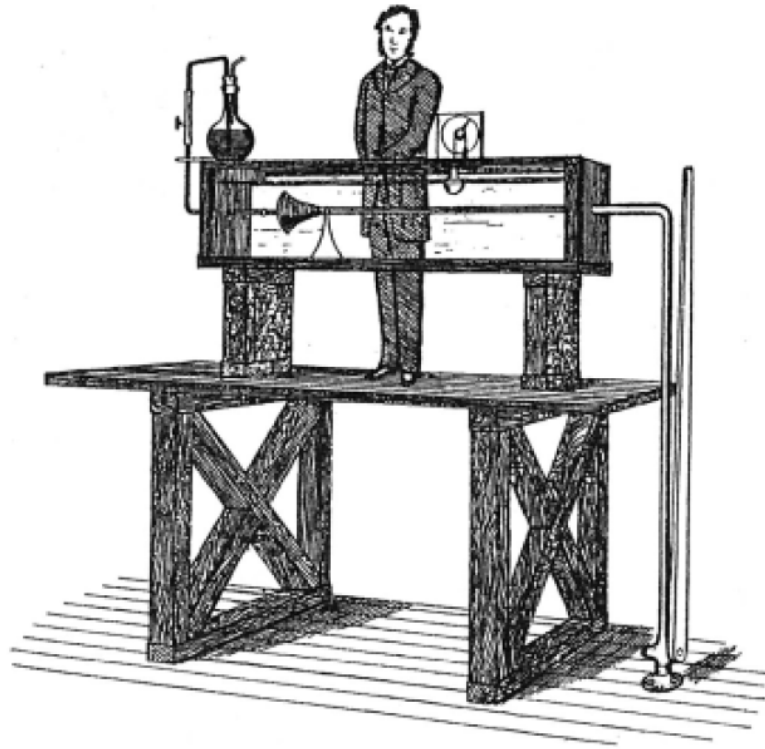
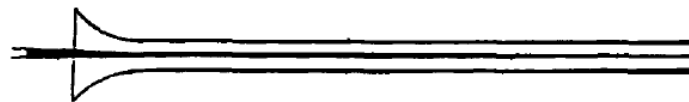


MOTI IN CONDOTTI

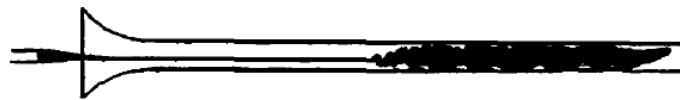


Osborne Reynolds e il suo esperimento

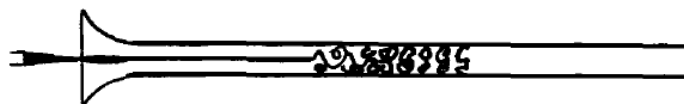
MOTO LAMINARE - MOTO TURBOLENTO



(a) Laminar flow



(b) Turbulent flow



(c) Turbulent flow (observed by electric spark)

$$Re = \frac{\rho V D}{\mu}$$

$$Re \leq 2300$$

Moto Laminare

$$2300 \leq Re \leq 4200$$

Moto Transizionale

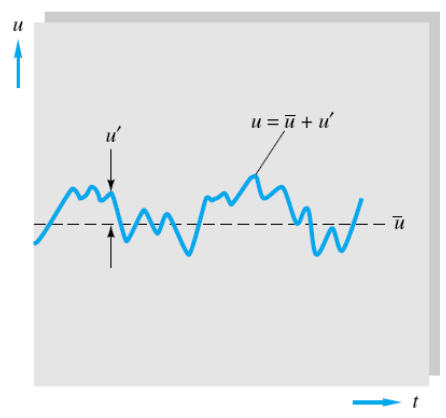
$$Re \geq 4200$$

Moto Turbolento

MOTO TURBOLENTO

MOTO TRIDIMENSIONALE INSTAZIONARIO

$$\underline{V} = \underline{V}(t, x, y, z) = \begin{cases} u = u(t, x, y, z) \\ v = v(t, x, y, z) \\ w = w(t, x, y, z) \end{cases} \quad p = p(t, x, y, z)$$

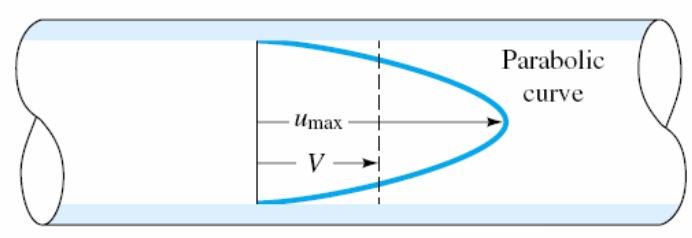


$$\bar{u} = \frac{1}{T} \int_0^T u \, dt \quad u' = u - \bar{u} \quad \bar{u'} = \frac{1}{T} \int_0^T (u - \bar{u}) \, dt = \bar{u} - \bar{u} = 0$$

In modo analogo anche per v, w, p e possibile definire le grandezze medie e fluttuanti

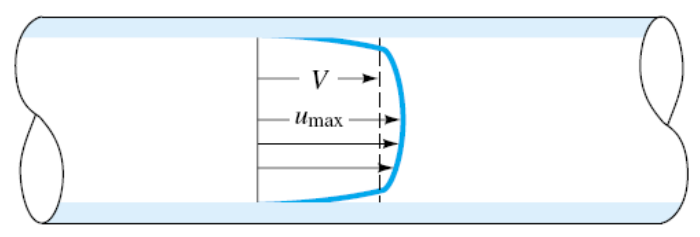
Nel caso di moti turbolenti, si utilizzeranno sempre valori medi delle grandezze

PROFILO DI VELOCITÀ



Moto Laminare
Re < 2300

V velocità media



Moto Turbolento
Re > 4200

Più unidimensionale

In moto turbolento $V \cong u_{\max}$

PERDITE DI CARICO IN REGIME INCOMPRESSIBILE

Equazione di conservazione massa

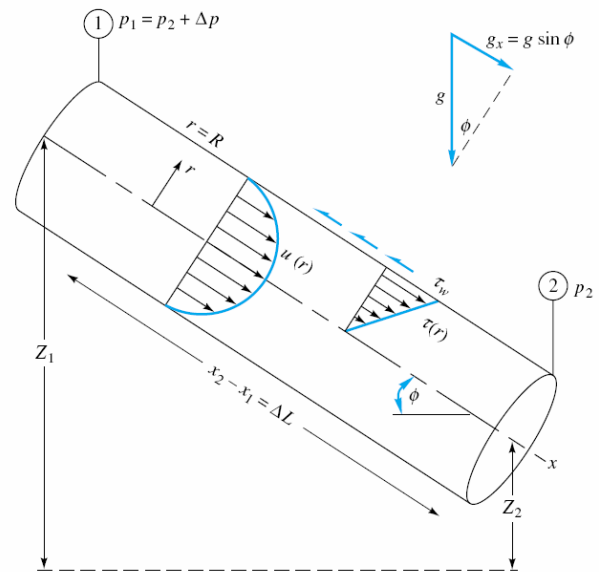
Moto unidimensionale stazionario

$$\rho_1 V_1 A_1 = \rho_2 V_2 A_2$$

Moto incompressibile ($\rho = \text{cost}$)

Sezione costante ($A = \text{cost}$)

$$V_1 = V_2 = V = \text{cost}$$



PERDITE DI CARICO IN REGIME INCOMPRESSIBILE

Bilancio quantità di moto

$$\dot{m} (V_2 - V_1) + p_1 A_1 n_1 + p_2 A_2 n_2 + \underline{S} = \underline{M} \underline{g}$$

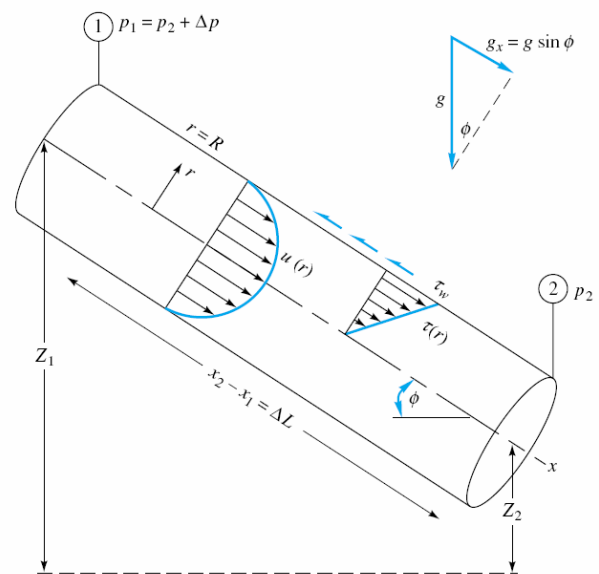
$$- \cancel{\dot{m} V} + \cancel{\dot{m} V} - \cancel{pA} + (\cancel{p} + \Delta p) A + S_x = \rho A \Delta L \underline{g} \cdot \underline{i}$$

$$S_x = \tau_p \rho \Delta L \quad \tau_p \equiv \tau_w \text{ in figura}$$

$$\Delta L \underline{g} \cdot \underline{i} = -g(z_1 - z_2) = -g \Delta z$$

$$\text{posto } \underline{g} \equiv g$$

$$A \Delta p + \rho g A \Delta z + \tau_p \rho \Delta L = 0$$



dividendo per A e indicando con $D_e = 4A/\rho$ il *diametro idraulico equivalente*

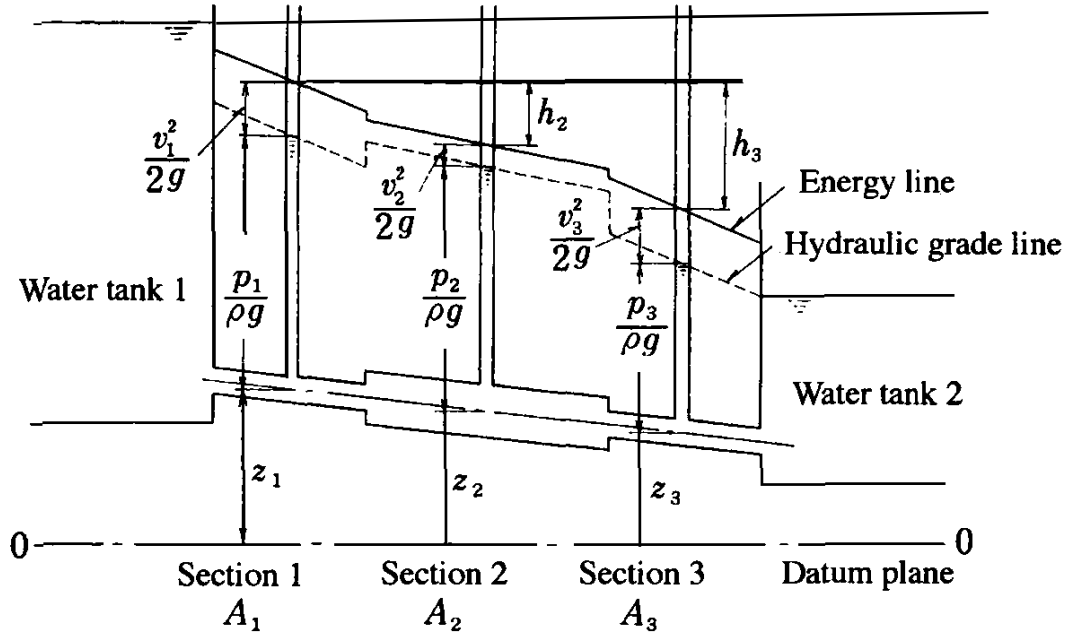
$$\Delta p + \rho g \Delta z + 4 \tau_p \frac{\Delta L}{D_e} = 0 \quad \Rightarrow \quad \frac{\Delta p}{\rho g} + \Delta z = - \frac{4 \tau_p}{\rho g} \frac{\Delta L}{D_e} = -h_f$$

BILANCIO DELLA QUANTITÀ DI MOTO

$$dp + \rho V dV + \rho g dz + 4\tau_p \frac{dx}{D_e} = 0$$

$$\frac{p_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\rho g} + \frac{V_2^2}{2g} + z_2 + h_2 = \frac{p_3}{\rho g} + \frac{V_3^2}{2g} + z_3 + h_3$$

con h_2, h_3 dette perdite di carico



PERDITE DI CARICO IN REGIME INCOMPRESSIBILE

$$\Delta p + \rho g \Delta z + 4\tau_p \frac{\Delta L}{D_e} = 0 \gg \gg \frac{\Delta p}{\rho g} + \Delta z = -\frac{4\tau_p}{\rho g} \frac{\Delta L}{D_e} = -h_f$$

Da un'analisi del fenomeno si vede che

$$\tau_p = F(\rho, V, \mu, D_e, \varepsilon)$$

Mediante il **Teorema di Buckingham** si ottiene:

$$f = \frac{8\tau_p}{\rho V^2} = F\left(Re, \frac{\varepsilon}{D_e}\right) \quad \text{con } Re = \frac{\rho V D_e}{\mu}$$

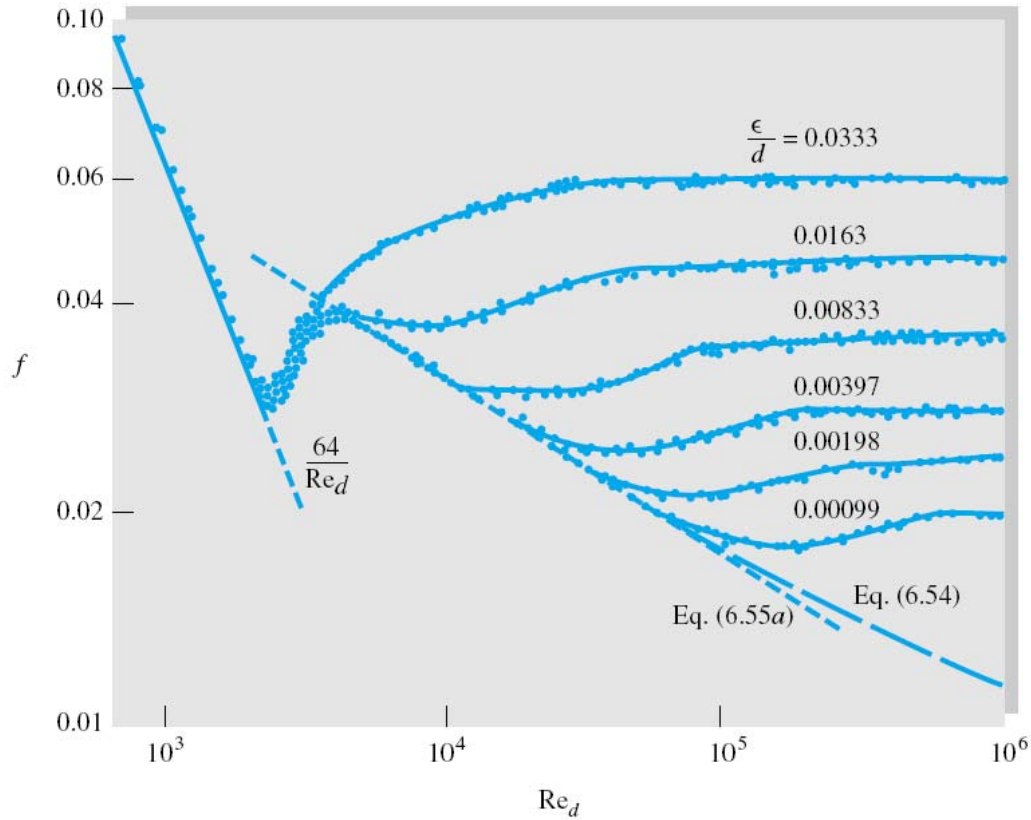
$$f \text{ coefficiente di Darcy; } h_f = f \frac{L}{D_e} \frac{V^2}{2g}$$

con $\Delta L = L$

Queste perdite di carico si chiamano **DISTRIBUITE**

In condotti circolari $D_e = D = d$

ESPERIMENTI DI NIKURADSE

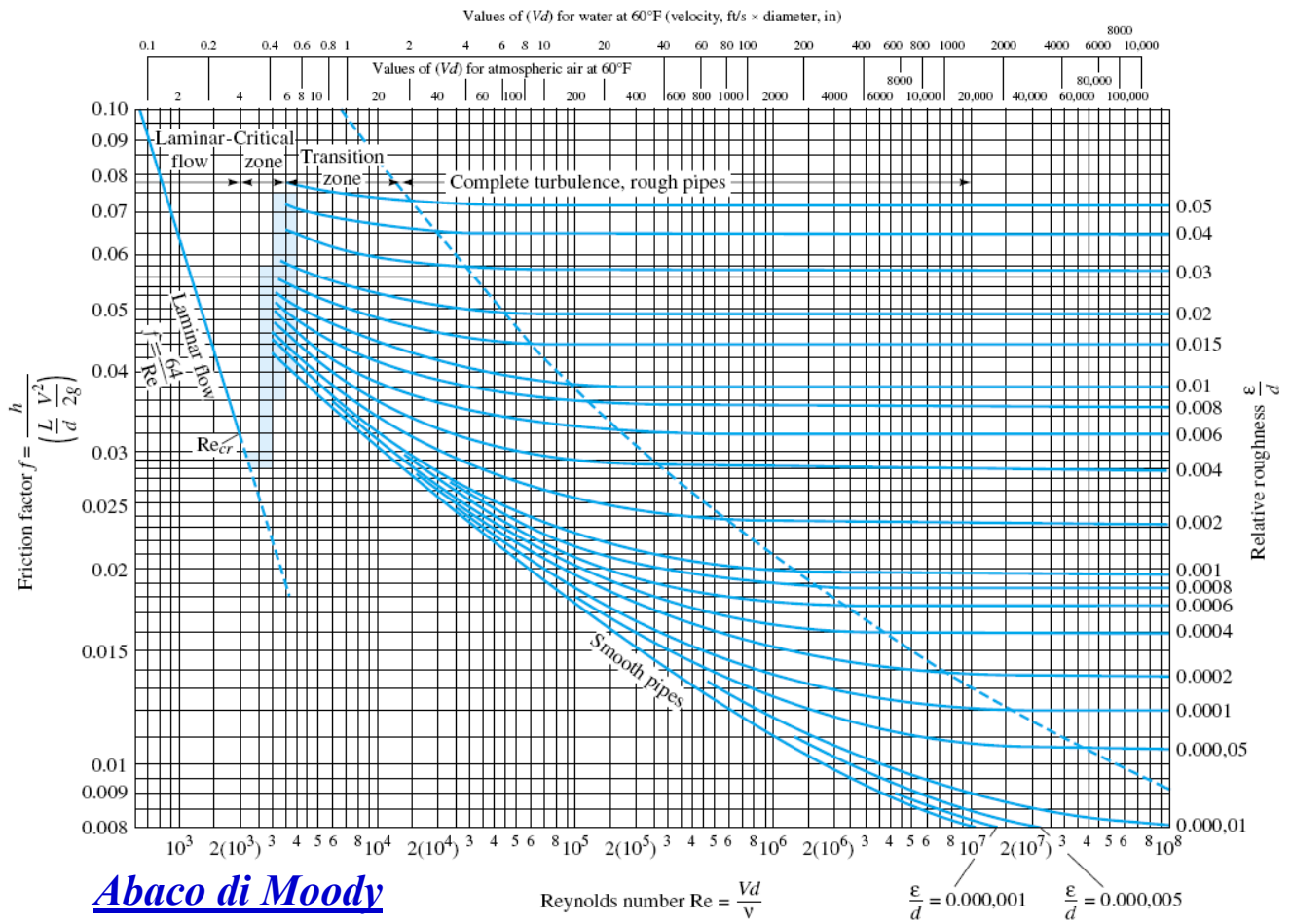


FORMULA DI COLEBROOK E WHITE

$$\frac{1}{f^{1/2}} = -2.0 \log \left(\frac{\epsilon/d}{3.7} + \frac{2.51}{Re_d f^{1/2}} \right)$$

$$Re = \frac{\rho V D_e}{\mu}$$

La formula di Colebrook e White si traduce nell'abaco di Moody



TIPICHE SCABREZZE

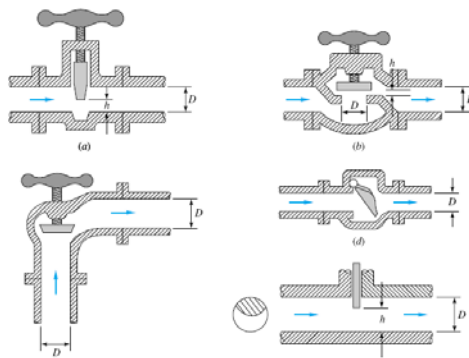
Material	Condition	ϵ		Uncertainty, %	
		ft	mm		
Steel	Sheet metal, new	0.00016	0.05	± 60	
	Stainless, new	0.000007	0.002	± 50	
	Commercial, new	0.00015	0.046	± 30	
	Riveted	0.01	3.0	± 70	
	Rusted	0.007	2.0	± 50	
Iron	Cast, new	0.00085	0.26	± 50	
	Wrought, new	0.00015	0.046	± 20	
	Galvanized, new	0.0005	0.15	± 40	
	Asphalted cast	0.0004	0.12	± 50	
Brass	Drawn, new	0.000007	0.002	± 50	
Plastic	Drawn tubing	0.000005	0.0015	± 60	
Glass	—	Smooth	Smooth		
	Concrete	Smoothed	0.00013	0.04	± 60
		Rough	0.007	2.0	± 50
Rubber	Smoothed	0.000033	0.01	± 60	
Wood	Stave	0.0016	0.5	± 40	

PERDITE DI CARICO CONCENTRATE

Le perdite di carico concentrate si hanno in:

- Ingressi. o uscite. di condotti
- Variazioni di sezione repentine
- Variazioni di sezione graduali
- Curve, condotti a T, in generale tutte le connessioni di condotti
- Valvole (aperte, o parzialmente chiuse)

Coefficiente di perdita
$$K = \frac{h_m}{V^2/(2g)} = \frac{\Delta p}{\frac{1}{2}\rho V^2}$$

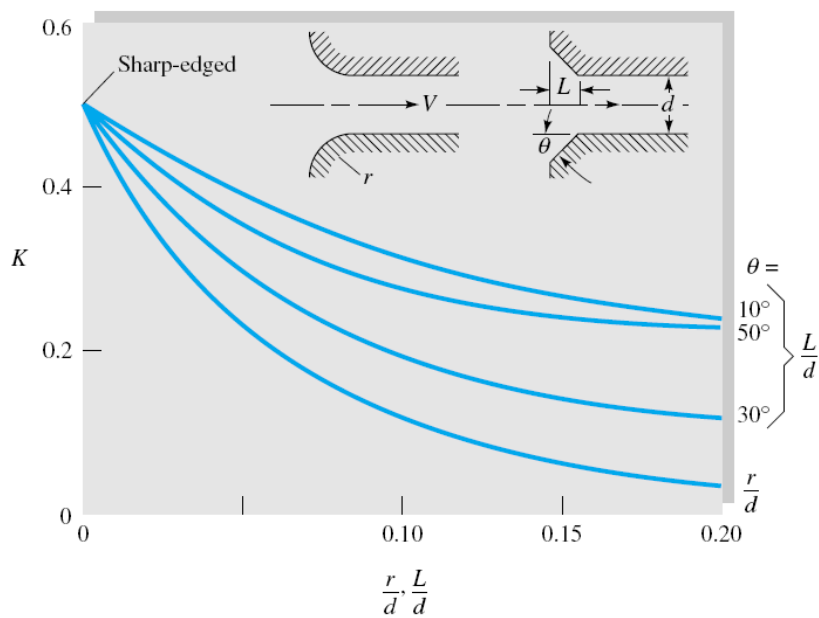
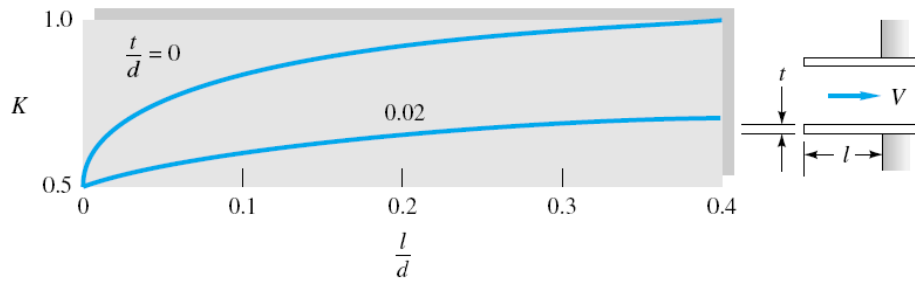
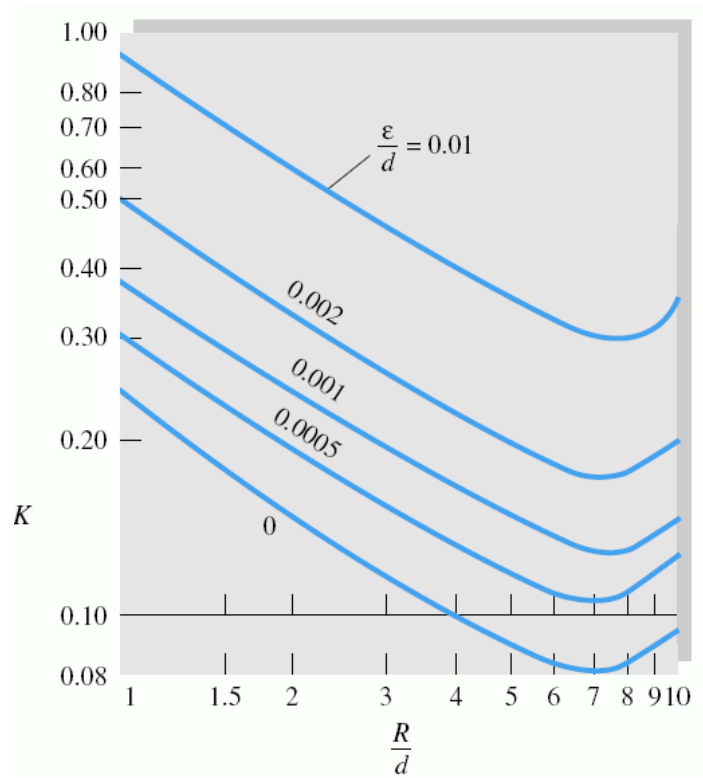
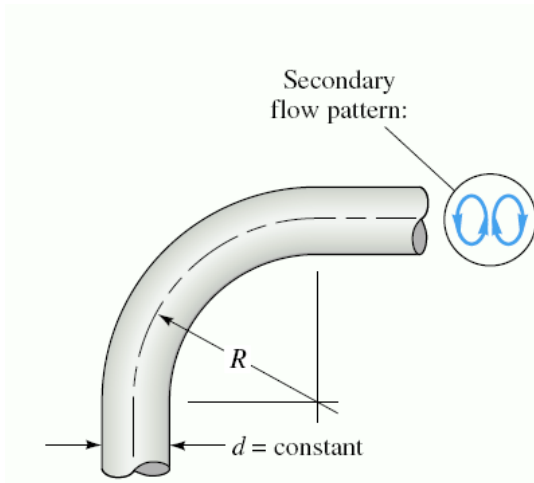


VALORI DI K

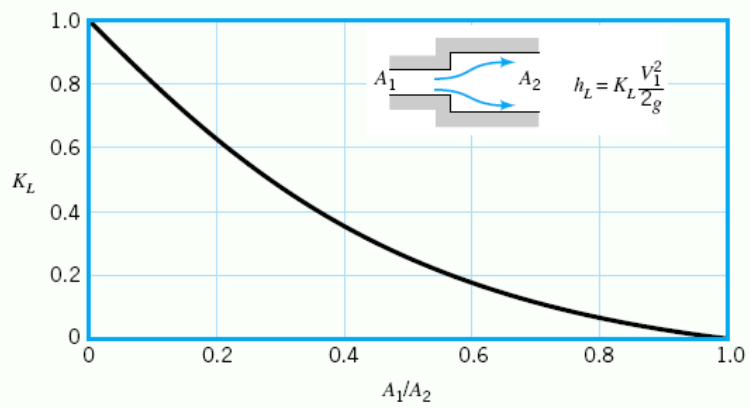
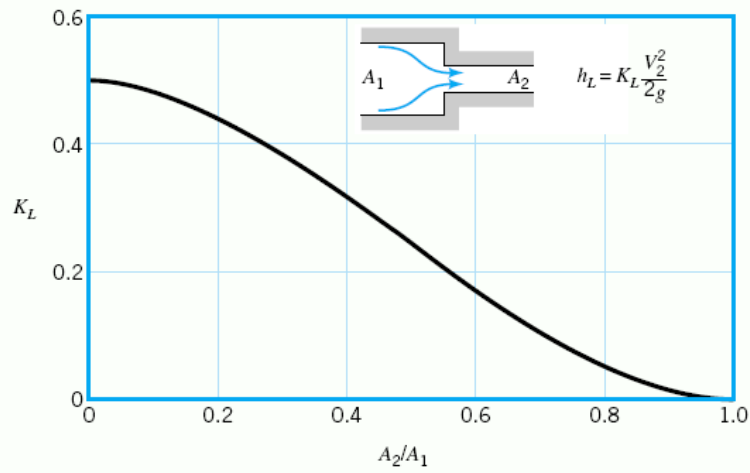
Fig. 6.17 Typical commercial valve geometries: (a) gate valve; (b) globe valve; (c) angle valve; (d) swing-check valve; (e) disk-type gate valve.

	Nominal diameter, in									
	Screwed				Flanged					
	1/2	1	2	4	1	2	4	8	20	
Valves (fully open):										
Globe	14	8.2	6.9	5.7	13	8.5	6.0	5.8	5.5	
Gate	0.30	0.24	0.16	0.11	0.80	0.35	0.16	0.07	0.03	
Swing check	5.1	2.9	2.1	2.0	2.0	2.0	2.0	2.0	2.0	
Angle	9.0	4.7	2.0	1.0	4.5	2.4	2.0	2.0	2.0	
Elbows:										
45° regular	0.39	0.32	0.30	0.29						
45° long radius					0.21	0.20	0.19	0.16	0.14	
90° regular	2.0	1.5	0.95	0.64	0.50	0.39	0.30	0.26	0.21	
90° long radius	1.0	0.72	0.41	0.23	0.40	0.30	0.19	0.15	0.10	
180° regular	2.0	1.5	0.95	0.64	0.41	0.35	0.30	0.25	0.20	
180° long radius					0.40	0.30	0.21	0.15	0.10	
Tees:										
Line flow	0.90	0.90	0.90	0.90	0.24	0.19	0.14	0.10	0.07	
Branch flow	2.4	1.8	1.4	1.1	1.0	0.80	0.64	0.58	0.41	

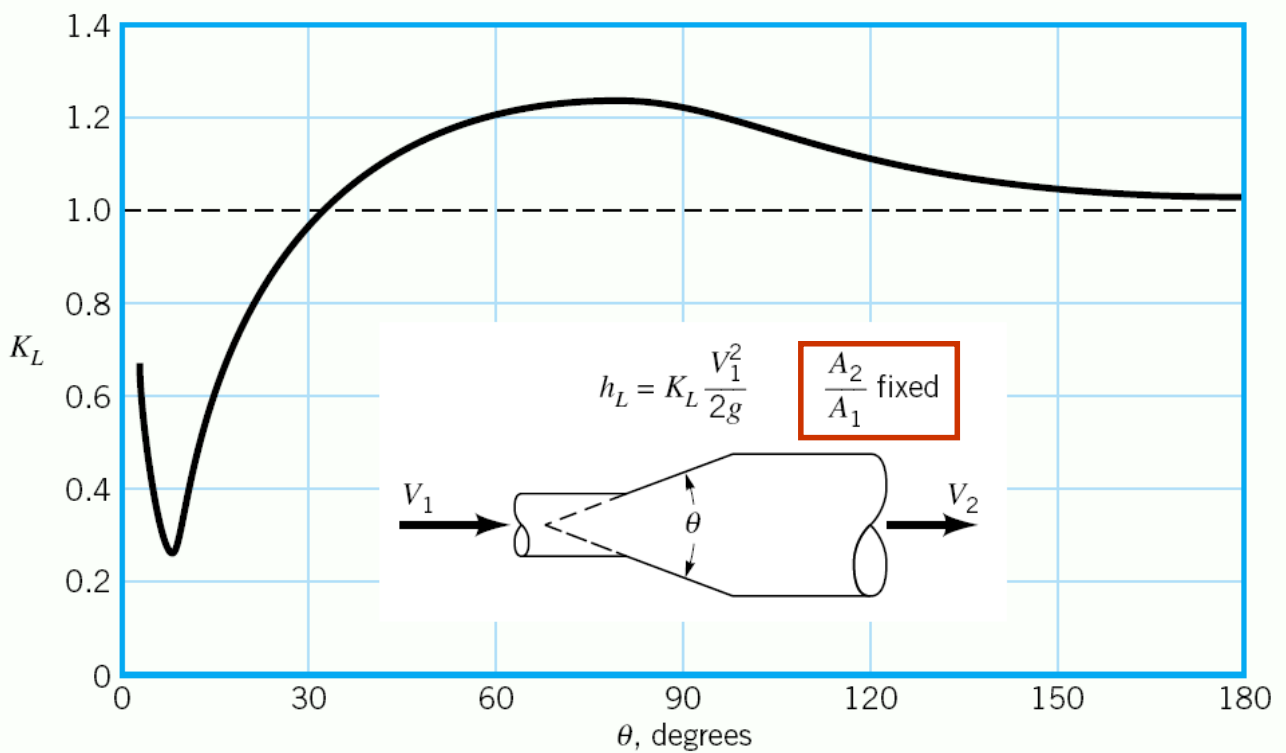
CURVE



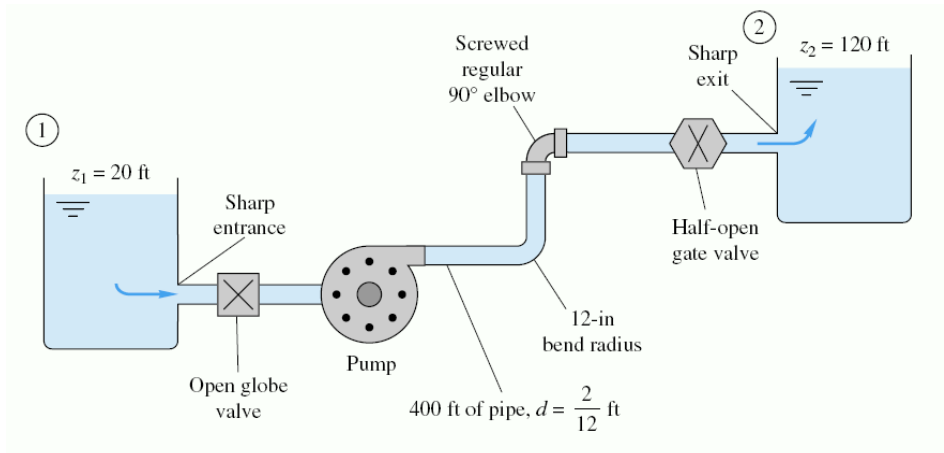
VARIAZIONI DI SEZIONE REPENTINE



ALLARGAMENTI GRADUALI DI SEZIONE



EXAMPLE Determinare la prevalenza e la potenza della pompa



$$\rho = 1.94 \text{ slugs/ft}^3$$

$$\nu = 0.000011 \text{ ft}^2/\text{s}$$

$$\epsilon/d = 0.001$$

$$Q = 0.2 \text{ ft}^3/\text{s}$$

$$\rho = 1000 \text{ Kg/m}^3$$

$$Q = 0.2 * 0.3048 * 0.3048 * 0.3048 = 5.663E-3 \text{ m}^3/\text{s}$$

$$\nu = 0.000011 * 0.3048 * 0.3048 = 1.02E-6 \text{ m}^2/\text{s}$$

EXAMPLE

$$\frac{p_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \left(\frac{p_2}{\rho g} + \frac{V_2^2}{2g} + z_2 \right) + h_f + \sum h_m - h_p$$

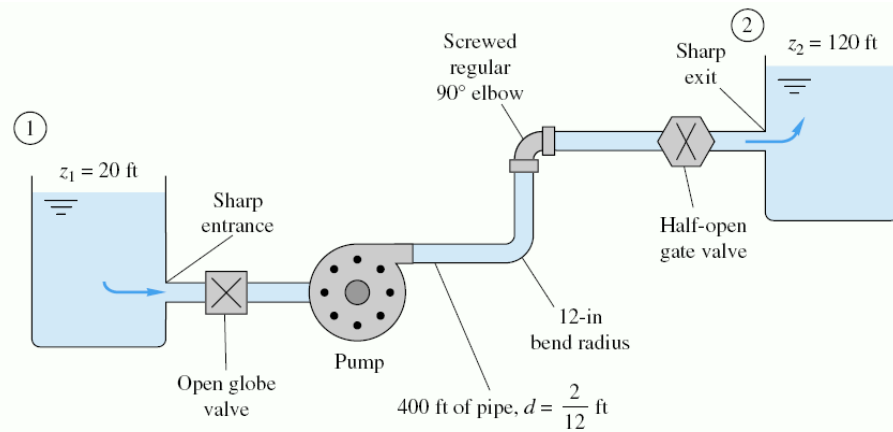
since $p_1 = p_2$ and $V_1 = V_2 \approx 0$,

$$h_p = z_2 - z_1 + h_f + \sum h_m = 120 \text{ ft} - 20 \text{ ft} + \frac{V^2}{2g} \left(\frac{fL}{d} + \sum K \right)$$

$$V = \frac{Q}{A} = \frac{0.2 \text{ ft}^3/\text{s}}{\frac{1}{4}\pi \left(\frac{2}{12} \text{ ft}\right)^2} = 9.17 \text{ ft/s} = 2.79 \text{ m/s}$$

$$Re_d = \frac{Vd}{\nu} = \frac{9.17 \left(\frac{2}{12}\right)}{0.000011} = 139,000$$

EXAMPLE



LOSS	Δ
Sharp entrance (Fig. 6.21)	0.5
Open globe valve (2 in, Table 6.5)	6.9
12-in bend (Fig. 6.20)	0.15
Regular 90° elbow (Table 6.5)	0.95
Half-closed gate valve (from Fig. 6.18 <i>b</i>)	2.7
Sharp exit (Fig. 6.21)	1.0
	$\Sigma K = 12.2$

EXAMPLE

For $\epsilon/d = 0.001$, from the Moody chart read $f = 0.0216$.

$$h_p = 120 \text{ ft} - 20 \text{ ft} + \frac{V^2}{2g} \left(\frac{fL}{d} + \sum K \right) = 100 \text{ ft} + \frac{(9.17 \text{ ft/s})^2}{2(32.2 \text{ ft/s}^2)} \left[\frac{0.0216(400)}{\frac{2}{12}} + 12.2 \right]$$

$$= 100 \text{ ft} + 84 \text{ ft} = 184 \text{ ft} \quad \text{pump head} \quad = 56.08 \text{ m/s}$$

$$P = \rho g Q h_p = [1.94(32.2) \text{ lbf/ft}^3](0.2 \text{ ft}^3/\text{s})(184 \text{ ft}) = 2300 \text{ ft} \cdot \text{lbf/s}$$

The conversion factor is $1 \text{ hp} = 550 \text{ ft} \cdot \text{lbf/s}$ $P = \frac{2300}{550} = 4.2 \text{ hp}$

$$P = \rho g Q h_p = 1000 * 9.81 * 5.663E-3 * 56.08 = 3115 \text{ W}$$



$$Q_1 = Q_2 = Q_3 = \text{const}$$

$$V_1 d_1^2 = V_2 d_2^2 = V_3 d_3^2$$

$$\Delta h_{A \rightarrow B} = \Delta h_1 + \Delta h_2 + \Delta h_3$$

$$\Delta h_{A \rightarrow B} = \frac{V_1^2}{2g} \left(\frac{f_1 L_1}{d_1} + \sum K_1 \right) + \frac{V_2^2}{2g} \left(\frac{f_2 L_2}{d_2} + \sum K_2 \right) + \frac{V_3^2}{2g} \left(\frac{f_3 L_3}{d_3} + \sum K_3 \right)$$

$$\Delta h_{A \rightarrow B} = \frac{V_1^2}{2g} (\alpha_0 + \alpha_1 f_1 + \alpha_2 f_2 + \alpha_3 f_3)$$

EXAMPLE



Given is a three-pipe series system, The total pressure drop is $p_A - p_B = 150,000$ Pa, and the elevation drop is $z_A - z_B = 5$ m. The pipe data are

Pipe	L , m	d , cm	ϵ , mm	ϵ/d
1	100	8	0.24	0.003
2	150	6	0.12	0.002
3	80	4	0.20	0.005

The fluid is water, $\rho = 1000$ kg/m³ and $\nu = 1.02 \times 10^{-6}$ m²/s. Calculate the flow rate Q in m³/h through the system.

EXAMPLE

$$\Delta h_{A \rightarrow B} = \frac{p_A - p_B}{\rho g} + z_A - z_B = \frac{150,000}{1000(9.81)} + 5 \text{ m} = 20.3 \text{ m}$$

$$V_2 = \frac{d_1^2}{d_2^2} V_1 = \frac{16}{9} V_1 \quad V_3 = \frac{d_1^2}{d_3^2} V_1 = 4V_1$$

$$\text{Re}_2 = \frac{V_2 d_2}{V_1 d_1} \text{Re}_1 = \frac{4}{3} \text{Re}_1 \quad \text{Re}_3 = 2 \text{Re}_1$$

Neglecting minor losses

Begin by estimating $f_1, f_2,$ and f_3 from the Moody-chart fully rough regime

$$f_1 = 0.0262 \quad f_2 = 0.0234 \quad f_3 = 0.0304$$

$$\Delta h_{A \rightarrow B} = \frac{V_1^2}{2g} \left[1250f_1 + 2500 \left(\frac{16}{9} \right)^2 f_2 + 2000(4)^2 f_3 \right]$$

$$V_1^2 \approx 2g(20.3)/(33 + 185 + 973) \quad V_1 = 0.58 \text{ m/s}$$

EXAMPLE

$$\text{Re}_1 \approx 45,400 \quad \text{Re}_2 = 60,500 \quad \text{Re}_3 = 90,800$$

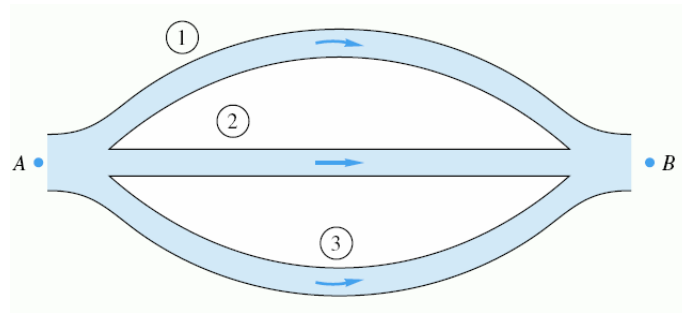
Hence, from the Moody chart,

$$f_1 = 0.0288 \quad f_2 = 0.0260 \quad f_3 = 0.0314$$

$$V_1 = 0.565 \text{ m/s} \quad Q = \frac{1}{4} \pi d_1^2 V_1 = 2.84 \times 10^{-3} \text{ m}^3/\text{s}$$

$$Q_1 = 10.2 \text{ m}^3/\text{h}$$

A second iteration gives $Q = 10.22 \text{ m}^3/\text{h}$, a negligible change.



$$\Delta h_{A \rightarrow B} = \Delta h_1 = \Delta h_2 = \Delta h_3$$

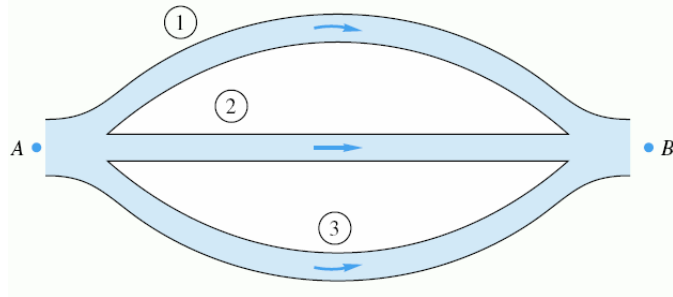
$$Q = Q_1 + Q_2 + Q_3$$

$$h_f = f(L/d)(V^2/2g) = fQ^2/C$$

$$C = \pi^2 g d^5 / 8L$$

$$h_f = \frac{Q^2}{\left(\sum \sqrt{C_i/f_i}\right)^2} \quad \text{where } C_i = \frac{\pi^2 g d_i^5}{8L_i}$$

EXAMPLE



Pipe	L , m	d , cm	ϵ , mm	ϵ/d
1	100	8	0.24	0.003
2	150	6	0.12	0.002
3	80	4	0.20	0.005

are connected in parallel

Total head loss of 20.3 m.

Compute the total flow rate Q , neglecting minor losses.

EXAMPLE

$$20.3 \text{ m} = \frac{V_1^2}{2g} 1250f_1 = \frac{V_2^2}{2g} 2500f_2 = \frac{V_3^2}{2g} 2000f_3$$

Guess fully rough flow in pipe 1: $f_1 = 0.0262$, $V_1 = 3.49 \text{ m/s}$; hence $\text{Re}_1 = V_1 d_1 / \nu = 273,000$.

From the Moody chart read $f_1 = 0.0267$; recompute $V_1 = 3.46 \text{ m/s}$, $Q_1 = 62.5 \text{ m}^3/\text{h}$.

Next guess for pipe 2: $f_2 \approx 0.0234$, $V_2 \approx 2.61 \text{ m/s}$; then $\text{Re}_2 = 153,000$, and hence $f_2 = 0.0246$, $V_2 = 2.55 \text{ m/s}$, $Q_2 = 25.9 \text{ m}^3/\text{h}$.

Finally guess for pipe 3: $f_3 \approx 0.0304$, $V_3 \approx 2.56 \text{ m/s}$; then $\text{Re}_3 = 100,000$, and hence $f_3 = 0.0313$, $V_3 = 2.52 \text{ m/s}$, $Q_3 = 11.4 \text{ m}^3/\text{h}$.

$$Q = Q_1 + Q_2 + Q_3 = 62.5 + 25.9 + 11.4 = 99.8 \text{ m}^3/\text{h}$$

These three pipes carry 10 times more flow in parallel than they do in series.