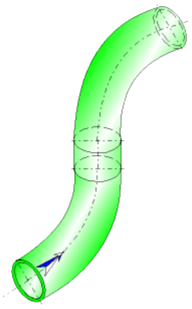
S-shaped Bends
(with flow in one plane)
Circular Cross-Section
(MILLER)



Model description:

This model of component calculates the head loss (pressure drop) of S-shaped bends (with flow in one plane) whose cross-section is circular and constant. In addition, the flow is assumed fully developed and stabilized upstream of the first bend.

An option allows to take into account the effect of the straight length at the exit of the second bend.

Model formulation:

Hydraulic diameter (m):

$$D = d$$

Cross-section area (m²):

$$A = \pi \cdot \frac{D^2}{4}$$

Mean velocity (m/s):

$$U = \frac{Q}{A}$$

Total length measured along the axis (m):

$$L = 2 \cdot \left(2 \cdot \pi \cdot r \cdot \frac{\theta_b}{360}\right) + L_s$$

Mass flow rate (kg/s):

$$G = Q \cdot \rho$$

Fluid volume (m^3):

$$V = A \cdot L$$

Fluid mass (kg):

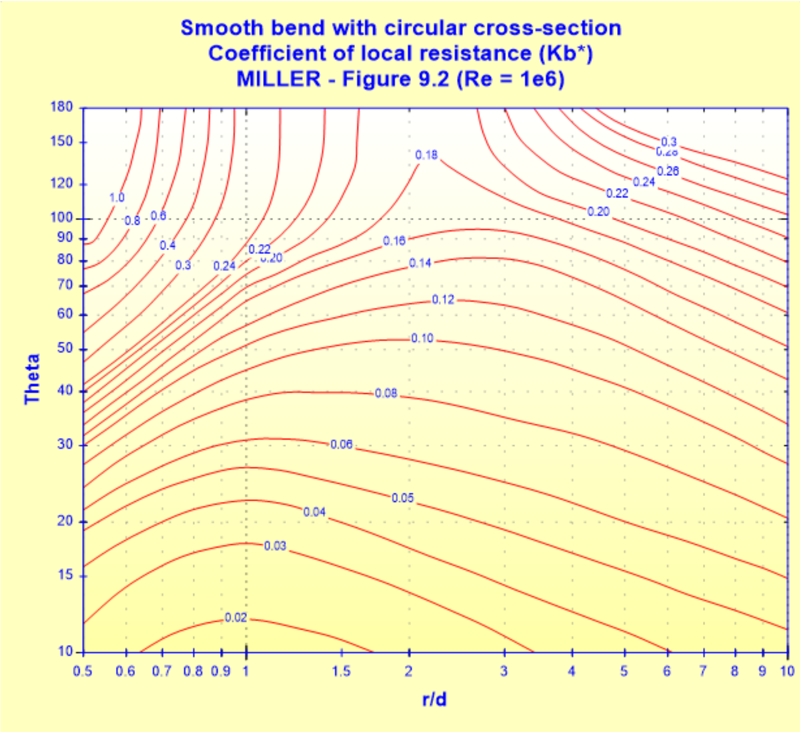
$$M = V \cdot \rho$$

Reynolds number:

$$\mathrm{Re} = \frac{U \cdot D}{\nu}$$

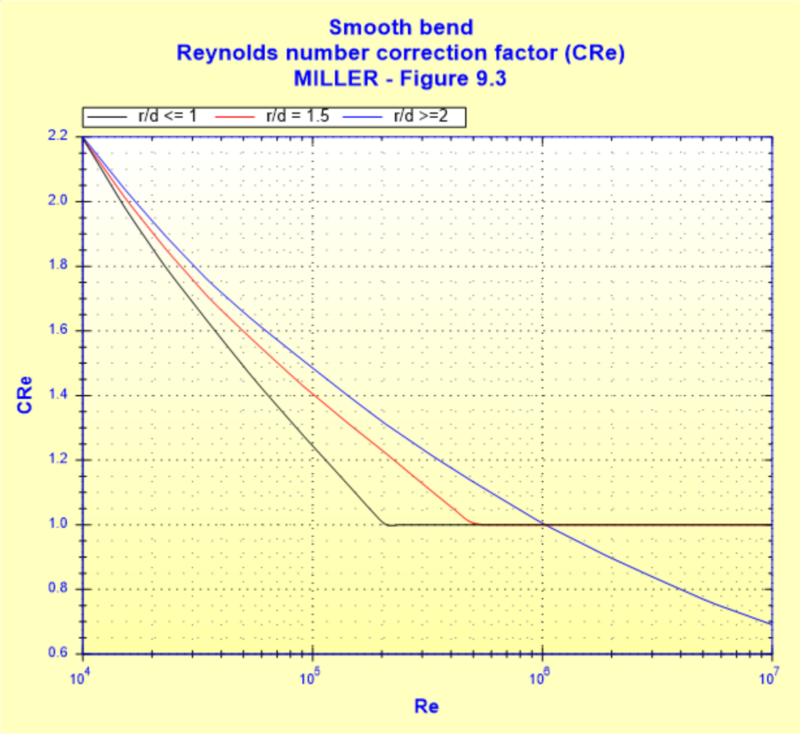
Basic resistance coefficient for one bend:

$$K_b^* = f\left(\frac{r}{d}, \theta_b\right)$$ ([1] figure 9.2)



Reynolds number correction factor:

$$C_{\mathrm{Re}} = f\left(\mathrm{Re}, \frac{r}{d}\right)$$ ([1] figure 9.3)



■ r/d ≥ 1

$$C_{Re} = f\left(Re, \frac{r}{d}\right)$$

([1] figure 9.3)

■ r/d < 1

● r/d > 0.7 or $K_b^* < 0.4$

$$C_{Re} = f\left(Re, \frac{r}{d}\right)$$

([1] figure 9.3 with r/d=1)

● otherwise (r/d ≤ 0.7 and $K_b^* \geq 0.4$)

$$C_{Re} = \frac{K_b^*}{K_b^* - 0.2C'_{Re} + 0.2}$$

([1] equation 9.2)

with:

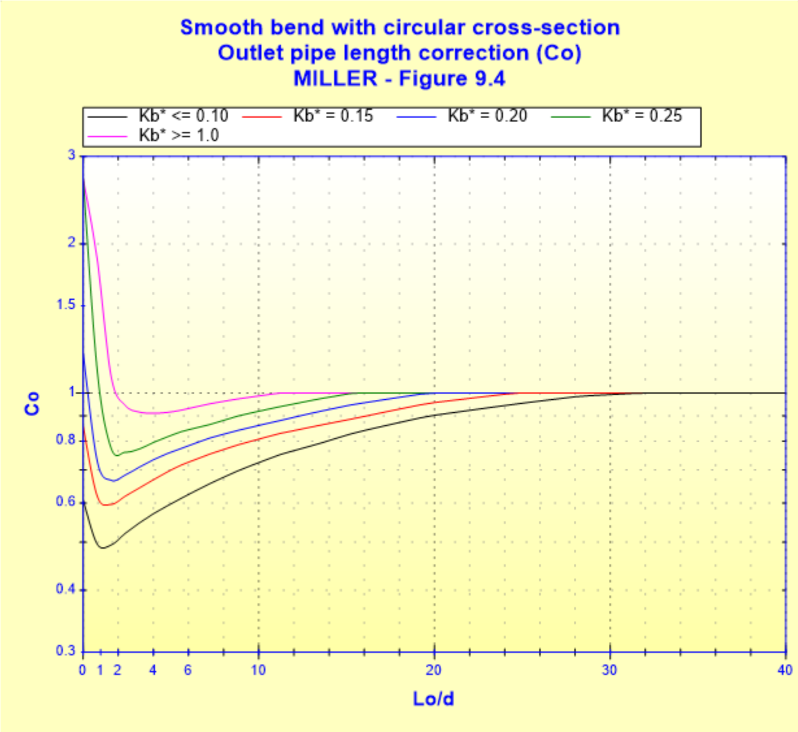
$$C'_{Re} = f\left(Re, \frac{r}{d}\right)$$

([1] figure 9.3 with r/d=1)

Outlet pipe length correction factor (optional):

$$C_o = f\left(\frac{L_o}{d}, K_b^*\right)$$

([1] figure 9.4)



■ r/d < 3 et θ_b < 100°

$$C_o = f\left(\frac{L_o}{d}, K_b^*\right)$$

([1] figure 9.4)

■ otherwise (r/d > 3 and/or θ_b > 100°)

$$C_o = 1$$

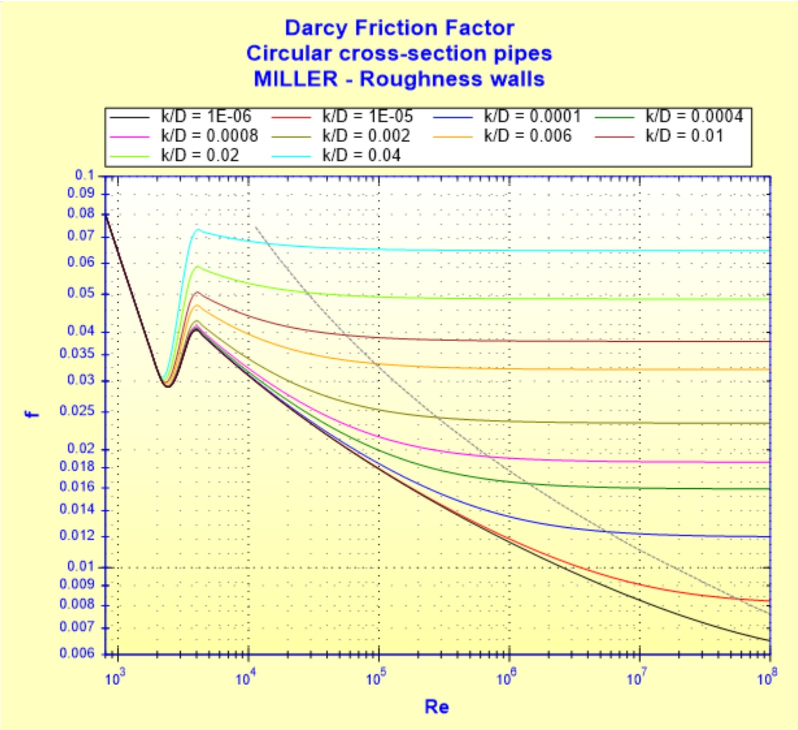
(negligible effect)

If this option is not activated, the factor C_o is equal to unity.

Darcy friction factor:

$$f = f\left(\mathrm{Re}, \frac{k}{D}\right)$$

See Straight Pipe - Circular Cross-Section and Roughness Walls (MILLER)



Roughness correction factor:

$$C_f = \frac{f_{rough}}{f_{smooth}}$$ ([1] equation 9.3)

with:

f_{rough}: Darcy friction factor for rough pipe at Re

f_{smooth}: Darcy friction factor for smooth pipe (k = 0) at Re

For Re > 10^6, C_f is calculated from equation (9.3) for Re = 10^6

Corrected loss coefficient for the first bend:

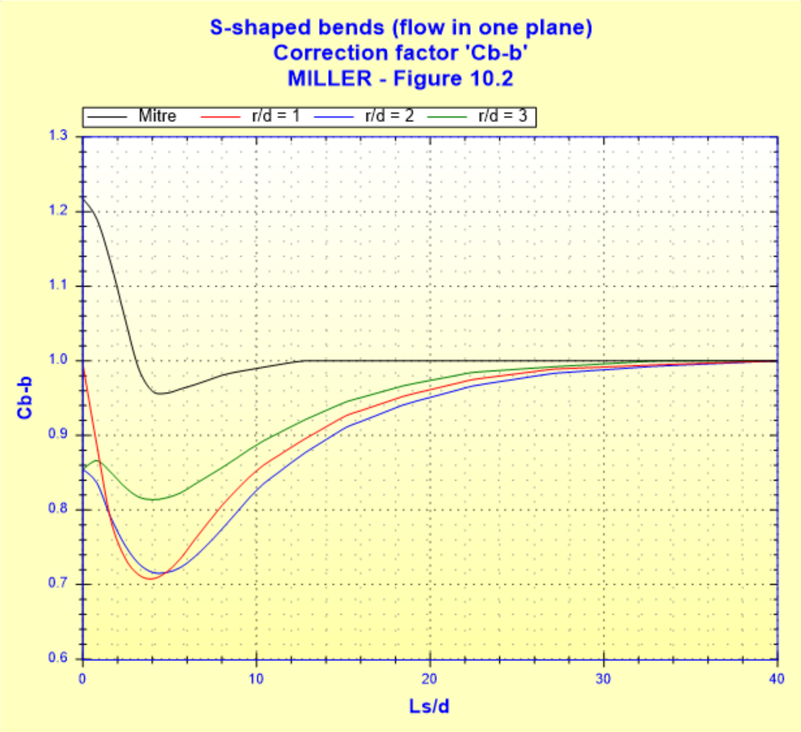
$$K_{b1} = K_b^* \cdot C_{Re} \cdot C_f$$ ([1] equation 9.4)

Corrected loss coefficient for the second bend:

$$K_{b2} = K_b^* \cdot C_{Re} \cdot C_f \cdot C_o$$ ([1] equation 9.4)

Interaction correction factor:

$$C_{b-b} = f\left(\frac{L_s}{d}, \frac{r}{d}\right)$$ ([1] figure 10.2)



Pressure loss coefficient of the two bends:

$$K_{b-b} = (K_{b1} + K_{b2}) \cdot C_{b-b}$$ ([1] equation 10.1)

Friction loss coefficient of the straight length between bends:

$$K_f = f \cdot \frac{L_s}{d}$$ ([1] equation 8.3)

Total pressure loss coefficient (based on the mean velocity in the bend):

$$K = K_{b-b} + K_f$$

Straight length of equivalent pressure loss (m):

$$L_{eq} = K \cdot \frac{d}{f}$$

Total pressure loss (Pa):

$$\Delta P = K \cdot \frac{\rho \cdot U^2}{2}$$

([1] equation 8.1b)

Total head loss of fluid (m):

$$\Delta H = K \cdot \frac{U^2}{2 \cdot g}$$

([1] equation 8.1a)

Hydraulic power loss (W):

$$Wh = \Delta P \cdot Q$$

Symbols, Definitions, SI Units:

D	Bend hydraulic diameter (m)
d	Bend internal diameter (m)
A	Cross-section area (m^2)
Q	Volume flow rate (m^3/s)
U	Mean velocity (m/s)
L_s	Straight length between the two bends (m)
L	Total length measured along the axis (m)
r	Radius of curvature (m)
θ_b	Curvature angle of each bend (°)
G	Mass flow rate (kg/s)
V	Fluid volume (m^3)
M	Fluid mass (kg)
Re	Reynolds number ()
K_b^*	Basic loss coefficient of one bend ()
C_{Re}	Reynolds number correction factor ()
C_o	Outlet pipe length correction factor ()
L_0	Length of the straight section downstream of the bend (m)
f	Darcy friction factor ()
k	Absolute roughness of walls (m)
C_f	Roughness correction factor ()
K_{b1}	Corrected loss coefficient for the first bend ()
K_{b2}	Corrected loss coefficient for the second bend ()
C_{b-b}	Interaction correction factor ()
K_{b-b}	Pressure loss coefficient of the two bends ()

K_f	Friction loss coefficient of the straight length between bends ()
K	Total pressure loss coefficient (based on the mean velocity in the bend) ()
L_{eq}	Straight length of equivalent pressure loss (m)
ΔP	Total pressure loss (Pa)
ΔH	Total head loss of fluid (m)
Wh	Hydraulic power loss (W)
ρ	Fluid density (kg/m^3)
ν	Fluid kinematic viscosity (m^2/s)
g	Gravitational acceleration (m/s^2)

Validity range:

- turbulent flow regime ($Re \geq 10^4$)
- stabilized flow upstream bend
- relative radius of curvature 'r/d': greater than or egal to 0.5 and lower than or egal to 10

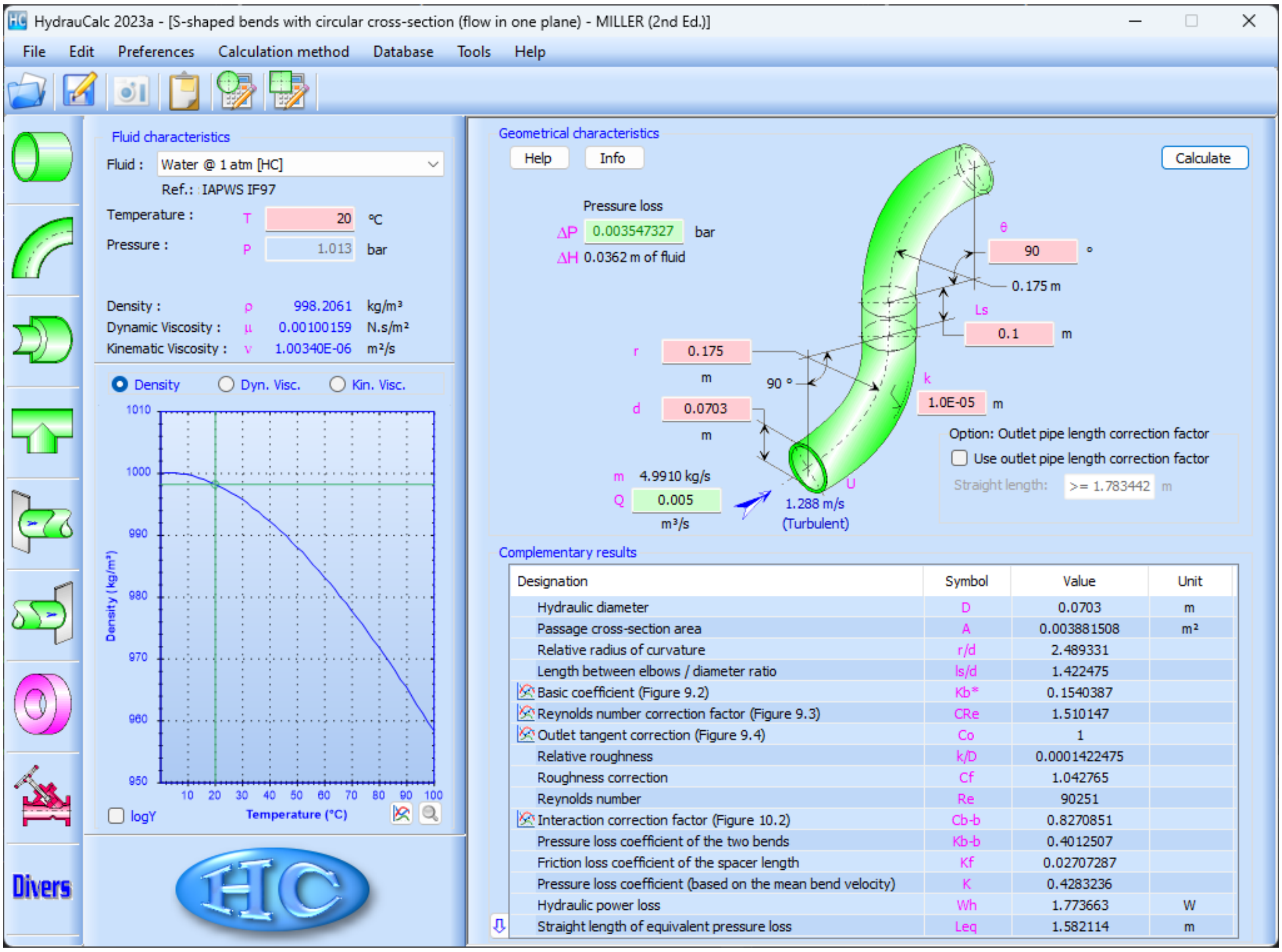
  for relative radius of curvature 'r/d' greater than 3, the pressure loss coefficient 'K' is estimated by taking into account the interaction correction factor 'Cb-b' corresponding to a relative radius of curvature 'r/d' of value 3.

- curvature angle: between 10° and 180°

  the interaction correction factor 'Cb-b' is only applicable for angles 'θ_b' between 70° and 90°,

  for angles 'θ_b' less than 70° or greater than 90°, the pressure loss coefficient 'K' is estimated by taking into account the interaction correction factor 'Cb-b' applicable to angles 'θ_b' between 70° and 90°

Example of application:



References:

[1] Internal Flow System, Second Edition, D.S. Miller