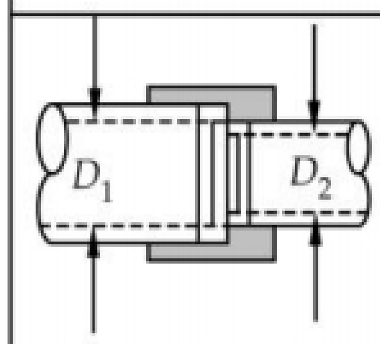
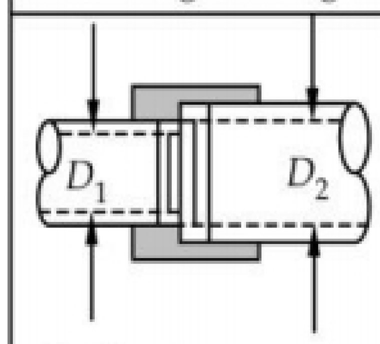
	threaded	flanged, welded, glued, bell & spigot
Return bend 	regular $K = 1.5$ $K = 1.5(ID)^{-0.57}$ ID from 0.3 to 4 in	regular $K = 0.3$ $K = 0.43(ID)^{-0.26}$ ID from 1 to 23 in long radius $K = 0.2$ $K = 0.43(ID)^{-0.53}$ ID from 1 to 23 in
T joint 	line flow $K = 0.9$ all sizes ID from 0.3 to 4 in branch flow $K = 1.9$ $K = 1.9(ID)^{-0.38}$ ID from 0.3 to 4 in	line flow $K = 0.14$ $K = 0.27(ID)^{-0.46}$ ID from 1 to 20 in branch flow $K = 0.69$ $K = 1.0(ID)^{-0.29}$ ID from 1 to 20 in
 Coupling	$K = 0.08$ $K = 0.083(ID)^{-0.69}$ ID from 0.4 to 4 in	$K = 0.08$ ID from 0.3 to 23 in
 Reducing bushing	$K = 0.5 - 0.167(D_2/D_1) - 0.125(D_2/D_1)^2 - 0.208(D_2/D_1)^3$ $0.25 < D_2/D_1 < 1$	
 Sudden expansion	$K = ((D_2/D_1)^2 - 1)^2$ $1 < D_2/D_1 < 5$	

TABLE 3.2 continued. *Loss coefficients for pipe fittings: valves.*

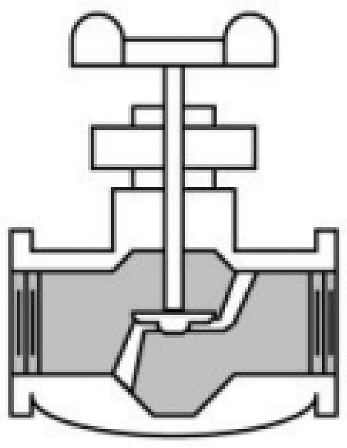
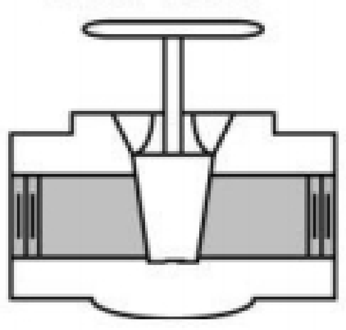
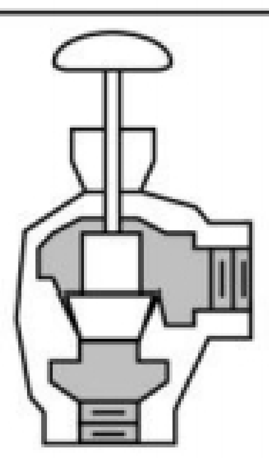
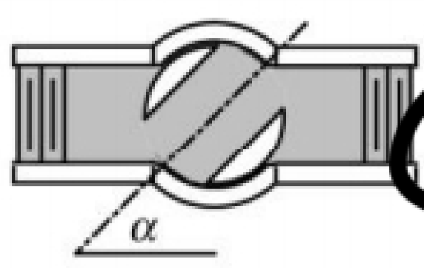
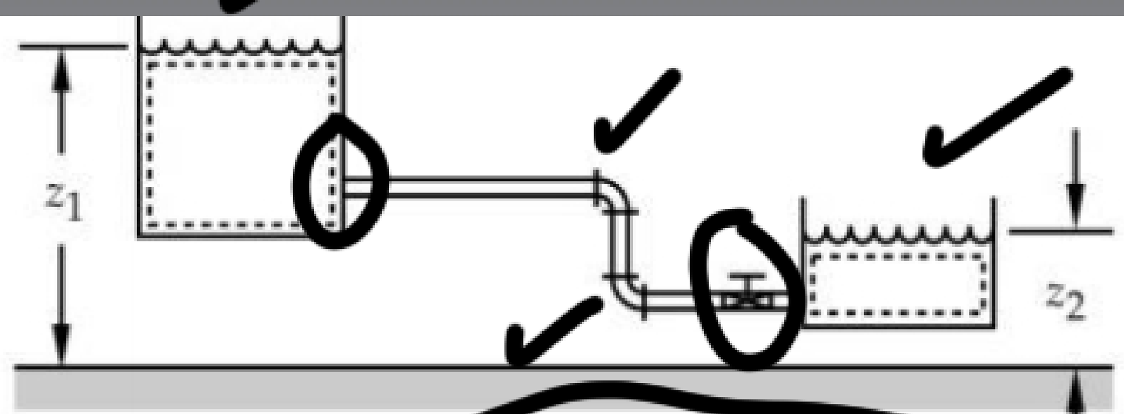
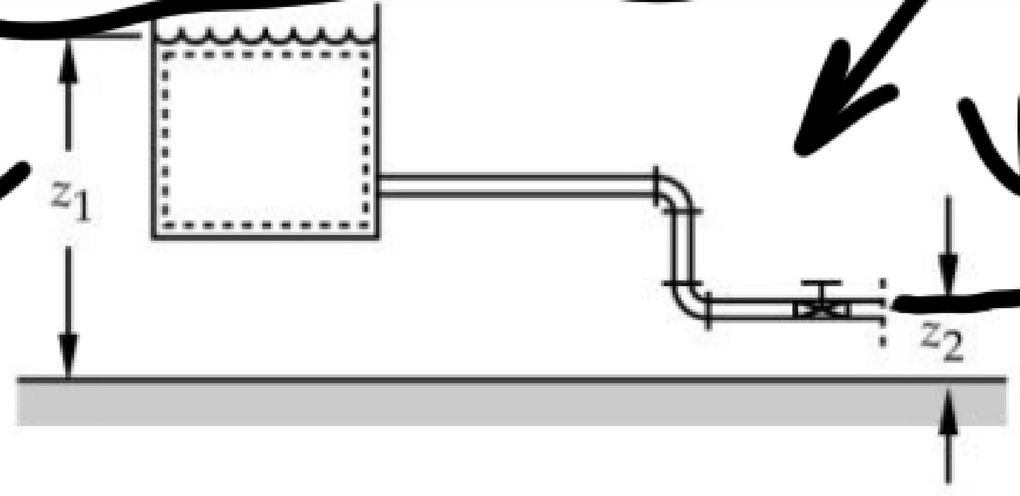
	threaded	flanged, welded, glued, bell & spigot
Globe valve 	fully open $K = 10$ $K = \exp\{2.158 - 0.459\ln(ID) + 0.259[\ln(ID)]^2 - 0.123[\ln(ID)]^3\}$ ID from 0.3 to 4 in	fully open $K = 10$ $K = \exp\{2.565 - 0.916\ln(ID) + 0.339[\ln(ID)]^2 - 0.01416[\ln(ID)]^3\}$ ID from 0.3 to 4 in
Gate Valve 	fully open $K = 0.15$ $K = 0.24(ID)^{-0.47}$ ID from 0.3 to 4 in	fully open $K = 0.15$ $K = 0.78(ID)^{-1.14}$ ID from 1 to 20 in
	All sizes Fraction closed: 0 | 1/4 | 3/8 | 1/2 | 5/8 | 3/4 | 7/8 K = 0.15 | 0.26 | 0.81 | 2.06 | 5.52 | 17.0 | 97.8	
 Angle Valve	fully open $K = 2.0$ $K = 4.5(ID)^{-1.08}$ ID from 0.6 to 4 in	fully open $K = 2.0$ $K = \exp\{1.569 - 1.43\ln(ID) + 0.8[\ln(ID)]^2 - 0.137[\ln(ID)]^3\}$ ID from 1 to 20 in
 Ball Valve	All sizes α: 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 K = 0.05 | 0.29 | 1.56 | 5.47 | 17.3 | 25.6 | 206 | 485 | ∞	
Check Valves Swing Type Ball Type Lift Type	$K = 2.5$ $K = 70.0$ $K = 12.0$	$K = 2.5$ $K = 70.0$ $K = 12.0$

FIGURE 3.7.

Modified Bernoulli equation written for various systems.

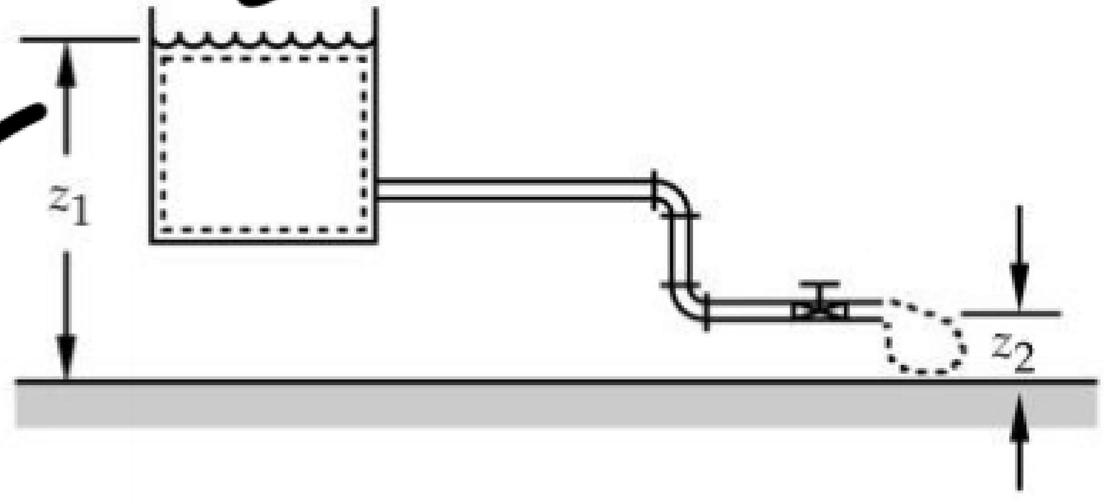


$$\text{(a)}\quad z_1 = z_2 + \frac{fL}{D_h}\frac{V^2}{2g} + (K_{inlet} + 2K_{90^\circ\,elbow} + K_{valve} + K_{exit})\frac{V^2}{2g}$$



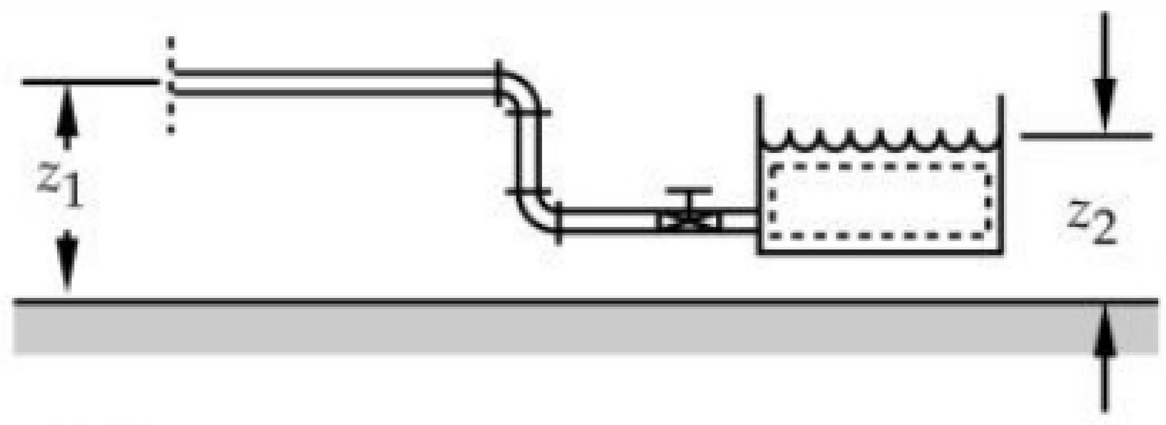
V_2 P_2

$$\text{(b)}\quad z_1 = \frac{p_2}{\rho g} + \frac{V_2^2}{2g} + z_2 + \frac{fL}{D_h}\frac{V^2}{2g} + (K_{inlet} + 2K_{90^\circ\,elbow} + K_{valve})\frac{V^2}{2g}$$

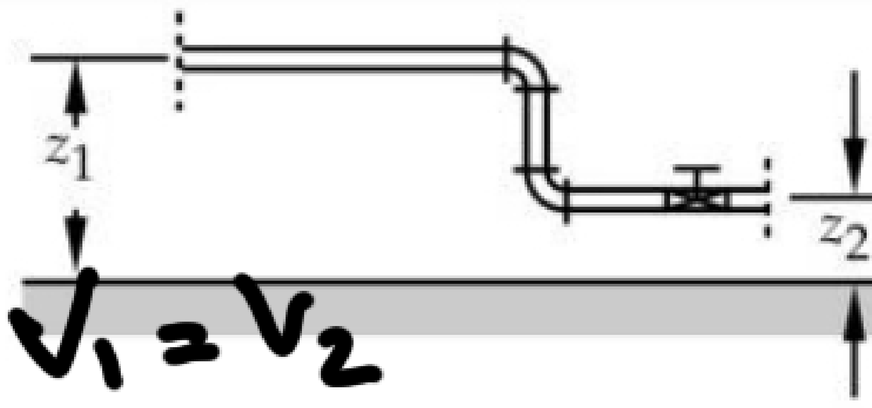


$$\text{(c)}\quad z_1 = z_2 + \frac{fL}{D_h}\frac{V^2}{2g} + (K_{inlet} + 2K_{90^\circ\,elbow} + K_{valve} + K_{exit})\frac{V^2}{2g}$$

2



$$\text{(d)}\quad \frac{p_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = z_2 + \frac{fL}{D_h}\frac{V^2}{2g} + (2K_{90^\circ\,elbow} + K_{valve} + K_{exit})\frac{V^2}{2g}$$



$V_1 = V_2$

$A_1V_1 = A_2V_2$

$V_1 = V_2$

$$\text{(e)}\quad \frac{p_1}{\rho g} + z_1 = \frac{p_2}{\rho g} + z_2 + \frac{fL}{D_h}\frac{V^2}{2g} + (2K_{90^\circ\,elbow} + K_{valve})\frac{V^2}{2g}$$

$P_{absolute} = P_{atm} + P_{gauge}$

$\therefore P_{gauge} = P_{abs} - P_{atm}$

26

$$\frac{P_2}{\gamma} - \frac{P_1}{\gamma} = \frac{P_{2gauge}}{\gamma}$$

3.6 – Series piping systems

* A continuous flow path made up of different diameter and/or roughness pipes is a series piping system.
* You will either know the volumetric flow rate (Type I) or the pressure drop (Type II) and have to calculate the other.

$Q = ✓$

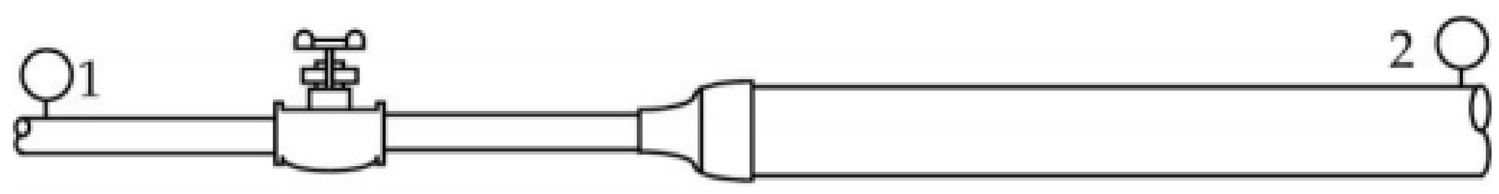


FIGURE 3.11. *A series piping system.*

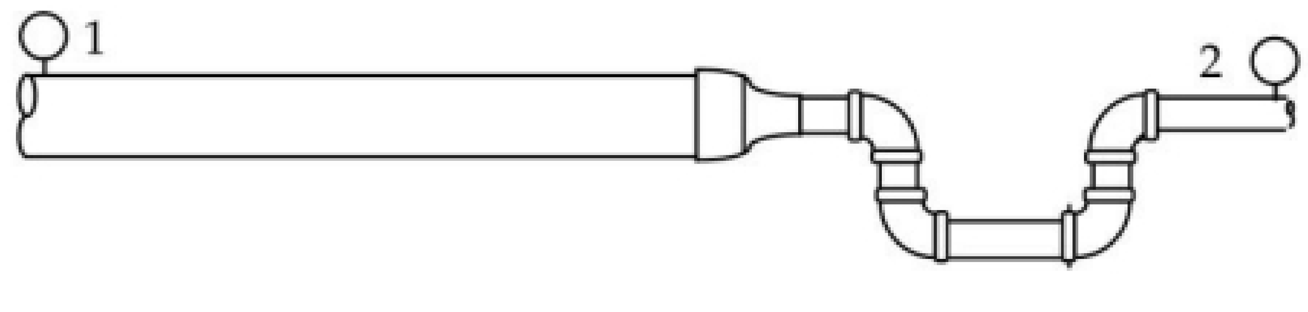


FIGURE 3.12. *A series piping system with flow rate unknown.*

3.7 – Noncircular paths

* Circular pipes and tubes are widespread and preferred, but some different configurations are unavoidable.
* The most common are the annulus and the rectangular duct, such as for forced air.
* If you run across these, or even stranger flow paths, you can look them up or try to derive the governing equations.

$$V_z = \left(-\frac{dp}{dz}\right)\left(\frac{R^2}{4\mu}\right)\left[1-\left(\frac{r}{R}\right)^2 - \frac{1-\kappa^2}{ln(\kappa)}\, ln\,\frac{r}{R}\right] \quad \left(\begin{matrix}\text{laminar flow}\\ \text{annular duct}\end{matrix}\right) \tag{3.29}$$

where $\kappa = OD_p/ID_a$. (See Problem 3.34 for a detailed derivation of this equation.) The volume flow rate is found by integrating Equation 3.29 over the cross section:

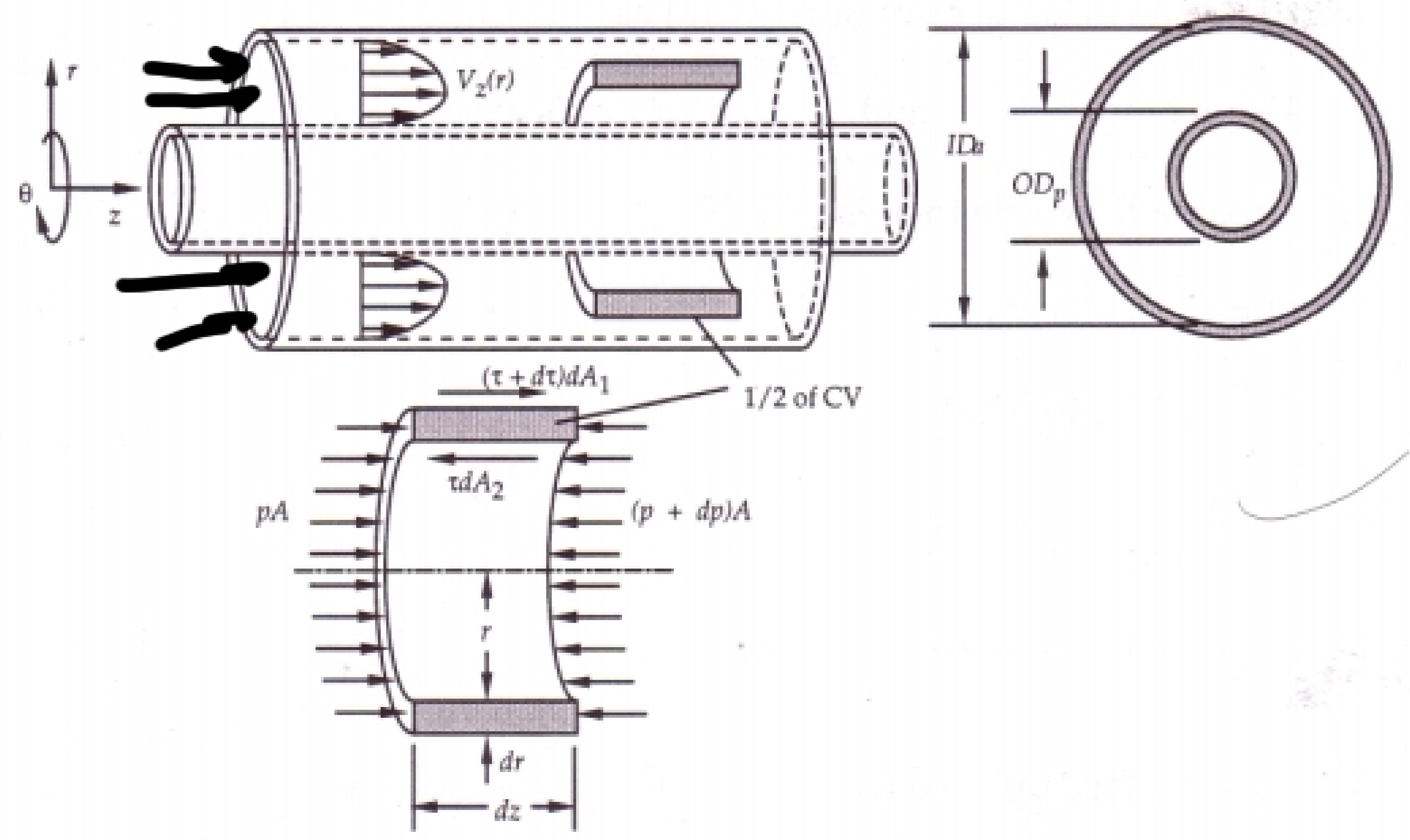


FIGURE 3.12. *Laminar flow in an annulus.*

$$Q = \int_0^{2\pi}\int_{\kappa R}^{R} V_z\, r dr d\theta$$

which becomes

$$Q = \int_0^{2\pi}\int_{\kappa R}^{R}\left(-\frac{dp}{dz}\right)\left(\frac{R^2}{4\mu}\right)\left[1-\left(\frac{r}{R}\right)^2 - \frac{1-\kappa^2}{ln(\kappa)}\, ln\,\frac{r}{R}\right] r dr d\theta$$

Integrating gives the volume flow rate as

$$Q = \left(-\frac{dp}{dz}\right)\left(\frac{\pi R^4(1-\kappa^2)}{8\mu}\right)\left(1+\kappa^2+\frac{1-\kappa^2}{ln(\kappa)}\right) \tag{3.30}$$

$$V = \frac{Q}{A} = \frac{Q}{\pi(R^2 - \kappa^2 R^2)} = \frac{Q}{\pi R^2(1 - \kappa^2)}$$

or

$$V = \left(-\frac{dp}{dz}\right)\left(\frac{R^2}{8\mu}\right)\left(1 + \kappa^2 + \frac{1 - \kappa^2}{ln(\kappa)}\right) \tag{3.31}$$

The hydraulic diameter for the annular flow section is

$$\boxed{D_h = \frac{4A}{P} = \frac{4(\pi(ID_a/2)^2 - \pi(OD_p/2)^2)}{\pi(ID_a) + \pi(OD_p)}}$$

ID
OD

which simplifies to

$$D_h = ID_a - OD_p \tag{3.32}$$

Equation 3.8a relates the pressure drop to the friction factor:

$$dp = -\frac{\rho V^2}{2g_c}\frac{fdz}{D_h} \tag{3.8a}$$

Combining Equations 3.8a, 3.31 and 3.32, after considerable simplification we get:

$$\frac{1}{f} = \frac{\mathbf{Re}}{64}\left(\frac{1 + \kappa^2}{(1 - \kappa)^2} + \frac{1 + \kappa}{(1 - \kappa)ln(\kappa)}\right) \tag{3.33}$$

where

$$\mathbf{Re} = \frac{VD}{\nu} = \frac{V(ID_a - OD_p)}{\nu}$$

$\nu = \mu/\rho$

m^2/sec

Laminar Flow of a Newtonian Fluid in a Rectangular Duct

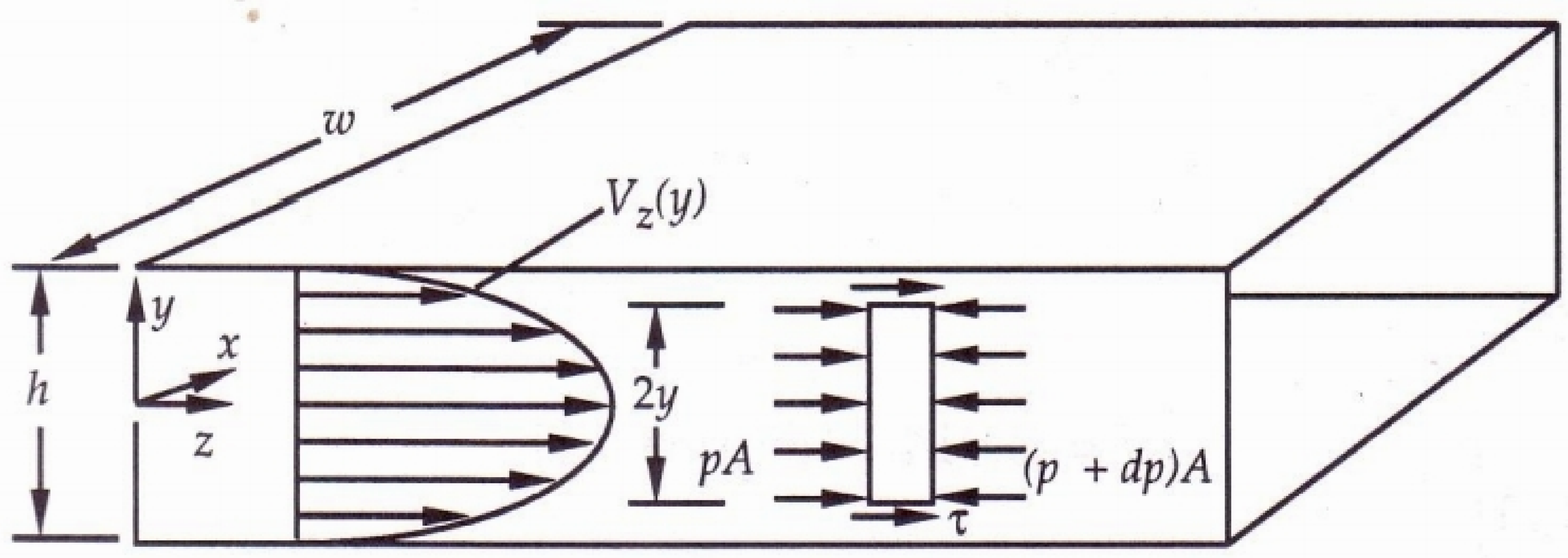


FIGURE 3.13. *Laminar flow through a rectangular duct.*

$$V_z = \left(-\frac{dp}{dz}\right)\left(\frac{h^2}{2\mu}\right)\left(\frac{1}{4} - \frac{y^2}{h^2}\right) \quad \left(\begin{array}{c}\text{laminar flow}\\ \text{2-D rectangular duct}\end{array}\right) \tag{3.34}$$

(For details, see Problem 3.37.) The volume flow rate is found by integrating the velocity V_z over the cross sectional area

$$Q = \int_0^w \int_{-h/2}^{+h/2} \left(-\frac{dp}{dz}\right)\left(\frac{h^2}{2\mu}\right)\left(\frac{1}{4} - \frac{y^2}{h^2}\right) dy\,dx$$

Integrating and simplifying, we find

$$Q = \frac{h^3 w}{12\mu}\left(-\frac{dp}{dz}\right) \tag{3.35}$$

The average velocity then becomes

$$V = \frac{Q}{A} = \frac{h^2}{12\mu}\left(-\frac{dp}{dz}\right) \tag{3.36}$$

From Equation 3.8a, which relates the pressure loss to the average velocity in a duct for any cross section, we have

$$dp = -\frac{\rho V^2}{2g_c}\frac{f dz}{D_h} \tag{3.8a}$$

Also, for a 2-dimensional duct, the hydraulic diameter is

$$D_h = \frac{4A}{P} = \frac{4hw}{2h + 2w} \approx \frac{4hw}{2w}$$

$$\text{or} \quad D_h = 2h \tag{3.37}$$

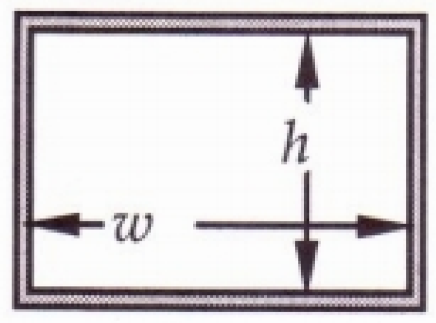
Combining Equations 3.8a, 3.36, and 3.37 gives

$$f = \frac{96\mu g_c}{\rho V D_h} = \frac{96\mu g_c}{\rho V(2h)}$$

$$\text{or} \quad f = \frac{96}{\mathbf{Re}} \tag{3.38}$$

$$\mathbf{Re} = \frac{\rho V(2h)}{\mu}$$

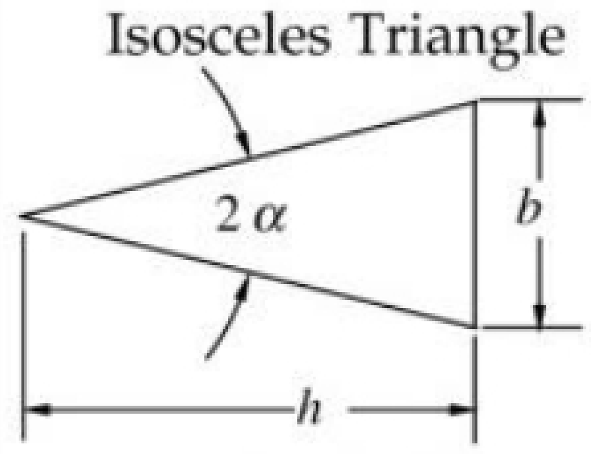
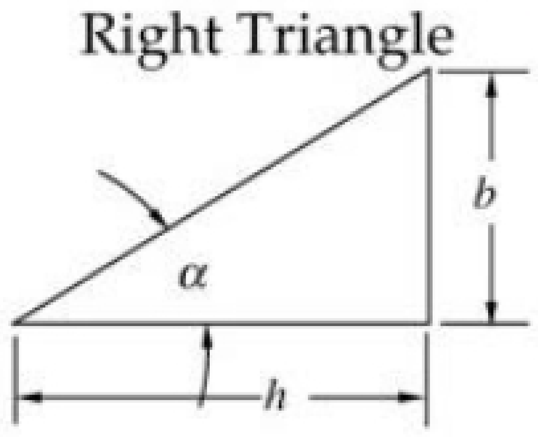
Rectangular Duct



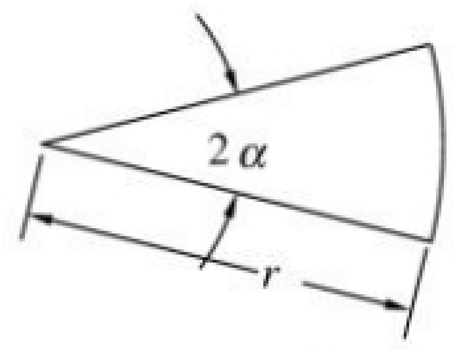
$A = wh$
$P = 2w + 2h$

h/w	$f{\cdot}\mathrm{Re}$	
0	96	2-D duct
0.05	89.81	
0.1	84.68	
0.125	82.34	
0.167	78.81	
0.25	72.93	
0.4	65.47	
0.5	62.19	
0.75	57.89	
1	56.91	square

TABLE 3.5. *Friction factor-Reynolds number product for laminar flow through various noncircular cross sections.*

	Isosceles Triangle	Right Triangle
		
	$A = bh/2$ $P = \tan^{-1}(b/2a)$	$A = bh/2$ $P = b + h + (b + h)^{1/2}$
α	$f \cdot \mathrm{Re}$	$f \cdot \mathrm{Re}$
0	48.0	48.0
10	51.6	49.9
20	52.9	51.2
30	53.3	52.0
40	52.9	52.4
50	52.0	52.4
60	51.1	52.0
70	49.5	51.2
80	48.3	49.9
90	48.0	48.0

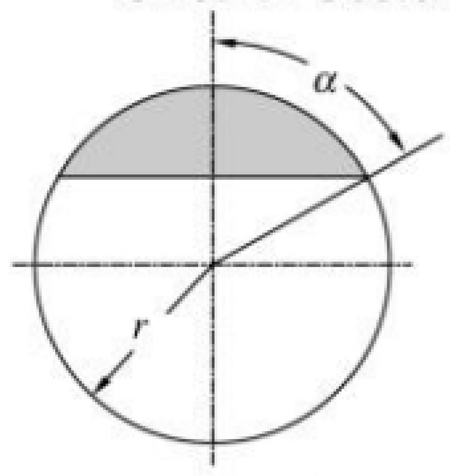
Circular Segment



$A = \alpha r^2$
$P = 2r(1 + \alpha)$

α	$f \cdot \mathrm{Re}$
0	62.2
10	62.2
20	62.3
30	62.4
40	62.5
60	62.8
90	63.1
120	63.3
150	63.7
180	64.0

Circular Sector



$A = r^2(\alpha - \sin\alpha\cos\alpha)$
$P = 2r(\alpha + \sin\alpha)$

α	$f \cdot \mathrm{Re}$
0	48.0
10	51.8
20	54.5
30	56.7
40	58.4
50	59.7
60	60.8
70	61.7
80	62.5
90	63.1