UNIVERSIDAD DE LOS ANDES
ESCUELA DE INGENIERÍA QUÍMICA

MATERIAL COMPLEMENTARIO PARA LA RESOLUCION DE PROBLEMAS DE OPERACIONES UNITARIAS I

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PROPIEDADES FISICAS DEL AGUA

Temperatura (ºC)	Densidad (Kg/m^3)	Viscosidad dinámica (Pa.s)
0	1000	$1.75 \cdot 10^{-3}$
5	1000	$1.52 \cdot 10^{-3}$
10	1000	$1.30 \cdot 10^{-3}$
15	1000	$1.15 \cdot 10^{-3}$
20	998	$1.02 \cdot 10^{-3}$
25	997	$8.91 \cdot 10^{-4}$
30	996	$8.00 \cdot 10^{-4}$
35	994	$7.18 \cdot 10^{-4}$
40	992	$6.51 \cdot 10^{-4}$
45	990	$5.94 \cdot 10^{-4}$
50	988	$5.41 \cdot 10^{-4}$
55	986	$4.98 \cdot 10^{-4}$
60	984	$4.60 \cdot 10^{-4}$
70	978	$4.02 \cdot 10^{-4}$
80	971	$3.50 \cdot 10^{-4}$

PROPIEDADES FISICAS DE OTROS COMPUESTOS @ 25 ºC

Fluido	Densidad (Kg/m^3)	Viscosidad dinámica (Pa.s)
Acetona	787	$3.16 \cdot 10^{-4}$
Alcohol etílico	787	$1.00 \cdot 10^{-3}$
Alcohol metílico	789	$5.60 \cdot 10^{-4}$
Alcohol propílico	802	$1.92 \cdot 10^{-3}$
Amoniaco	826	-
Benceno	876	$6.03 \cdot 10^{-4}$
Tetracloruro de carbono	1590	$9.10 \cdot 10^{-4}$
Etilenglicol	1100	$1.62 \cdot 10^{-2}$
Gasolina	680	$2.87 \cdot 10^{-4}$
Glicerina	1258	$9.60 \cdot 10^{-1}$
Queroseno	823	$1.64 \cdot 10^{-3}$
Mercurio	13540	$1.53 \cdot 10^{-3}$
Propano	495	$1.10 \cdot 10^{-4}$
Agua de mar	1030	$1.03 \cdot 10^{-3}$
Aceite de petróleo medio	852	$2.99 \cdot 10^{-3}$
Aceite de petróleo pesado	906	$1.07 \cdot 10^{-1}$

VISCOSIDADES DE LIQUIDOS

VISCOSIDADES DE LIQUIDOS*

Para usarse como Coordenadas con la Fig. 14

Líquido	X	Y	Líquido	X	Y
Acetaldehído	15.2	4.8	Cloruro Estánico	13.5	12.8
Acetato de Amilo	11.8	12.5	Cresol, meta	2.5	20.8
Acetato de Butilo	12.3	11.0	Dibromoetano	12.7	15.8
Acetato de Etilo	13.7	9.1	Dicloroetano	13.2	12.2
Acetato de Metilo	14.2	8.2	Diclorometano	14.6	8.9
Acetato de Vinilo	14.0	8.8	Difenilo	12.0	18.3
Acetona 100%	14.5	7.2	Eter Etílico	14.5	5.3
Acetona 35%	7.9	15.0	Etilbenceno	13.2	11.5
Agua	10.2	13.0	Etilenglicol	6.0	23.6
Acido Acético 100%	12.1	14.2	Fenol	6.9	20.8
Acido Acético 70%	9.5	17.0	Formiato de Etilo	14.2	8.4
Acido Butírico	12.1	15.3	Freon 11	14.4	9.0
Acido Clorosulfónico	11.2	18.1	Freon 12	16.8	5.6
Acido Fórmico	10.7	15.8	Freon 21	15.7	7.5
Acido Isobutírico	12.2	14.4	Freon 22	17.2	4.7
Acido Nítrico 95%	12.8	13.8	Freon 113	12.5	11.4
Acido Nítrico 60%	10.8	17.0	Freon 114	14.6	8.3
Acido Propiónico	12.8	13.8	Glicerina 100%	2.0	30.0
Acido Sulfúrico 110%	7.2	27.4	Glicerina 50%	6.9	19.6
Acido Sulfúrico 98%	7.0	24.8	Heptano	14.1	8.4
Acido Sulfúrico 60%	10.2	21.3	Hexano	14.7	7.0
Alcohol Alílico	10.2	14.3	Hidróxido de Sodio 50%	3.2	25.8
Alcohol Amílico	7.5	18.4	Yoduro de Etilo	14.7	10.3
Alcohol Butílico	8.6	17.2	Yoduro de Propilo	14.1	11.6
Alcohol Etílico 100%	10.5	13.8	Isobutano	14.5	3.7
Alcohol Etílico 95%	9.8	14.3	Mercurio	18.4	16.4
Alcohol Etílico 40%	6.5	16.6	Metanol 100%	12.4	10.5
Acido Clorhídrico 31.5%	13.0	16.6	Metanol 90%	12.3	11.8
Alcohol Isobutílico	7.1	18.0	Metanol 40%	7.8	15.5
Alcohol Isopropílico	8.2	16.0	Metiletilcetona	13.9	8.6
Alcohol Octílico	6.2	21.1	Naftaleno	7.9	18.1
Alcohol Propílico	9.1	16.5	Nitrobenceno	10.6	16.2
Amoniaco 100%	12.6	2.0	Nitrotolueno	11.0	17.0
Amoniaco 26%	10.1	13.9	Octano	13.7	10.0
Anhídrido Acético	12.7	12.8	Oxalato de Dietilo	11.0	16.4
Anilina	8.1	18.7	Oxalato de Dimetilo	12.3	15.8
Anisol	12.3	13.5	Oxalato de Dipropilo	10.3	17.7
Benceno	12.5	10.9	Pentacloroetano	10.9	17.3
Bióxido de Azufre	15.2	7.1	Pentano	14.9	5.2
Bióxido de Carbono	11.6	0.3	Propano	15.3	1.0
Bisulfuro de Carbono	16.1	7.5	Salmuera $CaCl_2$ 25%	6.6	15.9
Bromo	14.2	13.2	Salmuera NaCl 25%	10.2	16.6
Bromotolueno	20.0	15.9	Sodio	16.4	13.9
Bromuro de Etilo	14.5	8.1	Tetracloroetano	11.9	15.7
Bromuro de Propilo	14.5	9.6	Tetracloroetileno	14.2	12.7
n-Butano	15.3	3.3	Tetracloruro de Carbono	12.7	13.1
Ciclohexanol	2.9	24.3	Tetracloruro de Titanio	14.4	12.3
Clorobenceno	12.3	12.4	Tribromuro de Fósforo	13.8	16.7
Cloroformo	14.4	10.2	Tricloruro de Arsénico	13.9	14.5
Clorotolueno, orto	13.0	13.3	Tricloruro de Fósforo	16.2	10.9
Clorotolueno, meta	13.3	12.5	Tricloroetileno	14.8	10.5
Clorotolueno, para	13.3	12.5	Tolueno	13.7	10.4
Cloruro de Etilo	14.8	6.0	Turpentina	11.5	14.9
Cloruro de Metilo	15.0	3.8	Xileno, orto	13.5	12.1
Cloruro de Propilo	14.4	7.5	Xileno, meta	13.9	12.1
Cloruro de Sulfurilo	15.2	12.4	Xileno, para	13.9	10.9

* De Perry, J. H., "Chemical Engineers' Handbook 3d. ed., McGraw-Hill Book Company, Inc., New York, 1950.

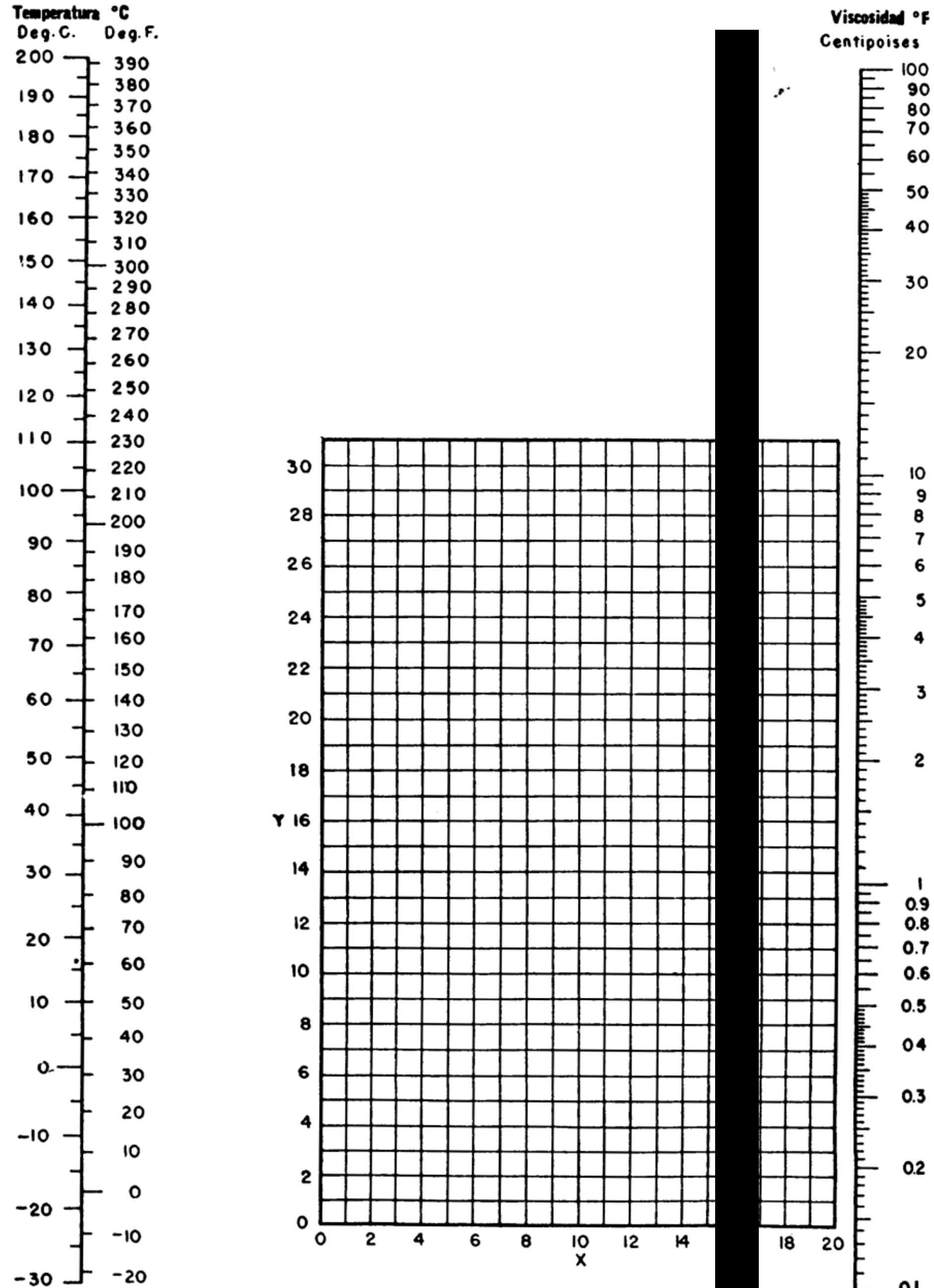


FIG. 14. Viscosidades de líquidos. (*Perry, "Chemical Eng*[redacted]*ers' Handbook"*, 3a. ed., *McGraw-Hill Book Company, Inc.*, New Y[redacted] 1950)

VISCOSIDADES DE GASES

Gas	X	Y
Acetato de Etilo	8.5	13.2
Acetona	8.9	13.0
Acetileno	9.8	14.9
Acido Acético	7.7	14.3
Agua	8.0	16.0
Aire	11.0	20.0
Alcohol Etílico	9.2	14.2
Alcohol Metílico	8.5	15.6
Alcohol Propílico	8.4	13.4
Amoniaco	8.4	16.0
Argón	10.5	22.4
Benceno	8.5	13.2
Bromo	8.9	19.2
Buteno	9.2	13.7
Butileno	8.9	13.0
Bióxido de Azufre	9.6	17.0
Bióxido de Carbono	9.5	18.7
Bisulfuro de Carbono	8.0	16.0
Bromuro de Hidrógeno	8.8	20.9
Cianógeno	9.2	15.2
Ciclohexano	9.2	12.0
Cianuro de Hidrógeno	9.8	14.9
Cloro	9.0	18.4
Cloroformo	8.9	15.7
Cloruro de Etilo	8.5	15.6
Cloruro de Hidrógeno	8.8	18.7
Cloruro de Nitrosilo	8.0	17.6
Etano	9.1	14.5
Eter Etílico	8.9	13.0
Etileno	9.5	15.1
Flúor	7.3	23.8
Freon 11	10.6	15.1
Freon 12	11.1	16.0
Freon 21	10.8	15.3
Freon 22	10.1	17.0
Freon 113	11.3	14.0
Helio	10.9	20.5
Hexano	8.6	11.8
Hidrógeno	11.2	12.4
$3H_2 + 1N_2$	11.2	17.2
Yodo	9.0	18.4
Yoduro de Hidrógeno	9.0	21.3
Mercurio	5.3	22.9
Metano	9.9	15.5
Monóxido de Carbono	11.0	20.0
Nitrógeno	10.6	20.0
Oxido Nítrico	10.9	20.5
Oxido Nitroso	8.8	19.0
Oxígeno	11.0	21.3
Pentano	7.0	12.8
Propano	9.7	12.9
Propileno	9.0	13.8
Sulfuro de Hidrógeno	8.6	18.0
Tolueno	8.6	12.4
2, 3, 3-Trimetilbutano	9.5	10.5
Xenón	9.3	23.0

* De Perry, J. H., "Chemical Engineers' Handbokk" 3d ed., McGraw-Hill Book Company. Inc., New York 1950.

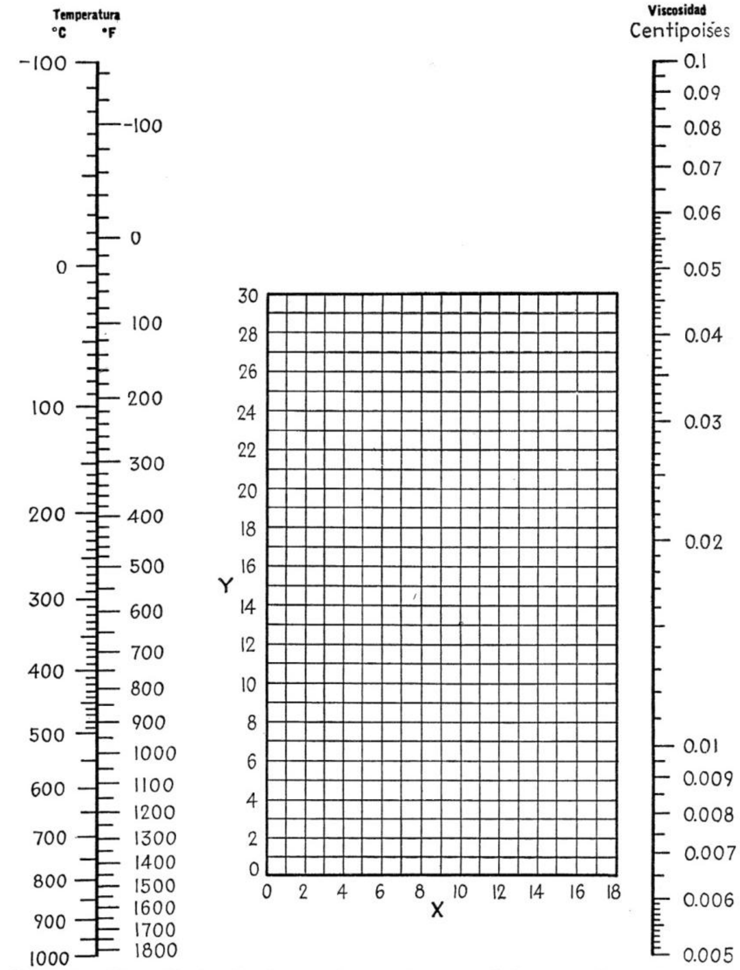


FIG. 15. Viscosidades de Gases. (*Perry, "Chemical Engineers' Handbook", 3d ed., McGraw-Hill Book Company, Inc., New York*, 1950)

Ecuaciones de variación

Ecuaciones de continuidad

Rectangular coordinates (x, y, z):

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho v_x) + \frac{\partial}{\partial y}(\rho v_y) + \frac{\partial}{\partial z}(\rho v_z) = 0$$

Cylindrical coordinates (r, θ, z):

$$\frac{\partial \rho}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(\rho r v_r) + \frac{1}{r}\frac{\partial}{\partial \theta}(\rho v_\theta) + \frac{\partial}{\partial z}(\rho v_z) = 0$$

Spherical coordinates (r, θ, ϕ):

$$\frac{\partial \rho}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}(\rho r^2 v_r) + \frac{1}{r \sin\theta}\frac{\partial}{\partial \theta}(\rho v_\theta \sin\theta) + \frac{1}{r \sin\theta}\frac{\partial}{\partial \phi}(\rho v_\phi) = 0$$

Ecuaciones de movimiento en sistema rectangular

$$\rho\left(\frac{\partial v_z}{\partial t} + v_x\frac{\partial v_x}{\partial x} + v_y\frac{\partial v_x}{\partial y} + v_z\frac{\partial v_x}{\partial z}\right)$$

$$= -\frac{\partial p}{\partial x} - \left(\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z}\right) + \rho g_x$$

In a similar way we can find the y and z components.

$$\rho\left(\frac{\partial v_y}{\partial t} + \mathrm{v_x}\frac{\partial v_y}{\partial x} + v_Y\frac{\partial v_y}{\partial y} + v_z\frac{\partial v_y}{\partial z}\right)$$

$$= -\frac{\partial p}{\partial y} - \left(\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z}\right) + \rho g_Y$$

$$\rho\left(\frac{\partial v_z}{\partial t} + v_x\frac{\partial v_z}{\partial x} + v_Y\frac{\partial v_z}{\partial y} + v_z\frac{\partial v_z}{\partial z}\right)$$

$$= -\frac{\partial p}{\partial z} - \left(\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}\right) + \rho g_z$$

Si el fluido es newtoniano y con densidad constante se puede escribir:

x component :
$$\rho\left(\frac{\partial v_x}{\partial t}+v_x\frac{\partial v_x}{\partial x}+v_y\frac{\partial v_x}{\partial y}+v_z\frac{\partial v_x}{\partial z}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 v_x}{\partial x^2}+\frac{\partial^2 v_x}{\partial y^2}+\frac{\partial^2 v_x}{\partial z^2}\right)+\rho g_x$$

y component :
$$\rho\left(\frac{\partial v_y}{\partial t}+v_x\frac{\partial v_y}{\partial x}+v_y\frac{\partial v_y}{\partial y}+v_z\frac{\partial v_y}{\partial z}\right)=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v_y}{\partial x^2}+\frac{\partial^2 v_y}{\partial y^2}+\frac{\partial^2 v_y}{\partial z^2}\right)+\rho g_y$$

z component :
$$\rho\left(\frac{\partial v_z}{\partial t}+v_x\frac{\partial v_z}{\partial x}+v_y\frac{\partial v_z}{\partial y}+v_z\frac{\partial v_z}{\partial z}\right)=-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 v_z}{\partial x^2}+\frac{\partial^2 v_z}{\partial y^2}+\frac{\partial^2 v_z}{\partial z^2}\right)+\rho g_z$$

Ecuaciones de movimiento en sistema cilíndrico

In terms of τ:

r-component[a]
$$\rho\left(\frac{\partial v_r}{\partial t}+v_r\frac{\partial v_r}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_r}{\partial \theta}-\frac{v_\theta^2}{r}+v_z\frac{\partial v_r}{\partial z}\right)=-\frac{\partial p}{\partial r}-\left(\frac{1}{r}\frac{\partial}{\partial r}(r\tau_{rr})+\frac{1}{r}\frac{\partial \tau_{r\theta}}{\partial \theta}-\frac{\tau_{\theta\theta}}{r}+\frac{\partial \tau_{rz}}{\partial z}\right)+\rho g_r$$

θ-component[b]
$$\rho\left(\frac{\partial v_\theta}{\partial t}+v_r\frac{\partial v_\theta}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_\theta}{\partial \theta}+\frac{v_r v_\theta}{r}+v_z\frac{\partial v_\theta}{\partial z}\right)=-\frac{1}{r}\frac{\partial p}{\partial \theta}-\left(\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\tau_{r\theta})+\frac{1}{r}\frac{\partial \tau_{\theta\theta}}{\partial \theta}+\frac{\partial \tau_{\theta z}}{\partial z}\right)+\rho g_\theta$$

z-component
$$\rho\left(\frac{\partial v_z}{\partial t}+v_r\frac{\partial v_z}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_z}{\partial \theta}+v_z\frac{\partial v_z}{\partial z}\right)=-\frac{\partial p}{\partial z}-\left(\frac{1}{r}\frac{\partial}{\partial r}(r\tau_{rz})+\frac{1}{r}\frac{\partial \tau_{\theta z}}{\partial \theta}+\frac{\partial \tau_{zz}}{\partial z}\right)+\rho g_z$$

In terms of velocity gradients for a Newtonian fluid with constant ρ and μ:

$$r\text{-component}\quad \rho\left(\frac{\partial v_r}{\partial t}+v_r\frac{\partial v_r}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_r}{\partial \theta}-\frac{v_\theta^2}{r}+v_z\frac{\partial v_r}{\partial z}\right)=-\frac{\partial p}{\partial r}$$

$$+\mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(r v_r)\right)+\frac{1}{r^2}\frac{\partial^2 v_r}{\partial \theta^2}-\frac{2}{r^2}\frac{\partial v_\theta}{\partial \theta}+\frac{\partial^2 v_r}{\partial z^2}\right]+\rho g_r$$

$$\theta\text{-component}\quad \rho\left(\frac{\partial v_\theta}{\partial t}+v_r\frac{\partial v_\theta}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_\theta}{\partial \theta}+\frac{v_r v_\theta}{r}+v_z\frac{\partial v_\theta}{\partial z}\right)=-\frac{1}{r}\frac{\partial p}{\partial \theta}$$

$$+\mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(r v_\theta)\right)+\frac{1}{r^2}\frac{\partial^2 v_\theta}{\partial \theta^2}+\frac{2}{r^2}\frac{\partial v_r}{\partial \theta}+\frac{\partial^2 v_\theta}{\partial z^2}\right]+\rho g_\theta$$

$$z\text{-component}\quad \rho\left(\frac{\partial v_z}{\partial t}+v_r\frac{\partial v_z}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_z}{\partial \theta}+v_z\frac{\partial v_z}{\partial z}\right)=-\frac{\partial p}{\partial z}$$

$$+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 v_z}{\partial \theta^2}+\frac{\partial^2 v_z}{\partial z^2}\right]+\rho g_z$$

Ecuaciones de movimiento en sistema esférico

In terms of τ:

$$r\text{-component}\quad \rho\left(\frac{\partial v_r}{\partial t}+v_r\frac{\partial v_r}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_r}{\partial \theta}+\frac{v_\phi}{r\sin\theta}\frac{\partial v_r}{\partial \phi}-\frac{v_\theta^2+v_\phi^2}{r}\right)$$

$$=-\frac{\partial p}{\partial r}-\left(\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\tau_{rr})+\frac{1}{r\sin\theta}\frac{\partial}{\partial \theta}(\tau_{r\theta}\sin\theta)\right.$$

$$\left.+\frac{1}{r\sin\theta}\frac{\partial \tau_{r\phi}}{\partial \phi}-\frac{\tau_{\theta\theta}+\tau_{\phi\phi}}{r}\right)+\rho g_r$$

$$\theta\text{-component}\quad \rho\left(\frac{\partial v_\theta}{\partial t}+v_r\frac{\partial v_\theta}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_\theta}{\partial \theta}+\frac{v_\phi}{r\sin\theta}\frac{\partial v_\theta}{\partial \phi}+\frac{v_r v_\theta}{r}-\frac{v_\phi^2\cot\theta}{r}\right)$$

$$=-\frac{1}{r}\frac{\partial p}{\partial \theta}-\left(\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\tau_{r\theta})+\frac{1}{r\sin\theta}\frac{\partial}{\partial \theta}(\tau_{\theta\theta}\sin\theta)+\frac{1}{r\sin\theta}\frac{\partial \tau_{\theta\phi}}{\partial \phi}\right.$$

$$\left.+\frac{\tau_{r\theta}}{r}-\frac{\cot\theta}{r}\tau_{\phi\phi}\right)+\rho g_\theta$$

$$\phi\text{-component}\quad \rho\left(\frac{\partial v_\phi}{\partial t}+v_r\frac{\partial v_\phi}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_\phi}{\partial \theta}+\frac{v_\phi}{r\sin\theta}\frac{\partial v_\phi}{\partial \phi}+\frac{v_\phi v_r}{r}+\frac{v_\theta v_\phi}{r}\cot\theta\right)$$

$$=-\frac{1}{r\sin\theta}\frac{\partial p}{\partial \phi}-\left(\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\tau_{r\phi})+\frac{1}{r}\frac{\partial \tau_{\theta\phi}}{\partial \theta}+\frac{1}{r\sin\theta}\frac{\partial \tau_{\phi\phi}}{\partial \phi}\right.$$

$$\left.+\frac{\tau_{r\phi}}{r}+\frac{2\cot\theta}{r}\tau_{\theta\phi}\right)+\rho g_\phi$$

In terms of velocity gradients for a Newtonian fluid with constant ρ and μ:

r-component $$\rho\left(\frac{\partial v_r}{\partial t}+v_r\frac{\partial v_r}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_r}{\partial \theta}+\frac{v_\phi}{r\sin\theta}\frac{\partial v_r}{\partial \phi}-\frac{v_\theta^2+v_\phi^2}{r}\right)$$

$$=-\frac{\partial p}{\partial r}+\mu\left(\frac{1}{r^2}\frac{\partial^2}{\partial r^2}(r^2v_r)+\frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial v_r}{\partial\theta}\right)+\frac{1}{r^2\sin^2\theta}\frac{\partial^2 v_r}{\partial\phi^2}\right)+\rho g_r$$

θ-component $$\rho\left(\frac{\partial v_\theta}{\partial t}+v_r\frac{\partial v_\theta}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_\theta}{\partial \theta}+\frac{v_\phi}{r\sin\theta}\frac{\partial v_\theta}{\partial \phi}+\frac{v_rv_\theta}{r}-\frac{v_\phi^2\cot\theta}{r}\right)$$

$$=-\frac{1}{r}\frac{\partial p}{\partial \theta}+\mu\left(\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial v_\theta}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial\theta}\left(\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}(v_\theta\sin\theta)\right)+\frac{1}{r^2\sin^2\theta}\frac{\partial^2 v_\theta}{\partial\phi^2}\right.$$
$$\left.+\frac{2}{r^2}\frac{\partial v_r}{\partial\theta}-\frac{2\cos\theta}{r^2\sin^2\theta}\frac{\partial v_\phi}{\partial\phi}\right)+\rho g_\theta$$

φ-component $$\rho\left(\frac{\partial v_\phi}{\partial t}+v_r\frac{\partial v_\phi}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_\phi}{\partial \theta}+\frac{v_\phi}{r\sin\theta}\frac{\partial v_\phi}{\partial \phi}+\frac{v_\phi v_r}{r}+\frac{v_\theta v_\phi}{r}\cot\theta\right)$$

$$=-\frac{1}{r\sin\theta}\frac{\partial p}{\partial \phi}+\mu\left(\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial v_\phi}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial\theta}\left(\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}(v_\phi\sin\theta)\right)+\frac{1}{r^2\sin^2\theta}\frac{\partial^2 v_\phi}{\partial\phi^2}\right.$$
$$\left.+\frac{2}{r^2\sin\theta}\frac{\partial v_r}{\partial\phi}+\frac{2\cos\theta}{r^2\sin^2\theta}\frac{\partial v_\theta}{\partial\phi}\right)+\rho g_\phi$$

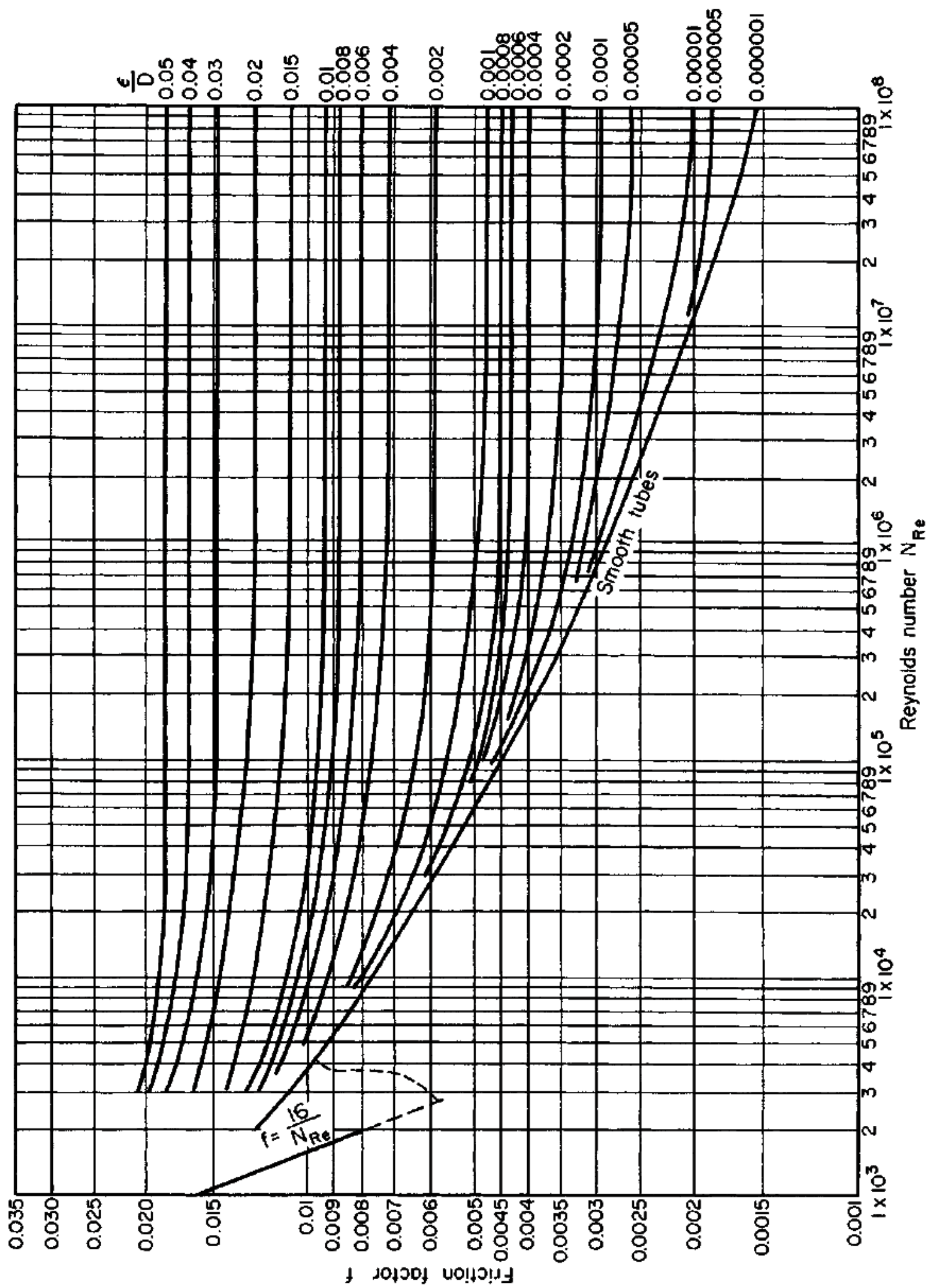
TUBERÍA DE ACERO COMERCIAL

	Calibre 40					Calibre 80			
Tamaño nominal	Diámetro exterior		Diámetro interior		Tamaño nominal	Diámetro exterior		Diámetro interior	
(plg)	(plg)	(mm)	(plg)	(mm)	(plg)	(plg)	(mm)	(plg)	(mm)
1/8	0.405	10.3	0.269	6.8	1/8	0.405	10.3	0.215	5.5
1/4	0.545	13.7	0.364	9.2	1/4	0.545	13.7	0.302	7.7
3/8	0.675	17.1	0.493	12.5	3/8	0.675	17.1	0.423	10.7
1/2	0.840	21.3	0.622	15.8	1/2	0.840	21.3	0.546	13.9
3/4	1.050	26.7	0.824	20.9	3/4	1.050	26.7	0.742	18.8
1	1.315	33.4	1.049	26.6	1	1.315	33.4	0.957	24.3
1 1/4	1.660	42.2	1.380	35.1	1 1/4	1.660	42.2	1.278	32.5
1 ½	1.900	48.3	1.610	40.9	1 ½	1.900	48.3	1.500	38.1
2	2.375	60.3	2.067	52.5	2	2.375	60.3	1.939	49.3
2 ½	2.875	73.0	2.469	62.7	2 ½	2.875	73.0	2.323	59.0
3	3.500	88.9	3.068	77.9	3	3.500	88.9	2.900	73.7
3 ½	4.000	101.6	3.548	90.1	3 ½	4.000	101.6	3.364	85.4
4	4.500	114.3	4.026	102.3	4	4.500	114.3	3.826	97.2
5	5.563	141.3	5.047	128.2	5	5.563	141.3	4.813	122.3
6	6.625	168.3	6.025	154.1	6	6.625	168.3	5.761	146.3
8	8.625	219.1	7.981	202.7	8	8.625	219.1	7.625	193.7
10	10.750	273.1	10.020	254.5	10	10.750	273.1	9.564	242.9
12	12.750	323.9	11.938	303.2	12	12.750	323.9	11.376	289.0
14	14.000	355.6	13.126	333.1	14	14.000	355.6	12.500	317.5
16	16.000	406.4	15.000	381.0	16	16.000	406.4	14.314	363.6
18	18.000	457.2	16.876	428.7	18	18.000	457.2	16.126	409.6

PERDIDAS POR FRICCION

Material	Rugosidad (m)	Rugosidad (pie)
Vidrio, plástico	liso	Liso
Tubería de cobre, latón, plomo	$1.5 \cdot 10^{-6}$	$5 \cdot 10^{-6}$
Hierro fundido sin revestir	$2.4 \cdot 10^{-4}$	$8 \cdot 10^{-4}$
Hierro fundido revestido de asfalto	$1.2 \cdot 10^{-4}$	$4 \cdot 10^{-4}$
Acero comercial o acero soldado	$4.6 \cdot 10^{-5}$	$1.5 \cdot 10^{-4}$
Hierro forjado	$4.6 \cdot 10^{-5}$	$1.5 \cdot 10^{-4}$
Acero remachado	$1.8 \cdot 10^{-3}$	$6 \cdot 10^{-3}$
concreto	$1.2 \cdot 10^{-3}$	$4 \cdot 10^{-3}$

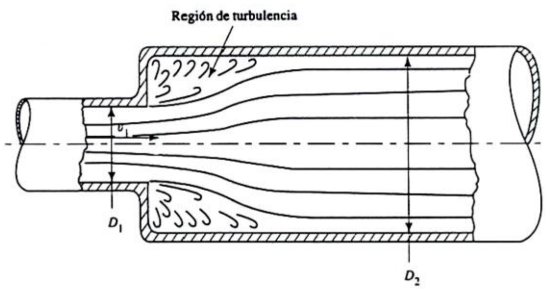
DIAGRAMA DE MOODY

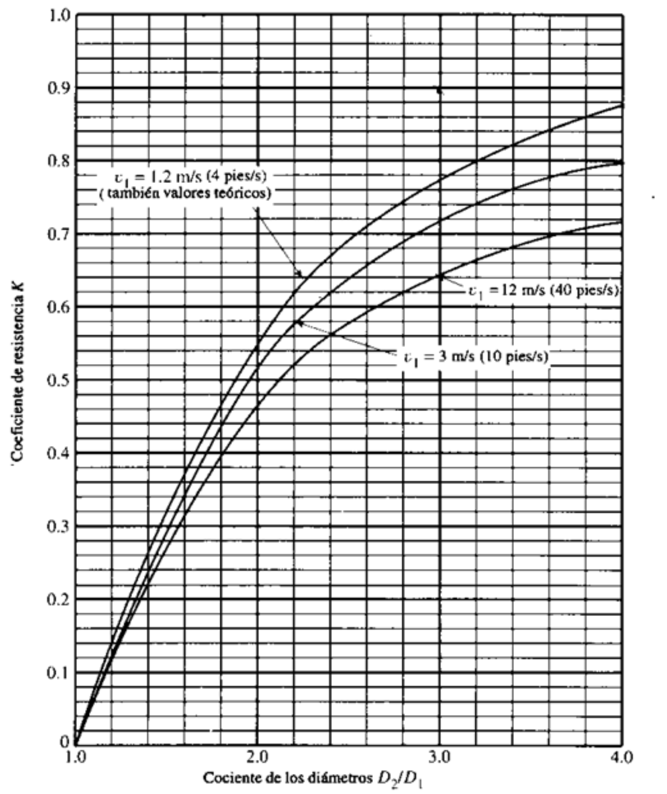


Fanning Friction Factors. Reynolds number Re = $DV\rho/\mu$, where D = pipe diameter, V = velocity, ρ = fluid density, and μ = fluid viscosity. (*Based on Moody*, Trans. ASME, *66*, *671* [*1944*].)

PERDIDA EN ACCESORIOS

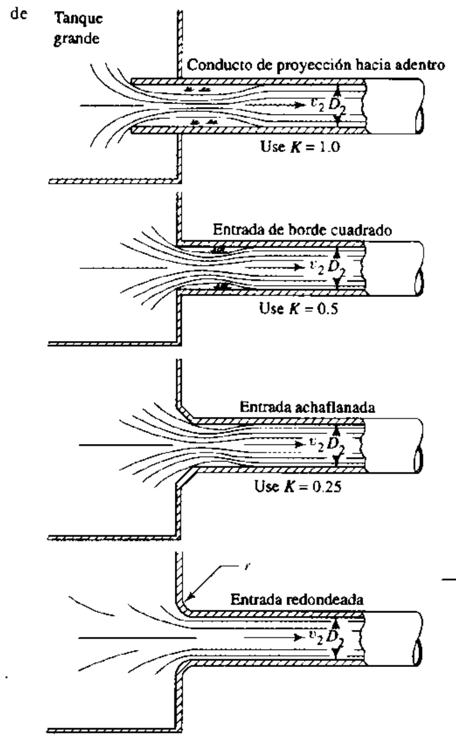
1. Dilatación súbita





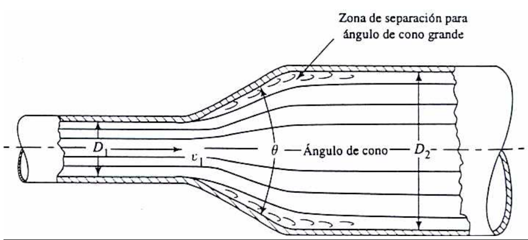
	Velocidad, v_1 (m/s)						
D_2/D_1	0.6	1.2	3	4.5	6	9	12
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.2	0.11	0.10	0.09	0.09	0.09	0.09	0.08
1.4	0.26	0.25	0.23	0.22	0.22	0.21	0.20
1.6	0.40	0.38	0.35	0.34	0.33	0.32	0.32
1.8	0.51	0.48	0.45	0.43	0.42	0.41	0.40
2.0	0.60	0.56	0.52	0.51	0.50	0.48	0.47
2.5	0.74	0.70	0.65	0.63	0.62	0.60	0.58
3.0	0.83	0.78	0.73	0.70	0.69	0.67	0.65
4.0	0.92	0.87	0.80	0.78	0.76	0.74	0.72
5.0	0.96	0.91	0.84	0.82	0.80	0.77	0.75
10.0	1.00	0.96	0.89	0.86	0.84	0.82	0.80
∞	1.00	0.98	0.91	0.88	0.86	0.83	0.81

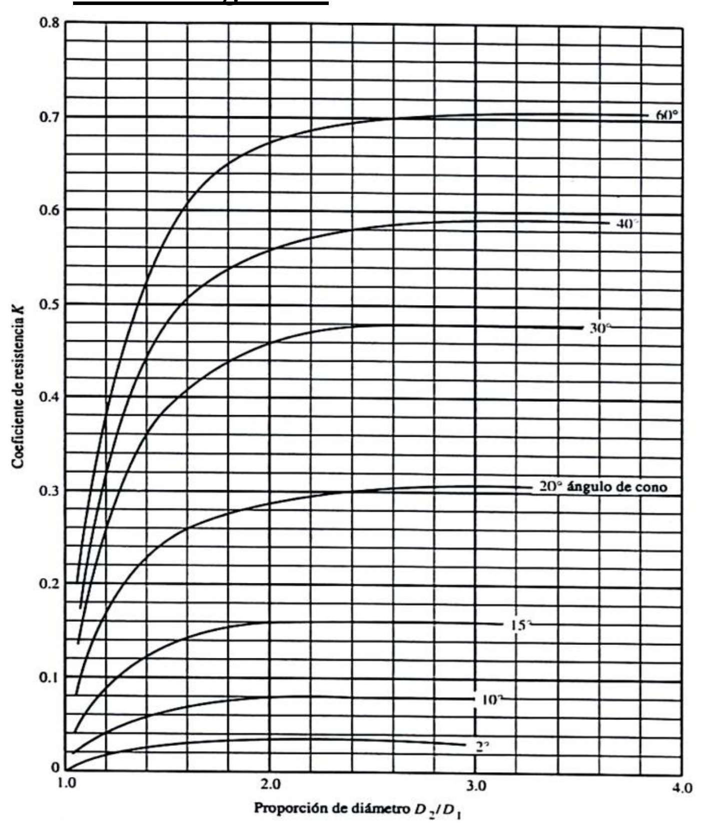
2. Pérdidas en la entrada a la tubería



r/D_2	K
0	0.50
0.02	0.28
0.04	0.24
0.06	0.15
0.10	0.09
>0.15	0.04 (Bier

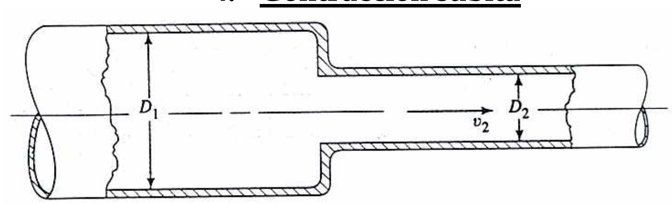
3. Dilatación gradual

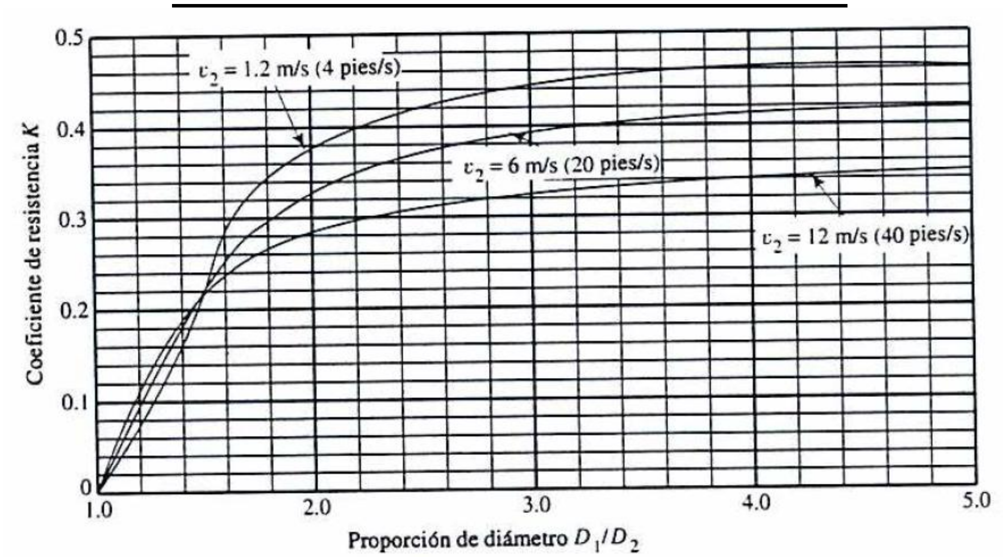




	Ángulo del cono (θ)							
D_2/D_1	2	6	10	20	30	40	50	60
1.1	0.01	0.01	0.03	0.10	0.16	0.19	0.21	0.23
1.2	0.02	0.02	0.04	0.16	0.25	0.31	0.35	0.37
1.4	0.02	0.03	0.06	0.23	0.36	0.44	0.50	0.53
1.6	0.03	0.04	0.07	0.26	0.42	0.51	0.57	0.61
1.8	0.03	0.04	0.07	0.28	0.44	0.54	0.61	0.65
2.0	0.03	0.04	0.07	0.29	0.46	0.56	0.63	0.68
2.5	0.03	0.04	0.08	0.30	0.48	0.58	0.65	0.70
3.0	0.03	0.04	0.08	0.31	0.48	0.59	0.66	0.71
∞	0.03	0.05	0.08	0.31	0.49	0.60	0.67	0.72

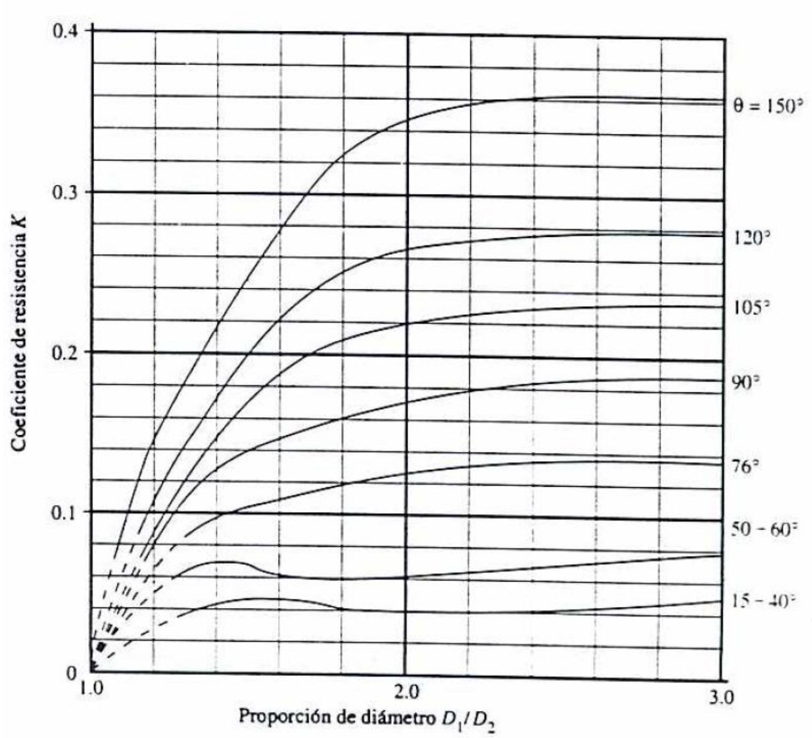
4. Contracción súbita

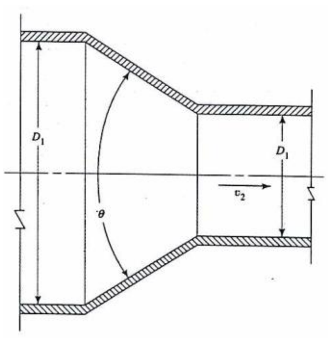


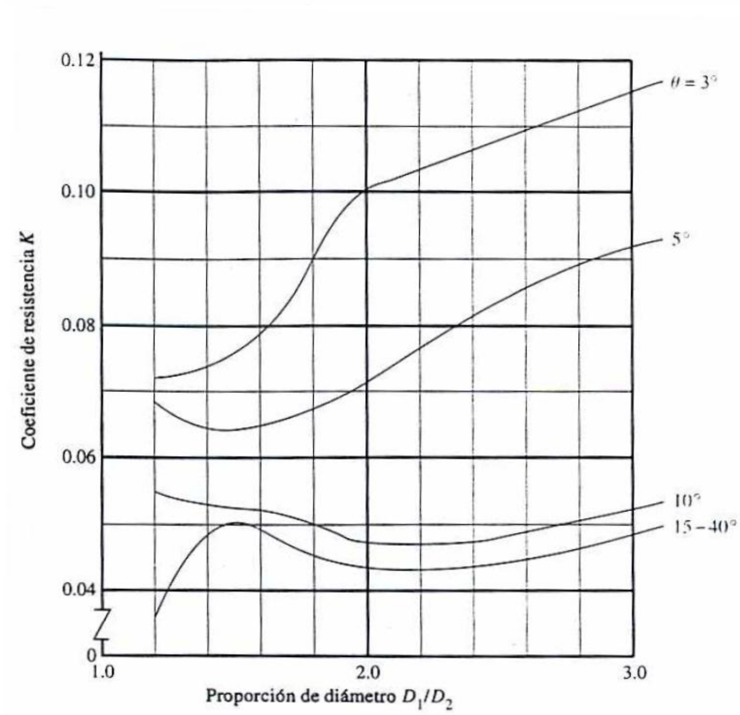


		Velocidad, v_1 (m/s)						
D_1/D_2	0.6	1.2	2.4	3	4.5	6	9	12
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.2	0.07	0.07	0.07	0.08	0.08	0.09	0.10	0.11
1.4	0.17	0.17	0.17	0.18	0.18	0.18	0.19	0.20
1.6	0.26	0.26	0.26	0.26	0.25	0.25	0.25	0.24
1.8	0.34	0.34	0.33	0.33	0.32	0.31	0.29	0.27
2.0	0.38	0.37	0.36	0.36	0.34	0.33	0.31	0.29
2.2	0.40	0.40	0.39	0.38	0.37	0.35	0.33	0.30
2.5	0.42	0.42	0.40	0.40	0.38	0.37	0.34	0.31
3.0	0.44	0.44	0.42	0.42	0.40	0.39	0.36	0.33
4.0	0.47	0.46	0.45	0.44	0.42	0.41	0.37	0.34
5.0	0.48	0.47	0.46	0.45	0.44	0.42	0.38	0.35
10.0	0.49	0.48	0.47	0.46	0.45	0.43	0.40	0.36
∞	0.49	0.48	0.47	0.47	0.45	0.44	0.41	0.38

5. Contracción gradual





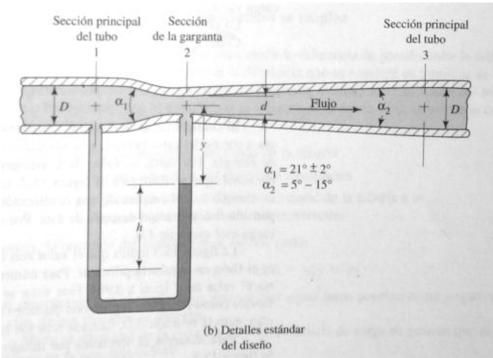


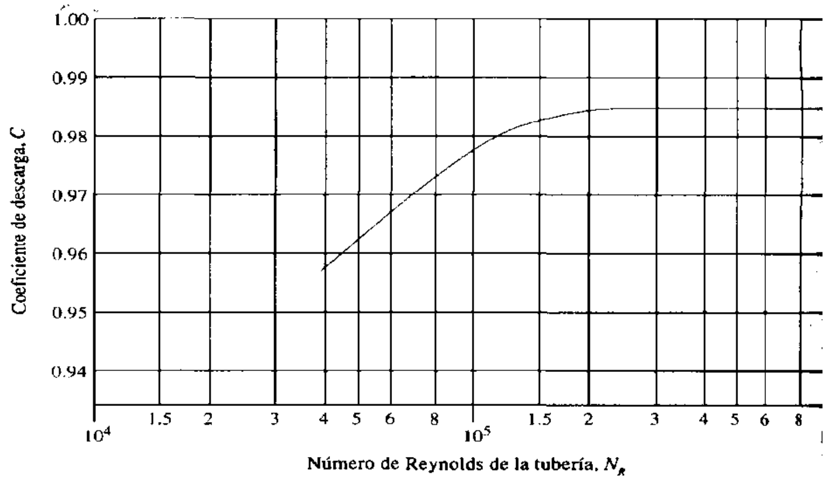
LONGITUDES EQUIVALENTES PARA ACCESORIOS

Tipo	L_e/D
Válvula de globo – 100 % abierta	340
Válvula de ángulo – 100 % abierta	150
Válvula de compuerta – 100 % abierta	8
¾ abierta	35
½ abierta	160
¼ abierta	900
Válvula de verificación (check) – tipo giratorio	100
Válvula de verificación – tipo bola	150
Válvula de mariposa – 100 % abierta	45
Codo estándar de 90º	30
Codo de radio largo de 90º	20
Codo de calle a 90º	50
Codo estándar de 45º	16
Codo de calle de 45º	26
Codo de devolución cerrada	50
Te estándar – con flujo a través de un tramo	20
Te estándar – con flujo a través de una rama	60

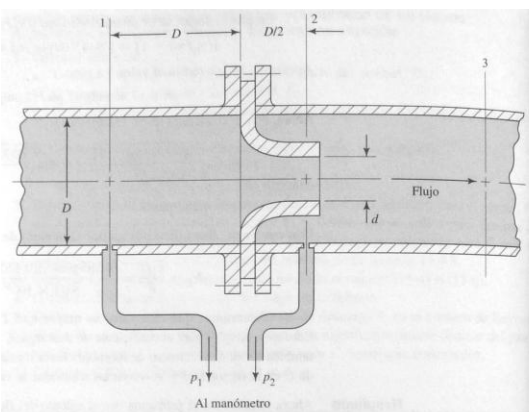
MEDIDORES DE FLUJO

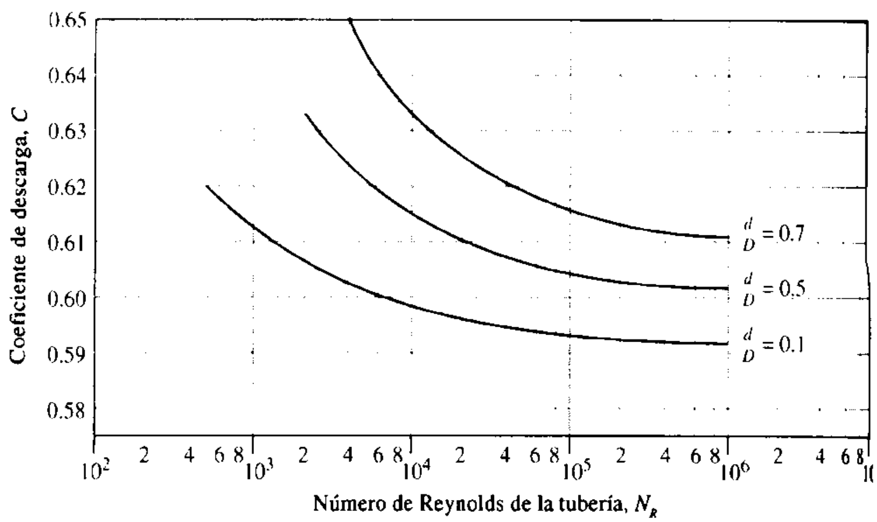
TUBO VENTURI



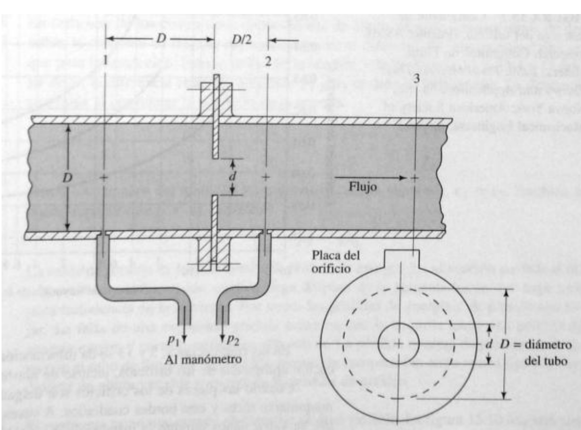


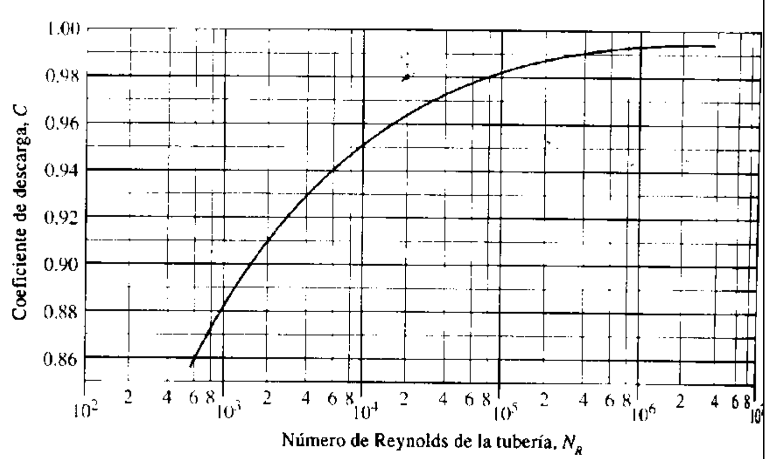
BOQUILLA DE FLUJO





PLACA ORIFICIO





Gas	Constante del gas, R $\frac{pie \cdot lb}{lb \cdot °R}$	Constante del gas, R $\frac{N \cdot m}{N \cdot K}$	k	Cociente de presión crítico
Aire	53.3	29.2	1.40	0.528
Amoniaco	91.0	49.9	1.32	0.542
Dióxido de carbono	35.1	19.3	1.30	0.546
Gas natural (típico; depende del gas)	79.1	43.4	1.27	0.551
Nitrógeno	55.2	30.3	1.41	0.527
Oxígeno	48.3	26.5	1.40	0.528
Propano	35.0	19.2	1.15	0.574
Refrigerante 12	12.6	6.91	1.13	0.578

PROPIEDADES PARA EL AIRE

Temperatura (ºC)	Densidad (Kg/m³)	Viscosidad dinámica (Pa.s)
-40	1.514	$1.51 \cdot 10^{-5}$
-30	1.452	$1.56 \cdot 10^{-5}$
-20	1.394	$1.62 \cdot 10^{-5}$
-10	1.341	$1.67 \cdot 10^{-5}$
0	1.292	$1.72 \cdot 10^{-5}$
10	1.247	$1.77 \cdot 10^{-5}$
20	1.204	$1.81 \cdot 10^{-5}$
30	1.164	$1.86 \cdot 10^{-5}$
40	1.127	$1.91 \cdot 10^{-5}$
50	1.092	$1.95 \cdot 10^{-5}$
60	1.060	$1.99 \cdot 10^{-5}$
70	1.029	$2.04 \cdot 10^{-5}$
80	0.9995	$2.09 \cdot 10^{-5}$
90	0.9720	$2.13 \cdot 10^{-5}$
100	0.9459	$2.17 \cdot 10^{-5}$

T= 15 ºC, P=1atm, ρ=1.225 Kg/m^3, μ=1.789 $\cdot 10^{-5}$ $Pa.s$

Torres Empacadas

La caída de presión y las condiciones de inundación para una columna empacada puede ser estimada a partir de la ecuación generalizada de Leva. Los factores de empaque (F) se obtienen de tablas.

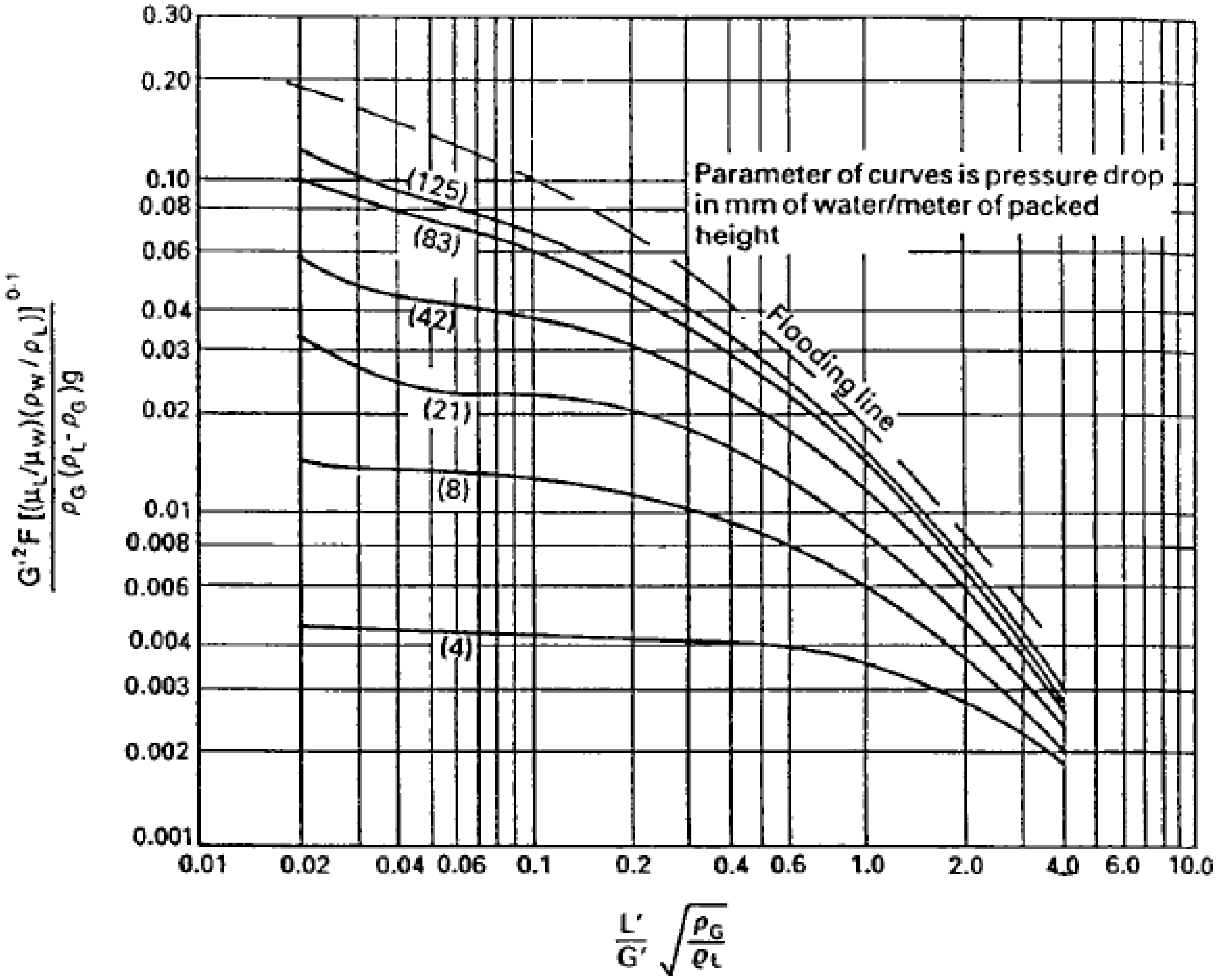


FIGURE 13-5 Generalized correlation for pressure drop in packed columns L = liquid mass flux [$lb_m/(s\,ft^2)$, $kg/(sm^2)$]; G = gas mass flux [$lb_m/(s\,ft^2)$, $kg/(sm^2)$]; ρ L = liquid density (lb_m/ft^3, kg/m^3), ρ_G = gas density (lb_m/ft^3, kg/m^3); F = packing factor (Table 13-1); μ_L = liquid viscosity (mNs/m^2), $g = (9.81\ m/s^2,\ 32.2\ ft/s^2)$, w = water at same T and P as column. (From Coulson et al., 1991.)

TABLE 13-1 Design Data for Various Column Packings

	Size		Wall thickness		Number		Bed density		Contact surface S_B		Free space %	Packing factor	
	in.	mm	in.	mm	ft^{-3}	m^{-3}	lb/ft^3	kg/m^3	ft^3/ft^3	m^3/m^3	(100 ε)	ft^3/ft^3	m^3/m^3
Ceramic Räschig rings	0.25	6.35	0.03	0.76	85,600	2,022,600	60	961	242	794	62	1600	5250
	0.38	9.65	0.05	1.27	24,700	972,175	61	977	157	575	67	1000	3280
	0.50	12.7	0.07	1.78	10,700	377,825	55	881	112	368	64	640	2100
	0.75	19.05	0.09	2.29	3090	109,110	50	801	73	240	72	255	840
	1.0	25.4	0.14	3.56	1350	47,670	42	673	58	190	71	160	525
	1.25	31.75			670	23,660	46	737			71	125	410
	1.5	38.1			387	13,665	43	689			73	95	310
	2.0	50.8	0.25	6.35	164	5790	41	657	29	95	74	65	210
	3.0	76.2			50	1765	35	561			78	36	120
Metal Räschig rings	0.25	6.35	0.03125	0.794	88,000	3,107,345	133	2131			72	700	2300
	0.38	9.65	0.03125	0.794	27,000	953,390	94	1506			81	390	1280
	0.50	12.7	0.03125	0.794	11,400	402,540	75	1201	127	417	85	300	980
	0.75	19.05	0.03125	0.794	3340	117,940	52	833	84	276	89	185	605
(*Note*: Bed densities	0.75	19.05	0.0625	1.59	3140	110,875	94	1506			80	230	750
are for mild steel;	1.0	25.0	0.03125	0.794	1430	50,494	39	625	63	207	92	115	375
multiply by 1.105,	1.0	25.0	0.0625	1.59	1310	46,260	71	1137			86	137	450
1.12, 1.37, 1.115 for	1.25	31.75	0.0625	1.59	725	25,600	62	993			87	110	360
stainless steel,	1.5	38.1	0.0625	1.59	400	14,124	49	785			90	83	270
copper, aluminum,	2.0	50.8	0.0625	1.59	168	5932	37	593	31	102	92	57	190
and monel,	3.0	76.2	0.0625	1.59	51	1800	25	400	22	72	95	32	105
respectively)													
Carbon Räschig rings	0.25	6.35	0.0625	1.59	85,000	3,001,410	46	737	212	696	55	1600	5250
	0.50	12.7	0.0625	1.59	10,600	374,290	27	433	114	374	74	410	1350
	0.75	19.05	0.125	3.175	3140	110,875	34	545	75	246	67	280	920
	1.0	25.0	0.125	3.175	1325	46,787	27	433	57	187	74	160	525
	1.25	31.75			678	23,940	31	496			69	125	410
	1.5	38.1			392	13,842	34	545			67	130	425
	2.0	50.8	0.250	6.35	166	5862	27	433	29	95	74	65	210
	3.0	76.2	0.312	7.92	49	1730	23	368	19	62	78	36	120
Metal Pall rings	0.625	15.9	0.018	0.46	5950	210,098	37	593	104	341	93	70	230
(*Note*: Bed densities	1.0	25.4	0.024	0.61	1400	49,435	30	481	64	210	94	48	160
are for mild steel)	1.25	31.75	0.030	0.76	375	13,240	24	385	39	128	95	28	92
	2.0	50.8	0.036	0.915	170	6003	22	353	31	102	96	20	66

	3.5	76.2	0.048	1.219	33	1165	17	273	20	65.6	97	16	52
Plastic Pall Rings	0.625	15.9	0.03	0.762	6050	213,630	7.0	112	104	341	87	97	320
(*Note*: Bed densities	1.0	25.4	0.04	1.016	1440	50,848	5.5	88	63	207	90	52	170
are for polypropylene)	1.5	38.1	0.04	1.016	390	13,770	4.75	76	39	128	91	40	130
	2.0	50.8	0.06	1.524	180	6356	4.25	68	31	102	92	25	82
	3.5	88.9	0.06	1.524	33	1165	4.0	64	26	85	92	16	52
Ceramic Intalox	0.25	6.35			117,500	4,149,010	54	865			65	725	2400
saddles	0.38	9.65			49,800	1,758,475	50	801			67	330	1080
	0.50	12.7			18,300	646,186	46	737			71	200	660
	0.75	19.05			5640	199,150	44	705			73	145	475
	1.0	25.4			2150	75,918	42	673			73	92	300
	1.5	38.1			675	23,835	39	625	59	194	76	52	170
	2.0	50.8			250	8828	38	609			76	40	130
	3.0	76.2			52	1836	36	577			79	22	72
Plastic Super Intalox	No. 1				1620	57,200	6.0	96	63	207	90	33	108
	No. 2				190	6710	3.75	60	33	108	93	21	69
	No. 3				42	1483	3.25	52	27	88.6	94	16	52
Intalox metal		25		4770		168,425					96.7	41	135
		40		1420		50,140					97.3	25	82
		50		416		14,685					97.8	16	52
		70		131		4625					98.1	13	43
Hy-Pak	No. 1				850	30,014	19	304			96	43	140
(*Note*: Bed densities	No. 1				107	3778	14	224			97	18	59
are for mild steel)	No. 3				31	1095	13	208			97	15	49
Plastic Cascade Mini	No. 1											25	82
Rings	No. 2											15	49
	No. 3											12	39
Metal Cascade Mini	No. 0											55	180
Rings	No. 1											34	110
	No. 2											22	72
	No. 3											14	46
	No. 4											10	33
Ceramic Cascade Mini	No. 2											38	125
Rings	No. 3											24	79
	No. 5											18	59

Note: The packing factor F replaces the term S_B/ε^3. Use of the given value of F in Fig. 13-5 permits more predictable performance of designs incorporating packed beds, because the values quoted are derived from operating characteristics of the packings rather than from their physical dimensions.

Source: Coulson et al. (1991).