Graphs, Formulas and Tables relevant to Transport Phenomena

Rohde, M.

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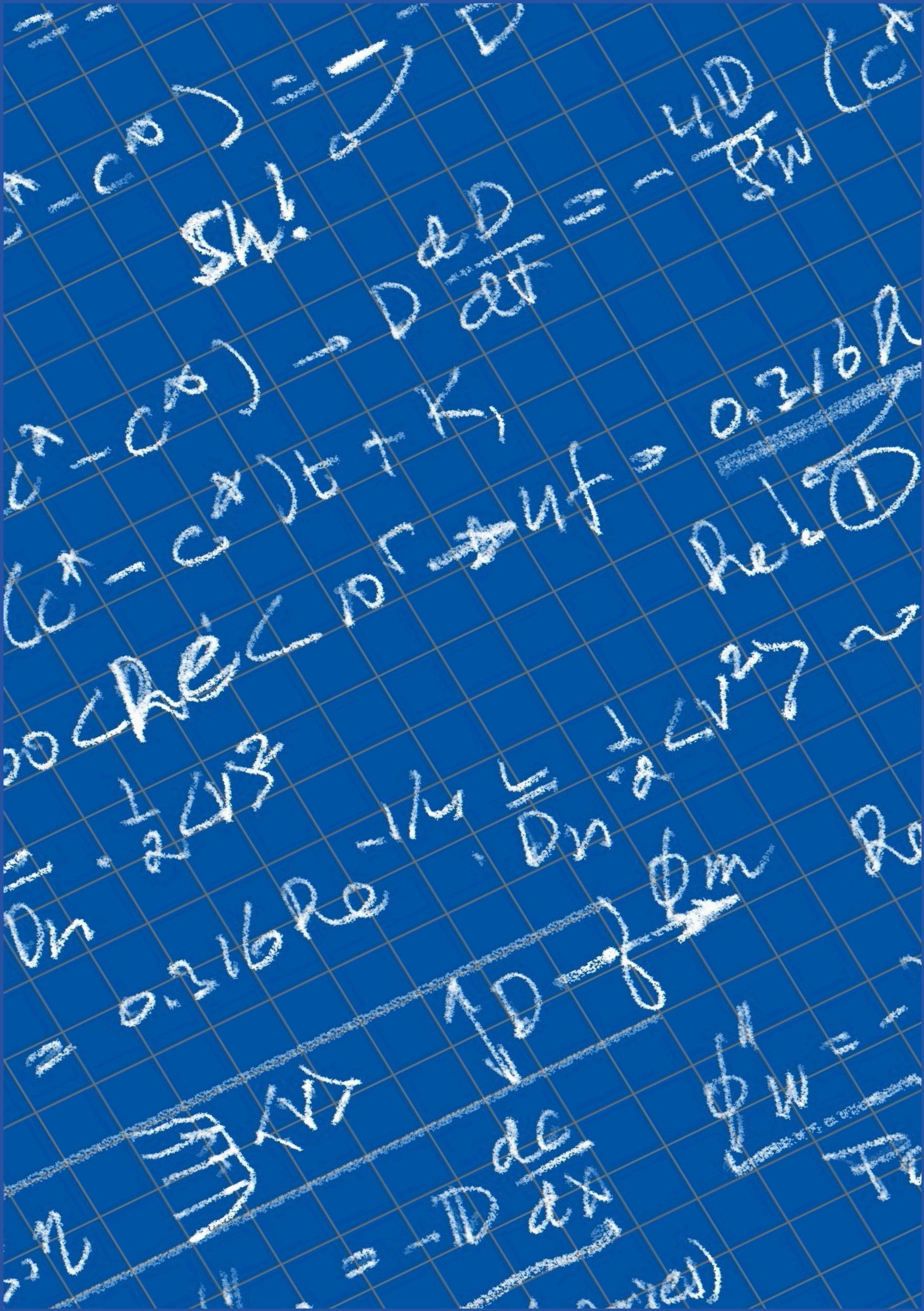

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Graphs, Formulas and Tables

relevant to

Transport Phenomena

Martin Rohde

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Colophon

Graphs, Formulas and Tables relevant to Transport Phenomena

Author

Martin Rohde
Delft University of Technology
Transport Phenomena in Nuclear Applications
Email: m.rohde@tudelft.nl
ORCID: `https://orcid.org/0000-0001-6696-1312`

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Contents

Definitions

Symbols used in this book

Greek

α	Linear thermal exp. coeff.	$m/(m.K)$
β	Cubic thermal exp. coeff.	$m^3/(m^3.K)$
γ	Cubic mass exp. coeff.	m^3/kg
η	Dynamic viscosity	$Pa.s$
ν	Kinematic viscosity	m^2/s
ρ	Mass density	kg/m^3
λ	Heat conductivity	$W/(mK)$
τ	Shear stress	N/m^2
ϕ_V	Volumetric flow rate	m^3/s
ϕ_m	Mass flow rate	kg/s
ϕ_q	Heat flow rate	J/s
ϕ_W	Work	J/s
ϕ_q''	Heat flux	W/m^2
ϕ_m''	Mass flux	$kg/(m^2s)$

Latin

a	Thermal diffusivity	m^2/s
A	Surface	m^2
c	Concentration	kg/m^3 mol/m^3
C_D	Drag coefficient	-
C_p	Specific heat capacity (at constant pressure)	$J/(kg.K)$
e	Specific energy	J/kg
E	Energy	J
e_{fr}	Energy dissipation	J/kg
f	Fanning friction factor	-
F_b	Buoyancy force	N
F_D	Drag force	N
g	Gravity constant	m/s^2
F_g	Gravitational force	N
g	Gravity constant	m/s^2
h	Heat transfer coeff.	$W/(m^2K)$
H	Height	m
H_s	Henry's coefficient	$mol/(m^3Pa)$

Latin (cont'd)

k	Mass transfer coefficient	m/s
k_r	Reaction constant	reaction-specific
K	Overall mass transfer coeff.	m/s
m	Mass	kg
m	Partition coefficient	-
M_w	Molar weight	g/mol
N	Rotational rate	s^{-1}
p	Pressure	Pa
P	Power	J/s
p_i	Partial pressure of i	Pa
Q	Heat source	J/s
R_A	Reaction rate of A	kg/s mol/s
t	Time	s
T	Temperature	$^oC,\ K$
u	Specific internal energy	J/kg
U	Overall heat transfer coeff.	$W/(m^2K)$
v	Velocity	m/s
V	Volume	m^3
x, y, z	Cartesian coordinates	m
x_i	Mole fraction of i	

Other

$\mathbb{D}$	Diffusion coefficient	m^2/s
ℓ	Length	m

Super/subscripts

$'$	Per m
$''$	Per m^2
$'''$	Per m^3

Dimensionless numbers

ℓ = characteristic length scale of the problem, e.g. a diameter $\ell = D$.

symbol	name	definition	relates to
Bm	Bingham	$\frac{\tau_0 \ell}{\eta v}$	momentum
Bi	Biot	$\frac{h_1 \ell}{\lambda_2}$	heat
Bi	Biot	$\frac{k_1 \ell}{\mathbb{D}_2}$	species
Fo	Fourier	$\frac{\mathbb{D} t}{\ell^2}$	species
Fo	Fourier	$\frac{a t}{\ell^2}$	heat
Gz	Graetz	$\frac{\mathbb{D} L}{\ell^2 v}$	species
Gz	Graetz	$\frac{a L}{\ell^2 v}$	heat
Gr	Grashof	$\frac{g \ell^3}{\nu^2} \beta \Delta T$	heat
Gr	Grashof	$\frac{g \ell^3}{\nu^2} \gamma \Delta c$	species
Le	Lewis	$\frac{a}{\mathbb{D}}$	heat, species
Nu	Nusselt	$\frac{h \ell}{\lambda}$	heat
Pe	Peclet	$\frac{v \ell}{a}$	heat
Pe	Peclet	$\frac{v \ell}{\mathbb{D}}$	species
Po	Power number	$\frac{P}{\rho N^3 D^5}$	Stirrers and pumps
Pr	Prandtl	$\frac{\nu}{a}$	heat
Ra	Rayleigh	$Gr \times Pr$	heat
Ra	Rayleigh	$Gr \times Sc$	species
Re	Reynolds	$\frac{\rho v \ell}{\eta}$	momentum
Sc	Schmidt	$\frac{\nu}{\mathbb{D}}$	species
Sh	Sherwood	$\frac{k \ell}{\mathbb{D}}$	species

Microscopic balances

All equations are given in Cartesian coordinates $(x_1, x_2, x_3) \equiv (x, y, z)$ where the index i indicates the direction. E.g. v_y corresponds to v_2, being the velocity component in the y direction.

Mass

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_1}(\rho v_1) + \frac{\partial}{\partial x_2}(\rho v_2) + \frac{\partial}{\partial x_3}(\rho v_3) = 0$$

Momentum

For each velocity component v_i:

General form

$$\rho\left(\frac{\partial v_i}{\partial t} + v_1\frac{\partial v_i}{\partial x_1} + v_2\frac{\partial v_i}{\partial x_2} + v_3\frac{\partial v_i}{\partial x_3}\right) = -\left(\frac{\partial}{\partial x_1}\tau_{1i} + \frac{\partial}{\partial x_2}\tau_{2i} + \frac{\partial}{\partial x_3}\tau_{3i}\right) - \frac{\partial p}{\partial x_i} + \rho g_i$$

Newtonian fluids, constant η

$$\boxed{\tau_{ji} = -\eta\left(\frac{\partial v_j}{\partial x_i} + \frac{\partial v_i}{\partial x_j}\right)} \rightarrow \rho\left(\frac{\partial v_i}{\partial t} + v_1\frac{\partial v_i}{\partial x_1} + v_2\frac{\partial v_i}{\partial x_2} + v_3\frac{\partial v_i}{\partial x_3}\right) = \eta\left(\frac{\partial^2 v_i}{\partial x_1^2} + \frac{\partial^2 v_i}{\partial x_2^2} + \frac{\partial^2 v_i}{\partial x_3^2}\right) - \frac{\partial p}{\partial x_i} + \rho g_i$$

Internal energy (no dissipation, no shock waves)

general form

$$\rho C_p\left(\frac{\partial T}{\partial t} + v_1\frac{\partial T}{\partial x_1} + v_2\frac{\partial T}{\partial x_2} + v_3\frac{\partial T}{\partial x_3}\right) = -\left(\frac{\partial \phi''_{q,1}}{\partial x_1} + \frac{\partial \phi''_{q,2}}{\partial x_2} + \frac{\partial \phi''_{q,3}}{\partial x_3}\right) + Q'''$$

Fourier's law, constant λ

$$\boxed{\phi''_{q,i} = -\lambda\frac{\partial T}{\partial x_i}} \rightarrow \rho C_p\left(\frac{\partial T}{\partial t} + v_1\frac{\partial T}{\partial x_1} + v_2\frac{\partial T}{\partial x_2} + v_3\frac{\partial T}{\partial x_3}\right) = \lambda\left(\frac{\partial^2 T}{\partial x_1^2} + \frac{\partial^2 T}{\partial x_2^2} + \frac{\partial^2 T}{\partial x_3^2}\right) + Q'''$$

Species

general form for species A

$$\left(\frac{\partial c_A}{\partial t} + v_1\frac{\partial c_A}{\partial x_1} + v_2\frac{\partial c_A}{\partial x_2} + v_3\frac{\partial c_A}{\partial x_3}\right) = -\left(\frac{\partial \phi''_{A,1}}{\partial x_1} + \frac{\partial \phi''_{A,2}}{\partial x_2} + \frac{\partial \phi''_{A,3}}{\partial x_3}\right) + R'''_A$$

Fick's law, constant $\mathbb{D}$

$$\boxed{\phi''_{A,i} = -\mathbb{D}_A\frac{\partial c_A}{\partial x_i}} \rightarrow \left(\frac{\partial c_A}{\partial t} + v_1\frac{\partial c_A}{\partial x_1} + v_2\frac{\partial c_A}{\partial x_2} + v_3\frac{\partial c_A}{\partial x_3}\right) = \mathbb{D}_A\left(\frac{\partial^2 c_A}{\partial x_1^2} + \frac{\partial^2 c_A}{\partial x_2^2} + \frac{\partial^2 c_A}{\partial x_3^2}\right) + R'''_A$$

Macroscopic balances

subscript '1': inlet, subscript '2':outlet, ϕ_m (kg/s): mass flow rate, ϕ_V (m^3/s): flow rate, ϕ_W (W): mechanical energy added (work, e.g. pump) in , ϕ_q (W): internal energy added, V (m^3): control volume, c_A $(kg/m^3, mol/m^3)$: concentration of species A, $\langle v\rangle$ (m/s): cross-sectional averaged velocity in a duct or in/upstream/downstream of a local restriction, e_{fr} (J/kg): energy dissipation, which can be calculated by

$$e_{fr} = \underbrace{\sum_i \left(4f\frac{1}{2}\langle v\rangle^2 \frac{L}{D_h}\right)_i}_{\text{ducts}} + \underbrace{\sum_j \left(K_w \frac{1}{2}\langle v\rangle^2\right)_j}_{\text{restrictions}}$$

with K_W: local friction loss factor, f: Fanning friction coefficient, $D_h \equiv 4A/S$: hydraulic diameter

Mass

transient

$$\frac{d}{dt}(\rho V) = \phi_{m,1} - \phi_{m,2}$$

stationary

$$\phi_{m,1} = \phi_{m,2}$$

Total energy

$$e \equiv u + \frac{1}{2}\langle v\rangle^2 + gz$$

transient

$$\frac{d}{dt}(\rho e V) = \phi_{m,1}\left(e + \frac{p}{\rho}\right)_1 - \phi_{m,2}\left(e + \frac{p}{\rho}\right)_2 + \phi_q + \phi_W$$

stationary

$$0 = \phi_m\left(e_1 - e_2 + \left(\frac{p}{\rho}\right)_1 - \left(\frac{p}{\rho}\right)_2\right) + \phi_q + \phi_W$$

Mechanical energy

$$e_m \equiv \frac{1}{2}\langle v\rangle^2 + gz$$

transient

$$\frac{d}{dt}(\rho e_m V) = \phi_m\left(e_{m,1} - e_{m,2} + \left(\frac{p}{\rho}\right)_1 - \left(\frac{p}{\rho}\right)_2\right) + \int_{V(t)} p\left(\frac{\partial v_i}{\partial x_i}\right) dV + \phi_W - \phi_m e_{fr} \qquad \boxed{\phi_{m,1} = \phi_{m,2}}$$

$$\rho V\frac{de_m}{dt} = \phi_m\left(e_{m,1} - e_{m,2} + \frac{p_1}{\rho} - \frac{p_2}{\rho}\right) + \phi_W - \phi_m e_{fr} \qquad \boxed{\phi_{m,1} = \phi_{m,2},\ \rho = \text{constant}}$$

stationary

$$0 = \phi_m\left(e_{m,1} - e_{m,2} - \int_1^2 \left(\frac{1}{\rho}\right) dp\right) + \phi_W - \phi_m e_{fr}$$

Bernoulli equation

$$\frac{p}{\rho} + gz + \frac{1}{2}\langle v\rangle^2 = \text{constant along a streamline.}$$

Internal energy (heat)

transient

$$\frac{d}{dt}(\rho u V) = \phi_m (u_1 - u_2) - \int_{V(t)} p\left(\frac{\partial v_i}{\partial x_i}\right) dV + \phi_q + \phi_m e_{fr} \qquad \boxed{\phi_{m,1} = \phi_{m,2}}$$

$$\rho V\frac{du}{dt} = \phi_m (u_1 - u_2) + \phi_q + \phi_m e_{fr} \qquad \boxed{\phi_{m,1} = \phi_{m,2},\ \rho = \text{constant}}$$

stationary

$$0 = \phi_m \left(u_1 - u_2 - \int_1^2 p\,d\left(\frac{1}{\rho}\right)\right) + \phi_q + \phi_m e_{fr}$$

Momentum

transient

$$\frac{d}{dt}(\rho v_i V) = \phi_{m,1} v_{i,1} - \phi_{m,2} v_{i,2} + \sum F_i$$

stationary

$$0 = \phi_m \left(v_{i,1} - v_{i,2}\right) + \sum F_i$$

Species

transient

$$\frac{d}{dt}(c_A V) = \phi_{V,1} c_{A,1} - \phi_{V,2} c_{A,2} + P_A$$

stationary

$$0 = \phi_V \left(c_{A,1} - c_{A,2}\right) + P_A$$

Important correlations

Flow

Laminar flow in tubes	$4f = \frac{64}{Re}$	
Turbulent flow in smooth tubes (Blasius)	$4f = 0.316 Re^{-0.25}$	$4 \times 10^3 < Re < 10^5$
Turbulent flow in smooth channels (McAdams)	$4f = 0.184 Re^{-0.20}$	$10^4 < Re < 10^6$

Heat transfer

forced convection

Laminar flow in circular tubes:		
developing along x	$Nu(x) = 1.08 Gz(x)^{-1/3}$	$Gz(x) < 0.05$
developing, averaged over $0 \le x \le L$	$\langle Nu \rangle_L = 1.62 Gz(L)^{-1/3}$	$Gz(L) < 0.05$
developed	$Nu = \langle Nu \rangle = 3.66$	$Gz(x) > 0.1$
Turbulent flow in tubes	$Nu = 0.027 Re^{0.8} Pr^{1/3}$	$Re > 10^4,\ Pr \ge 0.7$
Flat plate parallel to the flow, developing along x	$Nu(x) = 0.332 Re(x)^{0.5} Pr^{1/3}$	$Re(x) \equiv \frac{\rho v_{x=0} x}{\eta} < 3 \times 10^5$
Long cylinders perpendicular to flow	$\langle Nu \rangle = 0.57 Re^{0.5} Pr^{1/3}$	$10 < Re < 10^4,\ Pr > 0.7,\ Pe \gg 1$
Flow around spheres	$\langle Nu \rangle = 2 + 0.66 Re^{0.5} Pr^{1/3}$	$10 < Re < 10^4,\ Pr > 0.7,\ Pe \gg 1$

free convection

Single vertical plate	$\langle Nu \rangle = 0.52 Ra^{1/4}$	$10^4 < Ra < 10^8$
	$\langle Nu \rangle = 0.12 Ra^{1/3}$	$Ra > 10^8$
Between two large horizontal plates	$\langle Nu \rangle = 1$	$Ra < 10^3$
	$\langle Nu \rangle = 0.15 Ra^{1/4}$	$10^4 < Ra < 10^7$
	$\langle Nu \rangle = 0.17 Ra^{1/3}$	$Ra > 10^7$
Above single hot plate	$\langle Nu \rangle = 0.17 Ra^{1/3}$	$Ra > 10^8$

Species transfer

forced convection

Laminar flow in tubes:		
developing along x	$Sh(x) = 1.08 Gz(x)^{-1/3}$	$Gz(x) < 0.05$
developing, averaged over $0 \leq x \leq L$	$\langle Sh \rangle_L = 1.62 Gz(L)^{-1/3}$	$Gz(L) < 0.05$
developed	$Sh = \langle Sh \rangle = 3.66$	$Gz(x) > 0.1$
Turbulent flow in tubes	$Sh = 0.027 Re^{0.8} Sc^{1/3}$	$Re > 10^4,\ Sc \geq 0.7$
Flat plate parallel to the flow, developing along x	$Sh(x) = 0.332 Re(x)^{0.5} Sc^{1/3}$	$Re(x) \equiv \frac{\rho v_{x=0} x}{\eta} < 3 \times 10^5$
Long cylinders perpendicular to flow	$\langle Sh \rangle = 0.42 Sc^{1/5} + 0.57 Re^{0.5} Sc^{1/3}$	$1 < Re < 10^4,\ Sc > 0.7,\ Pe \gg 1$
Flow around spheres	$\langle Sh \rangle = 2 + 0.66 Re^{0.5} Sc^{1/3}$	$10 < Re < 10^4,\ Sc > 0.7,\ Pe \gg 1$

free convection

Single vertical plate	$\langle Sh \rangle = 0.55 Ra^{1/4}$	$10^4 < Ra < 10^8$
	$\langle Sh \rangle = 0.13 Ra^{1/3}$	$Ra > 10^8$
Between two large horizontal plates	$\langle Sh \rangle = 1$	$Ra < 10^3$
	$\langle Sh \rangle = 0.54 Ra^{1/4}$	$10^4 < Ra < 10^7$
	$\langle Sh \rangle = 0.17 Ra^{1/3}$	$Ra > 10^7$
Above singe plate of high concentration	$\langle Sh \rangle = 0.54 Ra^{1/4}$	$10^4 < Ra < 10^7$
	$\langle Sh \rangle = 0.15 Ra^{1/3}$	$10^7 < Ra < 10^{11}$

Combined species and heat transfer

Relation of Chilton and Colburn (for turbulent flow)

$$k = \frac{h}{\rho C_p}\left(\frac{\mathbb{D}}{a}\right)^{2/3} = \frac{h}{\rho C_p} Le^{-2/3}$$

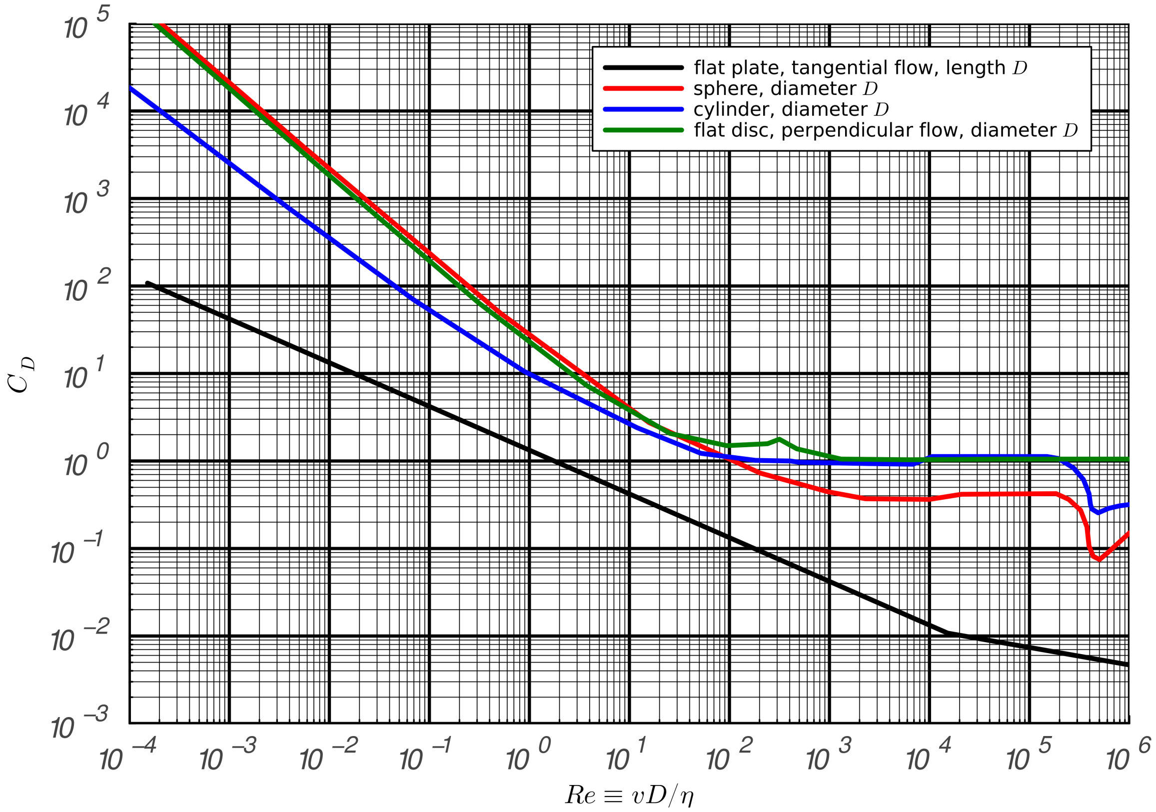
Analogy

Heat		Species
$\rho C_p T$	Concentration	$c_{kg,mol}$
ΔT	Driving difference	$\Delta c_{kg,mol}$
$\phi_q = \phi_V \cdot \rho \cdot C_p \cdot T$	Convection	$\phi_{kg,mol} = \phi_V \cdot c_{kg,mol}$
$\phi_q'' = -\lambda \frac{dT}{dx}$	Molecular transport	$\phi_{kg,mol}'' = -\mathbb{D}\frac{dc_{kg,mol}}{dx}$
$\phi_q = h \cdot A \cdot \Delta T$	based on transfer coefficient	$\phi_{kg,mol} = k \cdot A \cdot \Delta c_{kg,mol}$
$Fo = \frac{at}{\ell^2}$	Fourier number	$Fo = \frac{\mathbb{D}t}{\ell^2}$
Nu	Dimensionless transfer coefficient	Sh

Drag and friction

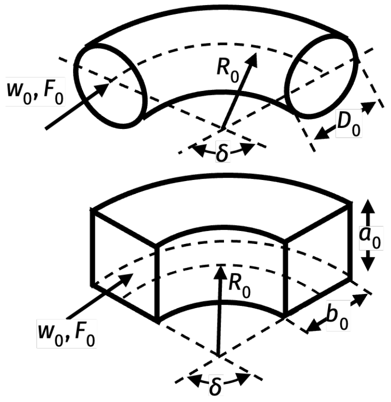
Drag coefficients around objects

Object	*Re*		C_D
Flat plate, perpendicular flow, width *W*, height *D*	$Re > 10^3$	W/D	
		1	1.18
		5	1.2
		10	1.2
		20	1.5
		30	1.6
		∞	1.95
Flat plate, tangential flow, length *L*	Laminar		$1.33Re^{-0.5}$
	$Re < 10^7$		$0.074Re^{-0.2}$
Sphere, diameter *D*	$Re < 1$		$24/Re$
Cylinder, perpendicular flow, width *W*, diameter *D*	$10^3 < Re < 3 \times 10^5$	W/D	
		1	0.63
		5	0.8
		10	0.83
		20	0.93
		30	1.0
		∞	1.2



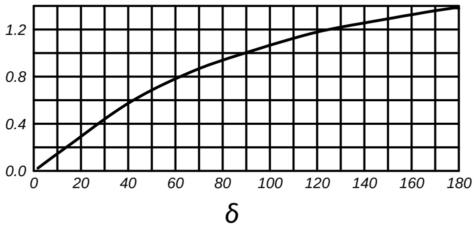
Friction coefficients by local restrictions

sharp and smooth bends ($Re > 3 \times 10^5$)



$$\boxed{K_W = A_1 B_1 C_1}$$

D_0, F_0 = tube diameter/area
a_0, b_0 = height/width rectangular duct
δ = bend angle
D_h = hydraulic diameter
w_0 = average velocity
R_0 = bend radius
$Re = w_0 D_h / v$

<table>
<tr><th></th><th>$0.5 \frac{R_0}{D_h} < 1.5$</th><th>$\frac{R_0}{D_h} \geq 1.5$</th></tr>
<tr><td>A_1</td><td>


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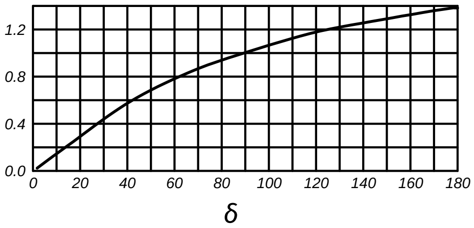

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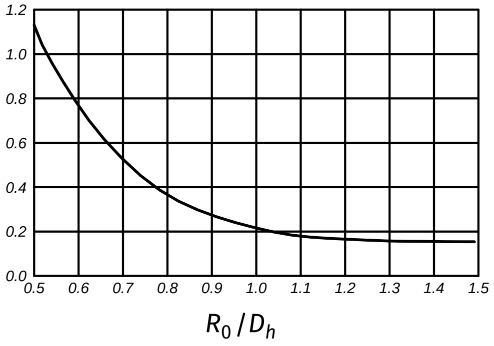
<tr><td>B_1
R_0 / D_h</td><td>


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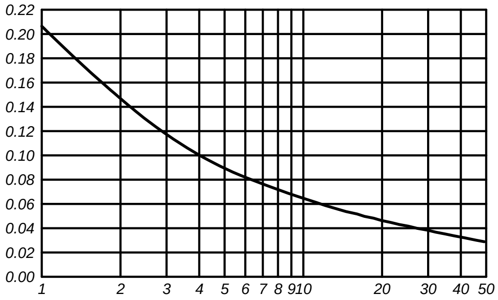

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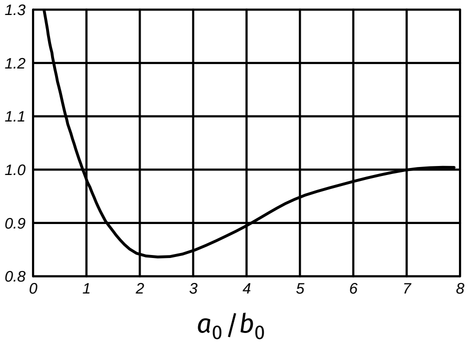

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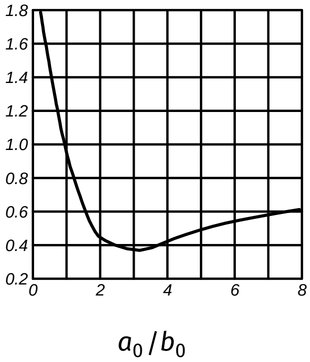

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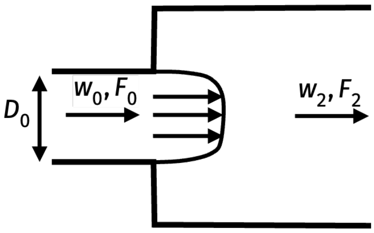
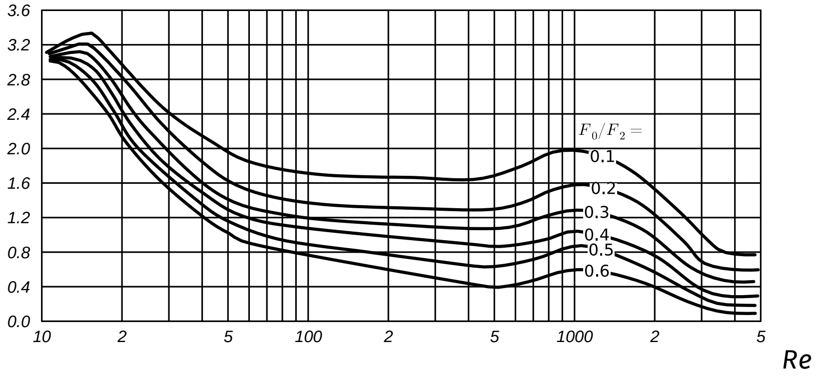
<tr><td>C_1(○)</td><td>1</td><td>1</td></tr>
</table>

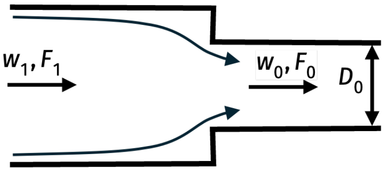
sudden expansion and contraction



$$\Delta p = K_W \cdot \frac{1}{2}\rho w_0^2$$

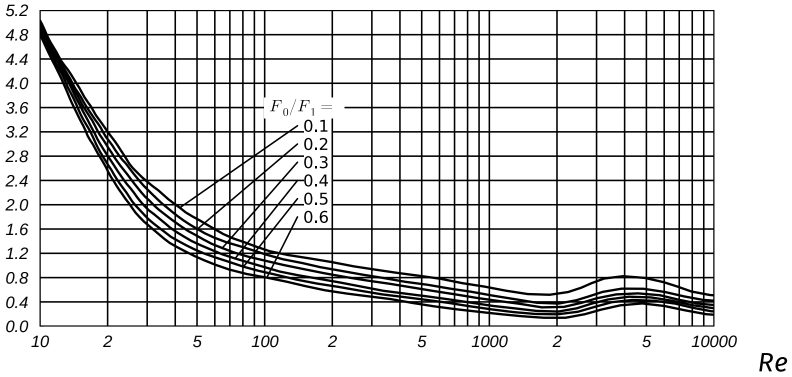
D_0, F_0, S_0 = inlet diameter/area/perimeter
w_0 = inlet average velocity
w_2 = outlet average velocity
F_2 = outlet area
$Re = w_0 D_h / \nu,\ D_h = 4F_0/S_0$

Re	K_W
$1 < Re < 8$	$\frac{26}{Re}$
$10 < Re < 3.5 \times 10^3$	
$Re \geq 3.5 \times 10^3$	$\left(1 - \frac{F_0}{F_2}\right)^2$

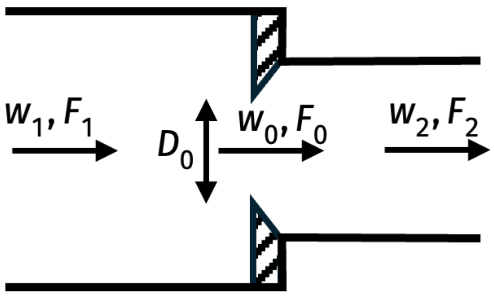


$$\Delta p = K_W \cdot \frac{1}{2}\rho w_0^2$$

D_0, F_0, S_0 = outlet diameter/area/perimeter
w_0 = outlet average velocity
w_1 = inlet average velocity
F_1 = inlet area
$Re = w_0 D_h / \nu,\ D_h = 4F_0/S_0$

Re	K_W
$1 < Re < 8$	$\frac{27}{Re}$
$10 < Re < 10^4$	
$Re \geq 10^4$	$0.5\left(1 - \frac{F_0}{F_1}\right)$

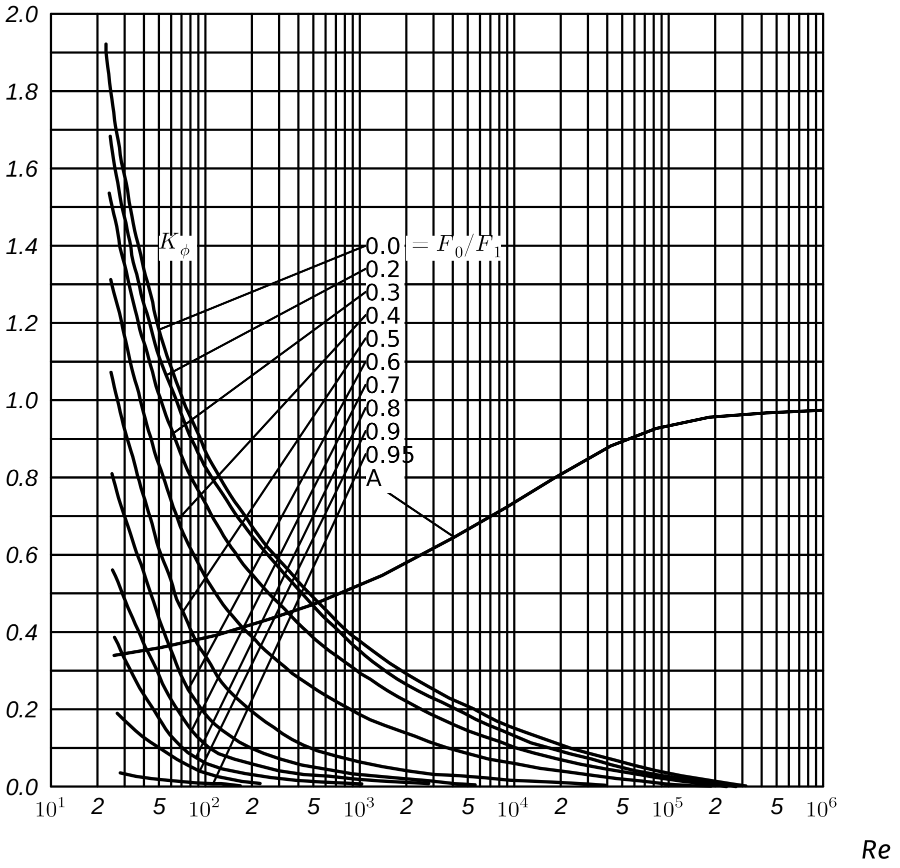
sharp-edged orifices (thickness <1.5% of D_h)



F_0, S_0, D_0 = orifice area/perimeter/diameter
F_1 = inlet area
F_2 = outlet area
w_0, w_1, w_2 = average velocity
$Re = w_0 D_h / \nu$, $D_h = 4F_0 / S_0$

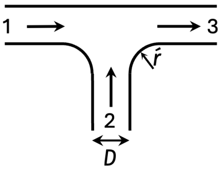
$$K_W = K_\phi + A\left(0.707\sqrt{1-\frac{F_0}{F_1}} + 1 - \frac{F_0}{F_2}\right)^2$$

$$\Delta p = K_W \cdot \frac{1}{2}\rho w_0^2$$

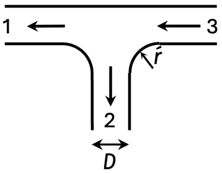
Re	K_ϕ, A
$Re < 10^5$	
$Re \geq 10^5$	$K_\phi = 0$ $A = 1$

converging and diverging T-junctions ($Re \equiv w_3 D/\nu > 10^5$)

$$\Delta p = K_W \cdot \frac{1}{2}\rho w_3^2$$



converging



diverging

① $$K_{1-3} = 0.045 + \left[1.38 - 1.94\left(\frac{\acute{r}}{D}\right)^{0.5} + 1.34\left(\frac{\acute{r}}{D}\right)\right]\left(\frac{Q_2}{Q_3}\right) - \left[0.90 - 0.95\left(\frac{\acute{r}}{D}\right)^{0.5} + 1.23\left(\frac{\acute{r}}{D}\right)\right]\left(\frac{Q_2}{Q_3}\right)^2$$

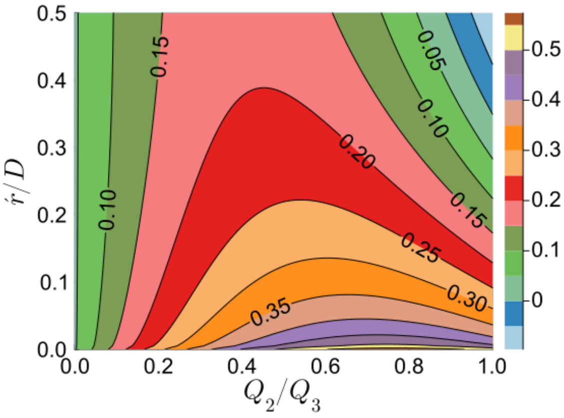
② $$K_{2-3} = \left[1.09 - 0.80\left(\frac{\acute{r}}{D}\right)^{0.5}\right] - \left[0.53 + 1.27\left(\frac{\acute{r}}{D}\right)^{0.5} - 1.86\left(\frac{\acute{r}}{D}\right)\right]\left(\frac{Q_1}{Q_3}\right)^2 - \left[1.48 - 2.28\left(\frac{\acute{r}}{D}\right)^{0.5} + 1.80\left(\frac{\acute{r}}{D}\right)\right]\left(\frac{Q_1}{Q_3}\right)^2$$

③ $$K_{3-1} = 1.55\left[0.22 - \left(\frac{Q_2}{Q_3}\right)\right]^2 - 0.03 \qquad 0 \le \left(\frac{Q_2}{Q_3}\right) \le 0.22$$

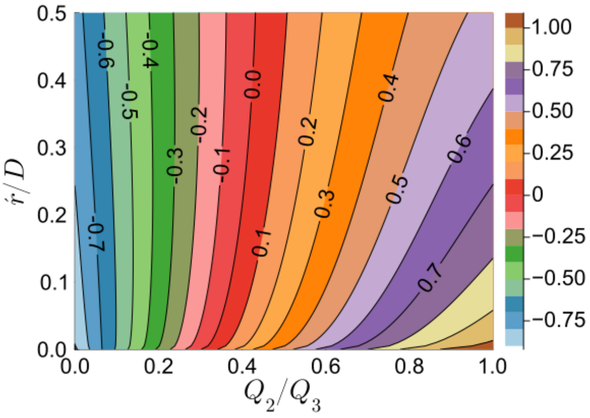
④ $$K_{3-1} = 0.65\left[\left(\frac{Q_2}{Q_3}\right) - 0.22\right]^2 - 0.03 \qquad 0.22 \le \left(\frac{Q_2}{Q_3}\right) \le 1$$

⑤ $$K_{3-2} = \left[0.99 - 0.23\left(\frac{\acute{r}}{D}\right)^{0.5}\right] - \left[0.82 + 0.29\left(\frac{\acute{r}}{D}\right)^{0.5} + 0.30\left(\frac{\acute{r}}{D}\right)\right]\left(\frac{Q_2}{Q_3}\right) + \left[1.02 - 0.64\left(\frac{\acute{r}}{D}\right)^{0.5} + 0.76\left(\frac{\acute{r}}{D}\right)\right]\left(\frac{Q_2}{Q_3}\right)^2$$

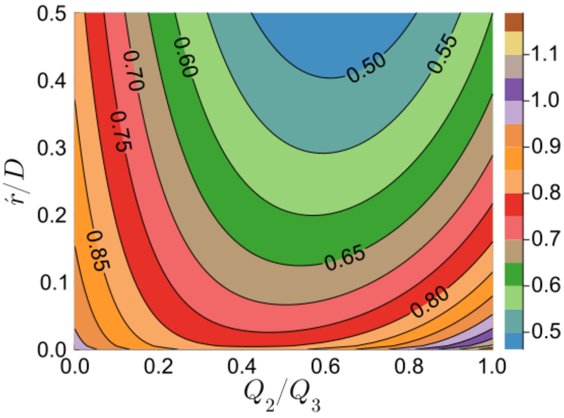
Equation ①



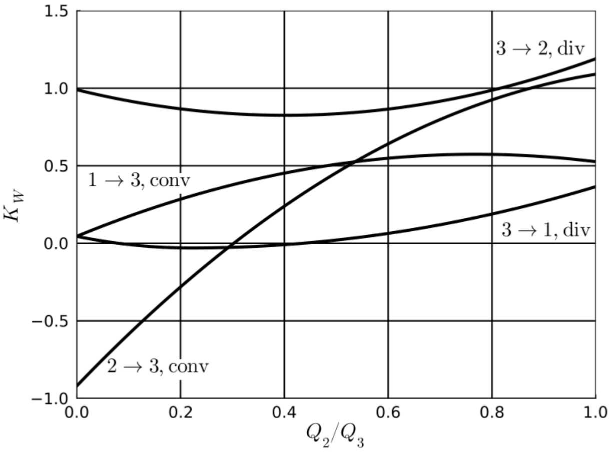
Equation ②



Equation ⑤

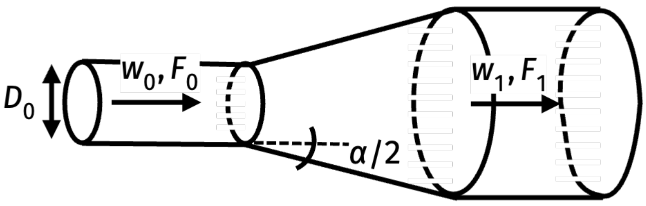


For sharp bends ($\acute{r}/D = 0$)



diffusors and contractions ($Re \equiv w_0 D_h / \nu > 10^4$)

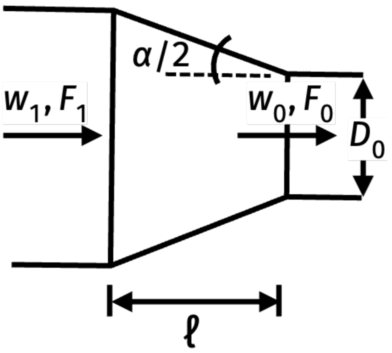
$$\Delta p = K_W \cdot \frac{1}{2} \rho w_0^2 \qquad D_h = 4F_0 / S_0$$



D_0, F_0, S_0 = inlet diameter/area/perimeter
w_0 = inlet average velocity
w_1 = outlet average velocity
F_1 = outlet area
α = diffusor angle

K_W

F_0/F_1	$\alpha = 3^\circ$	6	8	10	12	14	10	20	24	30	40	60	90	180
0	0.03	0.08	0.11	0.15	0.19	0.23	0.27	0.36	0.47	0.65	0.92	1.15	1.1	1 02
0.05	0.03	0.07	0.10	0.14	0.16	0.20	0.24	0.32	0.42	0.58	0.83	1.04	0.99	0.92
0.075	0.03	0.07	0.09	0.13	0.16	0.19	0.23	0.30	0.4	0.55	0.79	0.99	0.95	0.88
0.1	0.03	0.07	0.09	0.12	0.15	0.18	0.22	0.29	0.38	0.52	0.75	0.93	0.89	0.83
0.15	0.02	0.06	0.08	0.11	0.14	0.17	0.20	0.26	0.34	0.46	0.67	0.84	0.79	0.74
0.2	0.02	0.05	0.07	0.10	0.12	0.15	0.17	0.23	0.3	0.41	0.59	0.74	0.7	0.65
0.25	0.02	0.05	0.06	0.08	0.10	0.13	0.15	0.20	0.26	0.35	0.47	0.65	0.62	0.58
0.3	0.02	0.04	0.05	0.07	0.09	0.11	0.13	0.18	0.23	0.31	0.4	0.57	0.54	0.5
0.4	0.01	0.03	0.04	0.06	0.07	0.08	0.10	0.13	0.17	0.23	0.33	0.41	0.39	0.37
0.5	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.09	0.12	0.16	0.23	0.29	0.28	0.26
0.6	0.01	0.01	0.02	0.03	0.03	0.04	0.05	0.06	0.08	0.1	0.15	0.18	0.17	0.16



$$K_W = K' \left(1 - \frac{F_0}{F_1}\right)$$

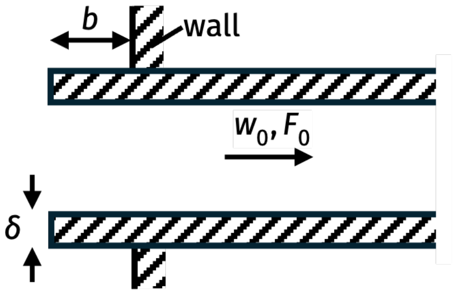
D_0, F_0, S_0 = outlet diameter/area/perimeter
w_0 = outlet average velocity
w_1 = inlet average velocity
F_1 = inlet area
α = contraction angle

K'

ℓ/D_h	$\alpha = 0^\circ$	10	20	30	40	60	100	140	180
0.025	0.5	0.47	0.45	0.43	0.41	0.4	0.42	0.45	0.5
0.05	0.5	0.45	0.41	0.36	0.33	0.3	0.35	0.42	0.5
0.075	0.5	0.42	0.35	0.3	0.26	0.23	0.3	0.4	0.5
0.1	0.5	0.39	0.32	0.25	0.22	0.18	0.27	0.38	0.5
0.15	0.5	0.37	0.27	0.2	0.16	0.15	0.25	0.37	0.5
0.6	0.5	0.27	0.18	0.13	0.11	0.12	0.23	0.36	0.5

circular or square pipe entrances and exits

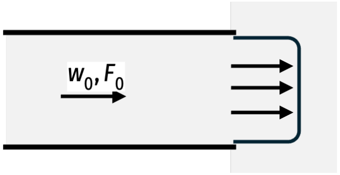
$$\Delta p = K_W \frac{1}{2} \rho w_0^2$$



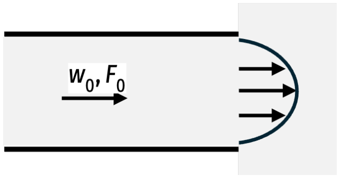
D_0, F_0, S_0 = inlet diameter/area/perimeter
w_0 = inlet average velocity
δ = pipe wall thickness
b = inlet length
$Re = w_0 D_h / \nu,\ D_h = 4F_0/S_0$

K_W for pipe entrances ($Re \equiv w_0 D_h / \nu > 10^4$)

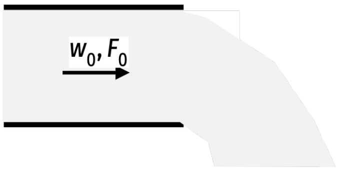
δ/D_h	$b/D_h = 0$	0.002	0.005	0.01	0.02	0.05	0.1	0.2	0.3	0.5	∞
0	0,50	0.57	0.63	0.68	0.73	0.8	0.86	0.92	0.97	1	1
0.004	0.5	0.54	0.58	0.63	0.67	0.74	0.8	0.86	0.9	0.94	0.94
0.008	0.5	0.53	0.55	0.58	0.62	0.68	0.74	0.81	0.85	0.88	0.88
0.012	0.5	0.52	0.53	0.55	0.58	0.63	0.68	0.75	0.79	0.83	0.83
0.016	0.5	0.51	0.51	0.53	0.55	0.58	0.64	0.7	0.74	0.77	0.77
0.02	0.5	0.51	0.51	0.52	0.53	0.55	0.6	0.66	0.69	0.72	0.72
0.024	0.5	0.5	0.5	0.51	0.52	0.53	0.58	0.62	0.65	0.68	0.68
0.03	0.5	0.5	0.5	0.51	0.52	0.52	0.54	0.57	0.59	0.61	0.61
0.04	0.5	0.5	0.5	0.51	0.51	0.51	0.51	0.52	0.52	0.54	0.54
0.05	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
∞	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5



turbulent: $K_W = 1$



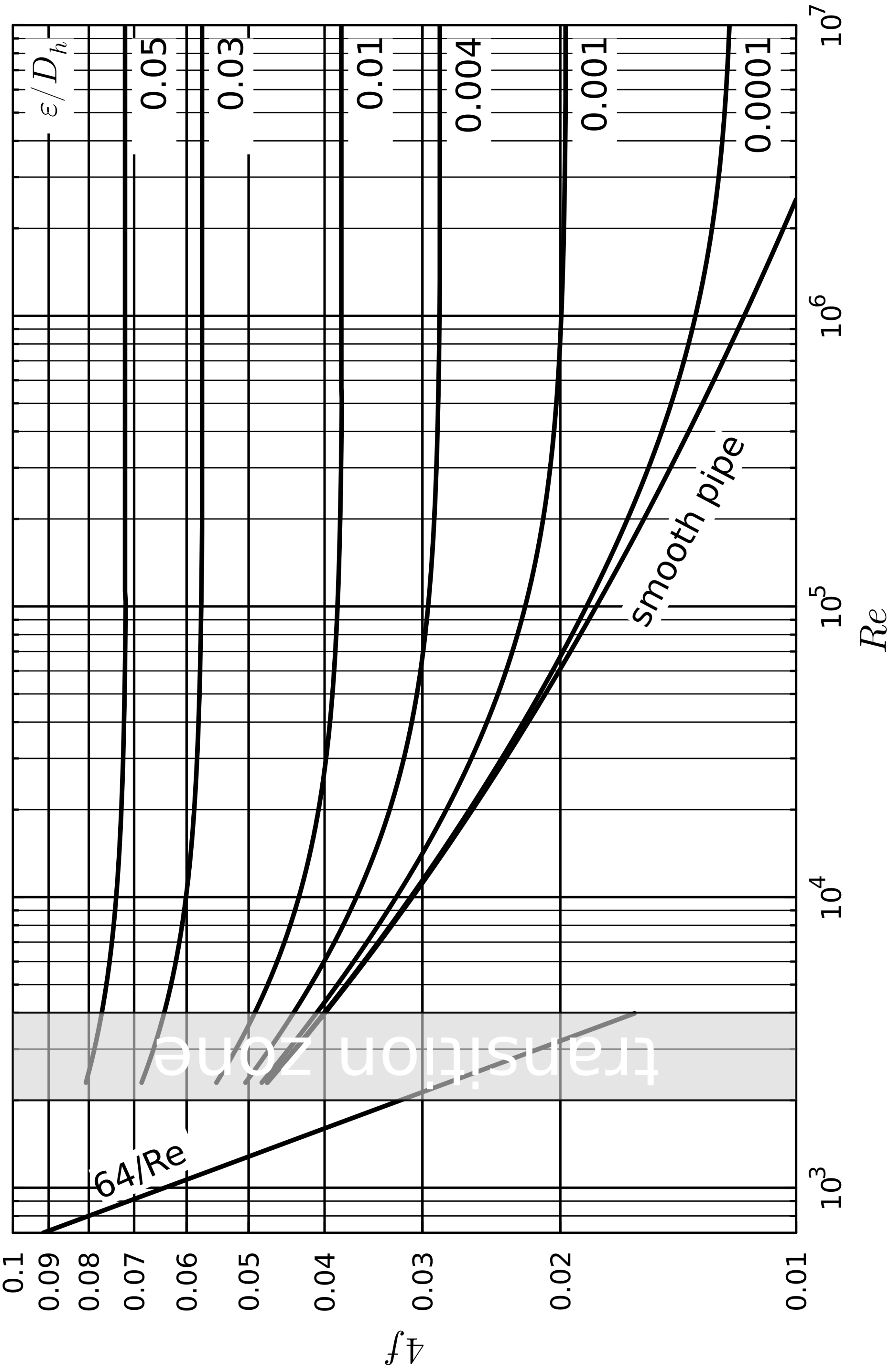
laminar: $K_W = 2$



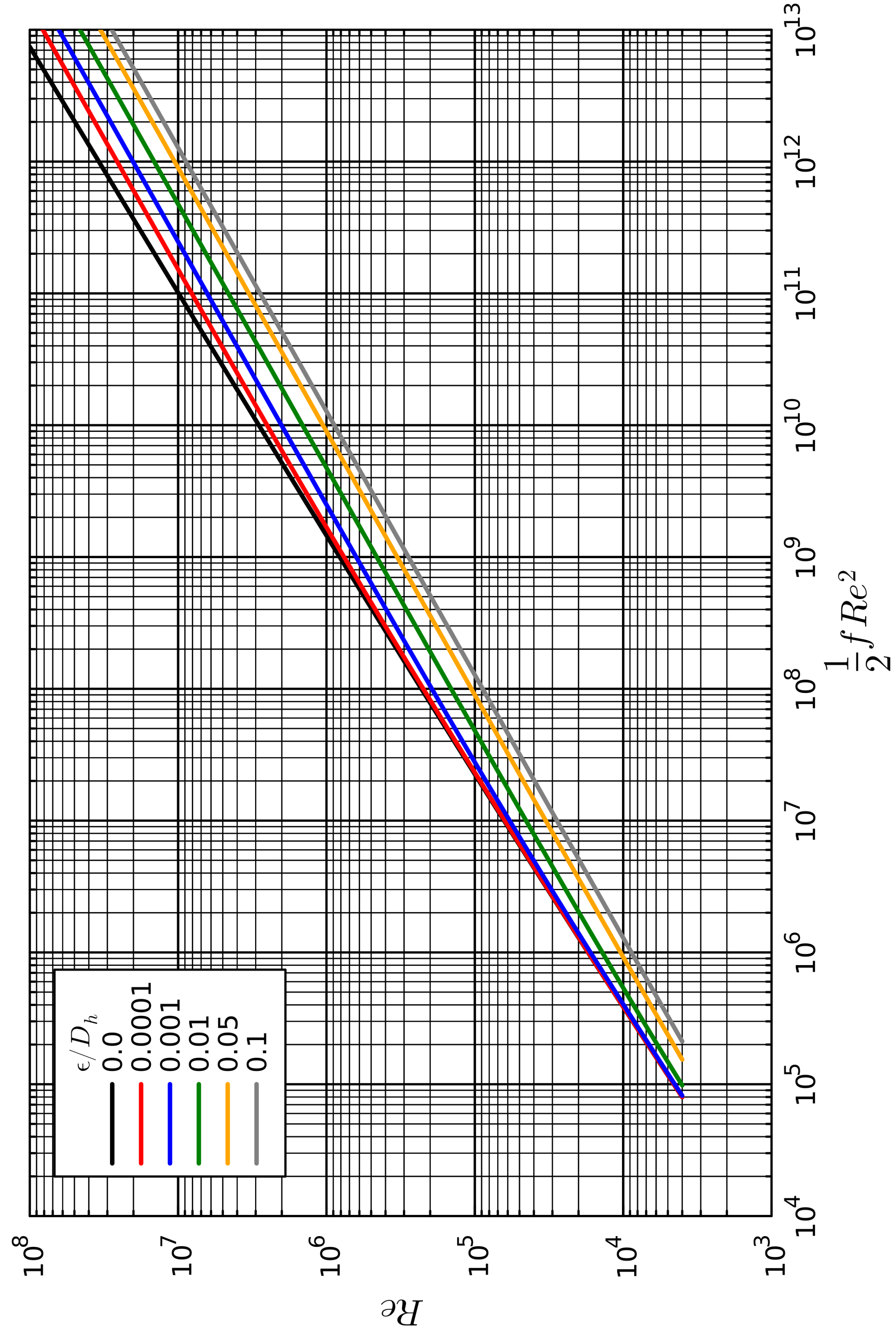
All regimes: $K_W = 0$

D_0, F_0, S_0 = outlet diameter/area/perimeter
w_0 = outlet average velocity
$Re = w_0 D_h / \nu,\ D_h = 4F_0/S_0$

Fanning friction factor in tubes

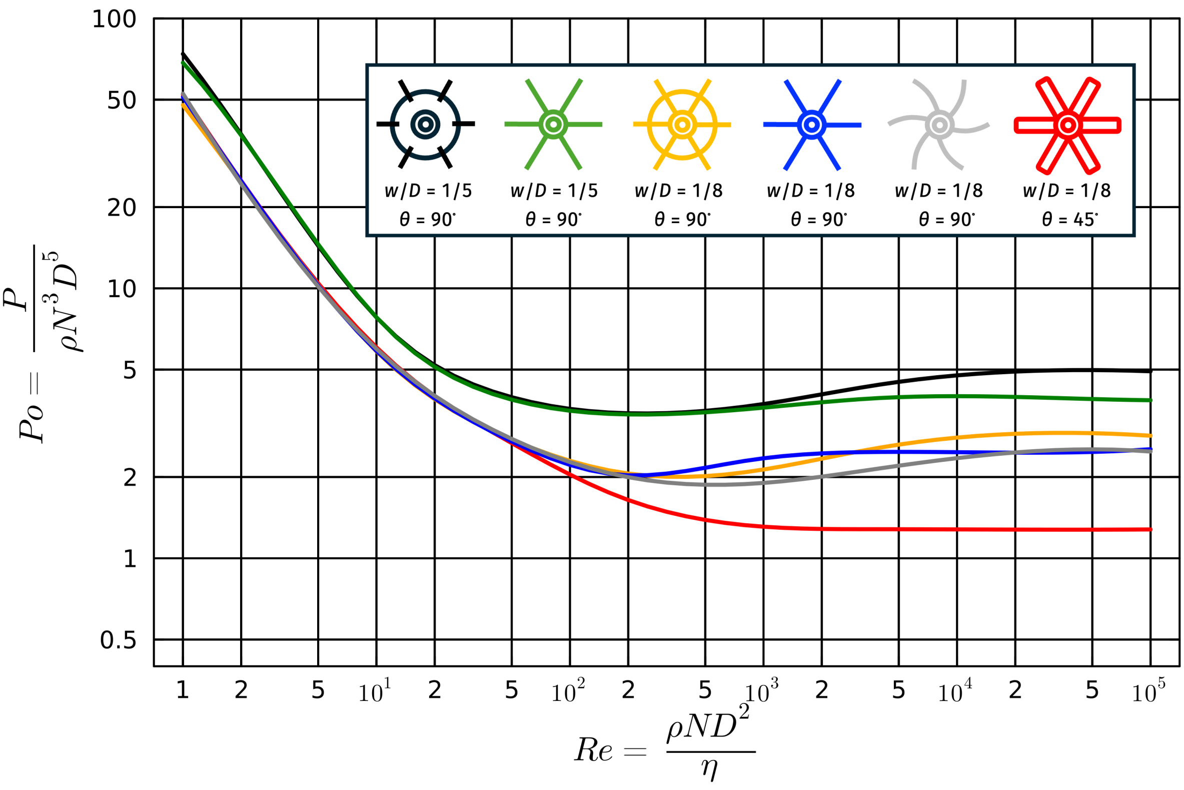


Fanning friction factor in tubes (turbulent range)

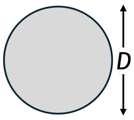
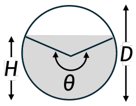
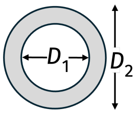
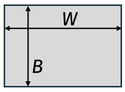


Impellers: power number Po vs Re

P = power applied (W), N = impeller frequency (s^{-1}), D = impeller diameter (m) and w = height of the impeller blade (m).



Hydraulic diameters

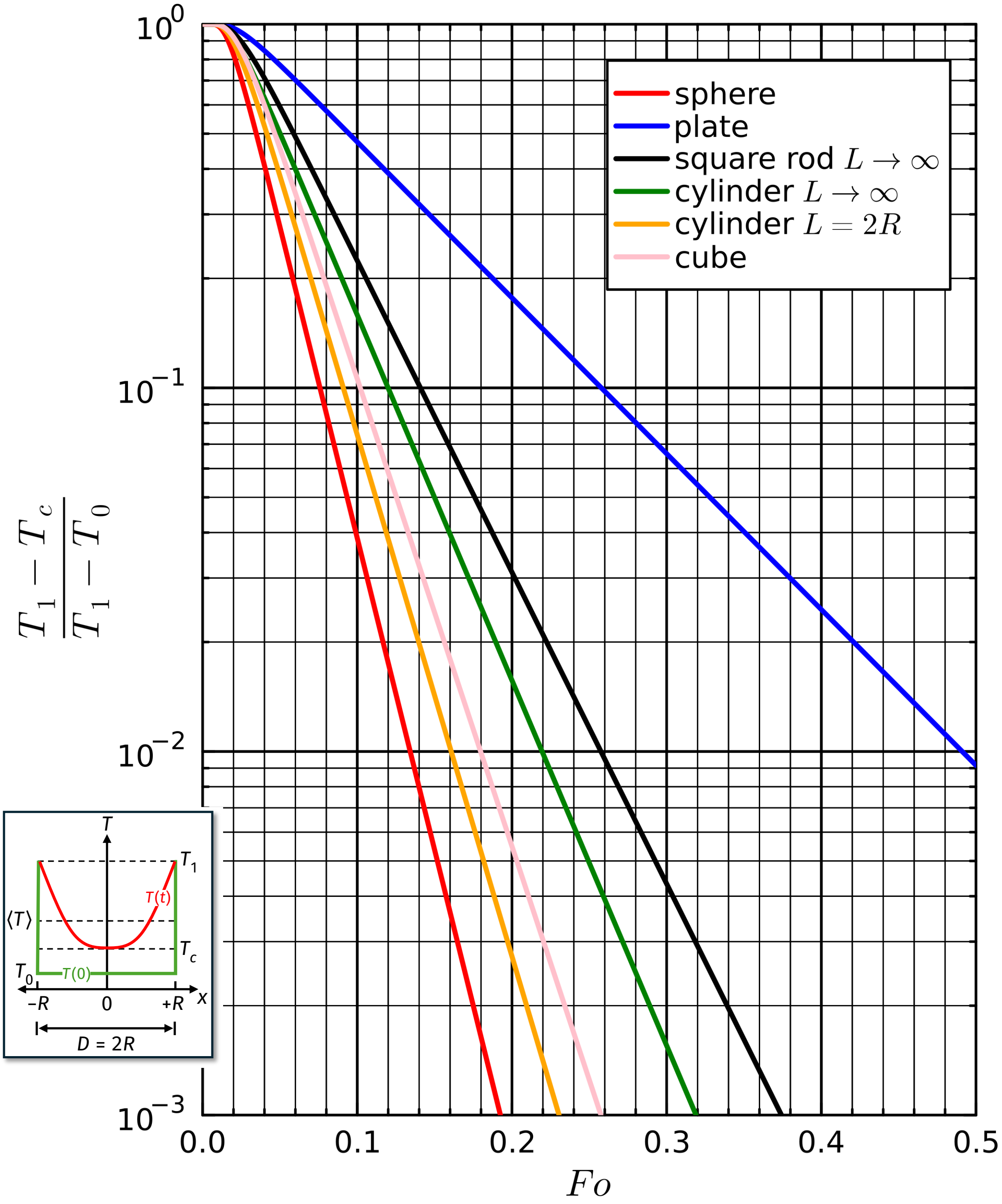
		Hydraulic diameter $D_h \equiv 4A/S$	Wetted area A	Wetted perimeter S
Fully filled, round		D	$\frac{\pi}{4}D^2$	πD
Partially filled, round		$\frac{D(\theta - \sin(\theta))}{\theta + 2\sin(\theta/2)}$ $\theta = 2\cos^{-1}(1 - 2H/D)$	$\frac{1}{8}D^2\left(\theta - \sin(\theta)\right)$	$\frac{D}{2}\theta + D\sin(\theta/2)$
Fully filled, annulus		$D_2 - D_1$	$\frac{1}{4}\pi\left(D_2^2 - D_1^2\right)$	$\pi(D_1 + D_2)$
Fully filled, rectangular		$\frac{2WB}{W + B}$	WB	$2(W + B)$

Non-stationary transport in objects

based on the center value (large range)

Graph hereunder for temperatures, for concentrations use c_1, c_c and c_0.

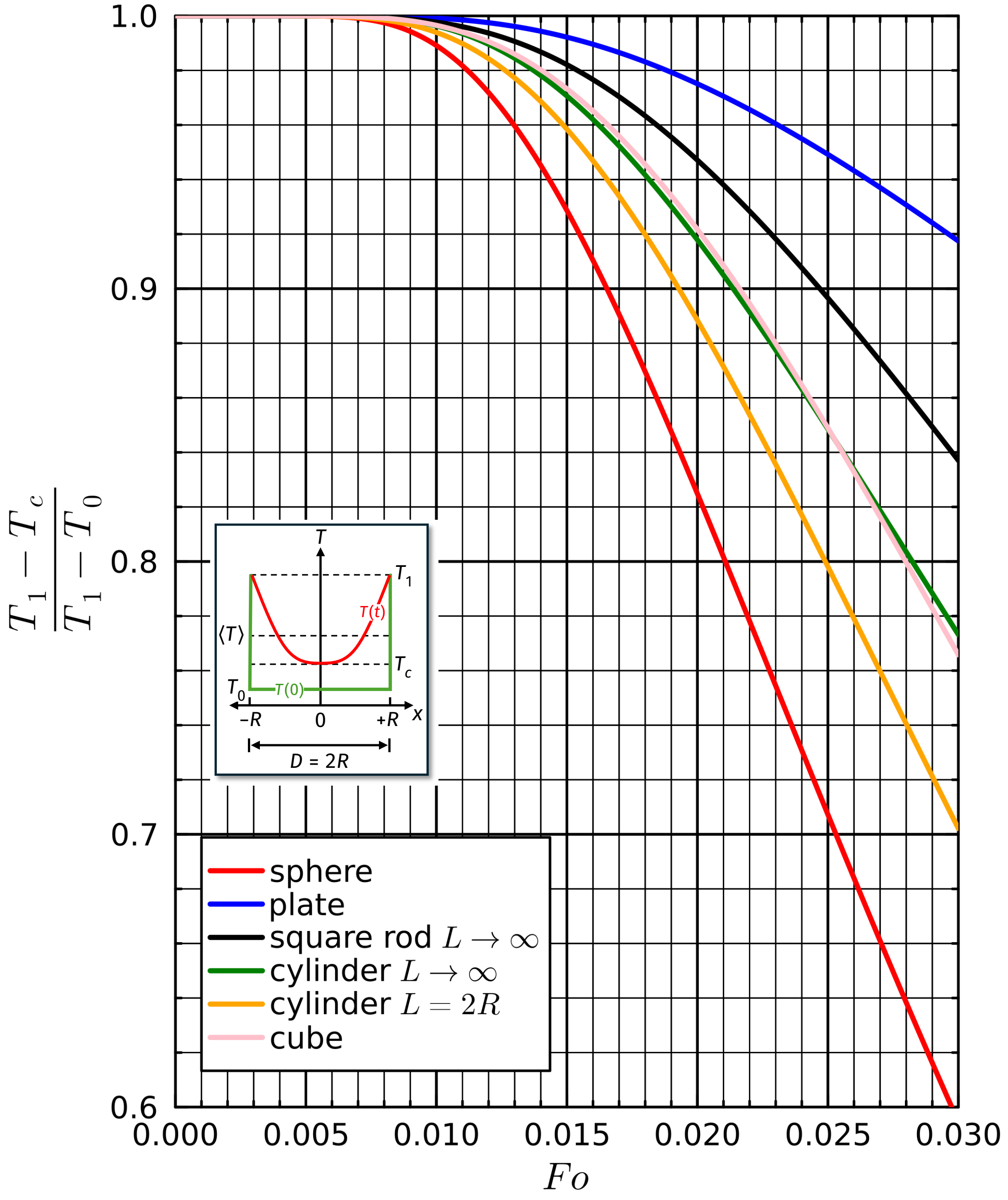
$Fo \equiv \frac{at}{D^2}$ (heat), $Fo \equiv \frac{\mathbb{D}t}{D^2}$ (species)



based on the center value ($Fo \leq 0.03$)

Graph hereunder for temperatures, for concentrations use c_1, c_c and c_0.

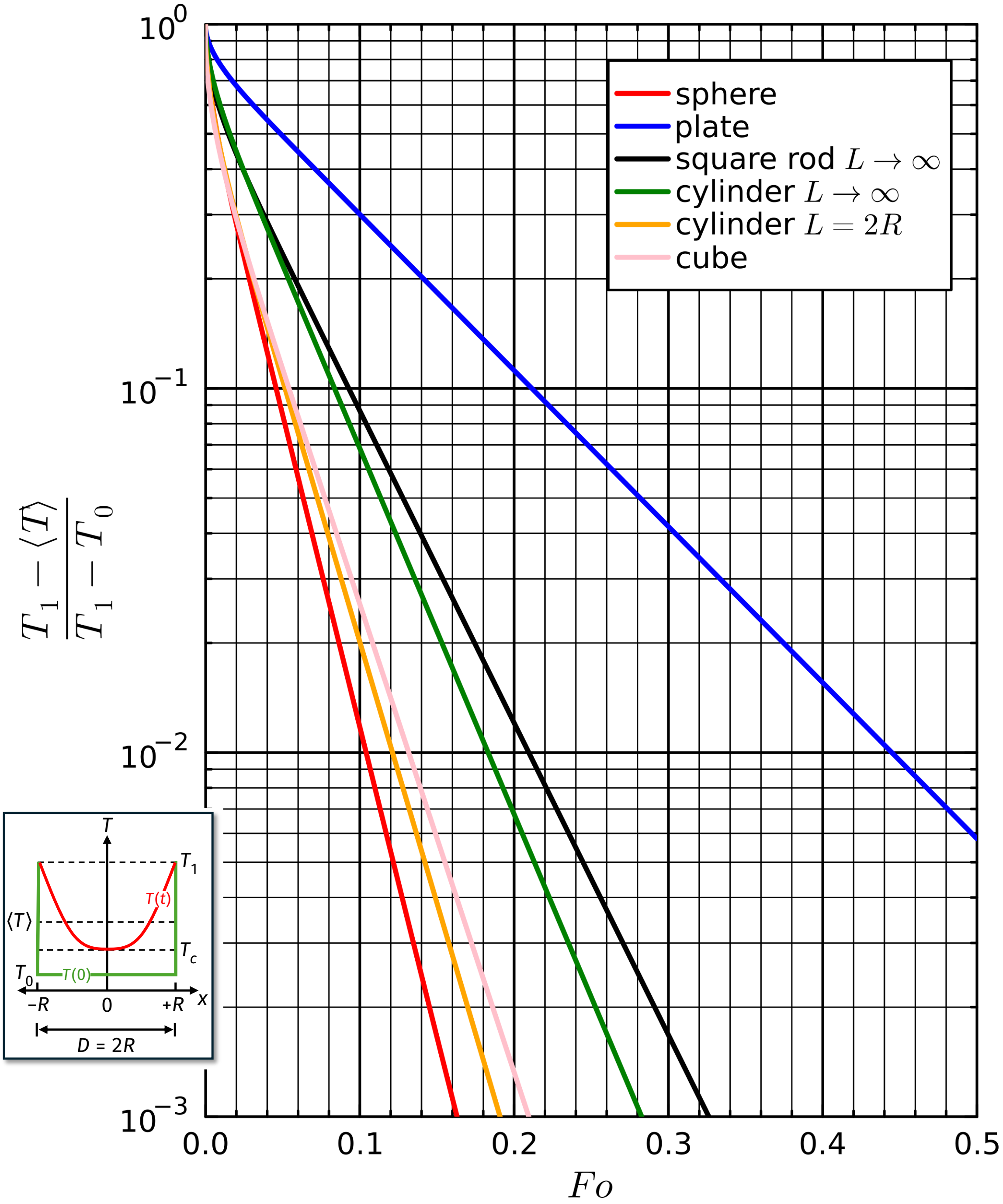
$$Fo \equiv \frac{at}{D^2} \text{ (heat)}, \ Fo \equiv \frac{\mathbb{D}t}{D^2} \text{ (species)}$$



based on the average value (large range)

Graph hereunder for temperatures, for concentrations use c_1, $\langle c \rangle$ and c_0.

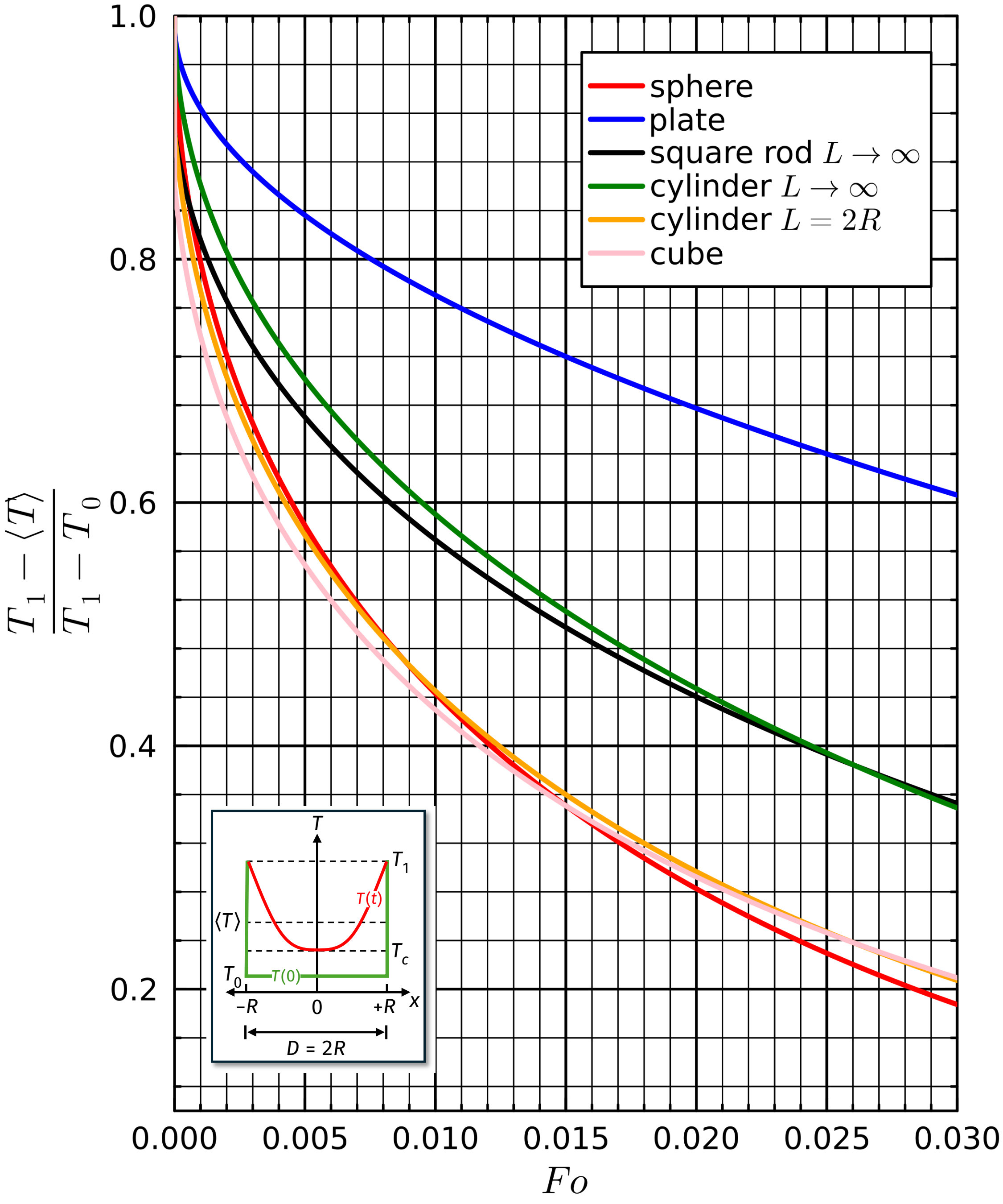
$Fo \equiv \frac{at}{D^2}$ (heat), $Fo \equiv \frac{\mathbb{D}t}{D^2}$ (species)



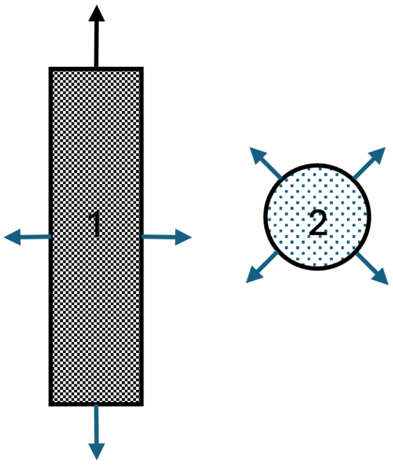
based on the average value ($Fo \le 0.03$)

Graph hereunder for temperatures, for concentrations use c_1, $\langle c \rangle$ and c_0.

$$Fo \equiv \frac{at}{D^2} \text{ (heat)}, \; Fo \equiv \frac{\mathbb{D}t}{D^2} \text{ (species)}$$



Radiation



T_1, T_2 = surface temperature
e_1, e_2 = surface emission coefficient
A_1, A_2 = radiating surface area
$F_{a \to b}$ = form factor
e_{eff} = effective emission coefficient

$$\phi_{net,1\to 2} = A_1 e_{eff} \sigma \left(T_1^4 - T_2^4\right)$$

Relevant formulas

Relation between form factors and surfaces

$$\frac{F_{1\to 2}}{F_{2\to 1}} = \frac{A_2}{A_1}$$

Effective emission coefficient between two bodies

$$e_{eff} = \left(\frac{1 - e_1}{e_1} + \frac{A_1}{A_2}\frac{1 - e_2}{e_2} + \frac{1}{F_{1\to 2}}\right)^{-1}$$

Emission coefficients of materials (T=300K)

Alloy 24ST Polished	0.09	Black Body Matt	1
Alumina, Flame sprayed	0.8	Black Enamel Paint	0.8
Aluminum Anodized	0.77	Black Epoxy Paint	0.89
Aluminum Commercial sheet	0.09	Black lacquer on iron	0.875
Aluminum Commercial Sheet	0.09	Black Parson Optical	0.95
Aluminum Foil	0.04	Black Silicone Paint	0.93
Aluminum Heavily Oxidized	0.2 - 0.31	Brass Dull Plate	0.22
Aluminum Highly Polished	0.039 - 0.057	Brass Oxidized 600$^{\circ}C$	0.6
Aluminum paint	0.27 - 0.67	Brass Polished	0.03
Aluminum Rough	0.07	Brass Rolled Plate Natural Surface	0.06
Anodize black	0.88	Brick, fire-clay	0.75
Antimony, polished	0.28 - 0.31	Brick, red rough	0.93
Asbestos board	0.96	Cadmium	0.02
Asbestos paper	0.93 - 0.945	Carbon filament	0.77
Asphalt	0.93	Carbon pressed filled surface	0.98
Basalt	0.72	Carbon, not oxidized	0.81
Beryllium	0.18	Cast Iron, newly turned	0.44
Beryllium, Anodized	0.9	Cast Iron, turned and heated	0.60 - 0.70
Bismuth, bright	0.34	Cement	0.54

Emission coefficients of materials (T=300K) (continued)

Clay	0.91	Paper offset	0.55
Coal	0.8	Pine	0.84
Concrete	0.85	Plaster	0.98
Concrete tiles	0.63	Plaster board	0.91
Concrete, rough	0.94	Plaster, rough	0.91
Copper electroplated	0.03	Plastics	0.90 - 0.97
Copper Nickel Alloy, polished	0.059	Platinum, polished plate	0.054 - 0.104
Copper Polished	0.023 - 0.052	Polyethylene, black plastic	0.92
Copper with thick oxide layer	0.78	Polypropylene	0.97
Cotton cloth	0.77	Polytetrafluoroethylene (PTFE)	0.92
Cromium polished	0.058	Porcelain glazed	0.93
Glass smooth	0.92 - 0.94	Porcelain, glazed	0.92
Glass, opal	0.87	PVC	0.91 - 0.93
Glass, pyrex	0.85 - 0.95	Pyrex	0.92
Gold highly polished	0.02 - 0.04	Quartz glass	0.93
Gold not polished	0.47	Rubber, foam	0.9
Granite, natural surface	0.96	Rubber, hard glossy plate	0.94
Gravel	0.28	Rubber, natural hard	0.91
Gypsum	0.85	Rubber, natural oft	0.86
Ice rough	0.985	Salt	0.34
Ice smooth	0.966	Sand	0.9
Inconel X Oxidized	0.71	Sandstone	0.59
Iron polished	0.14 - 0.38	Sapphire	0.48
Iron, dark gray surface	0.31	Sawdust	0.75
Iron, plate rusted red	0.61	Silica	0.79
Iron, rough ingot	0.87 - 0.95	Silicon Carbide	0.83 - 0.96
Lampblack paint	0.96	Silver Polished	0.02 - 0.03
Lead Oxidized	0.43	Snow	0.96 - 0.98
Lead pure unoxidized	0.057 - 0.075	Soil	0.90 - 0.95
Lime wash	0.91	Stainless Steel, polished	0.075
Limestone	0.90 - 0.93	Stainless Steel, type 301	0.54 - 0.63
Magnesia	0.72	Stainless Steel, weathered	0.85
Magnesite	0.38	Steel Galvanized New	0.23
Magnesium Oxide	0.20 - 0.55	Steel Galvanized Old	0.88
Magnesium Polished	0.07 - 0.13	Steel Oxidized	0.79
Marble White	0.95	Steel Polished	0.07
Masonry Plastered	0.93	Thoria	0.28
Mercury liquid	0.1	Tile	0.97
Mild Steel	0.20 - 0.32	Tin unoxidized	0.04
Molybdenum polished	0.05 - 0.18	Titanium polished	0.19
Mortar	0.87	Tungsten aged filament	0.032 - 0.35
Nichrome wire, bright	0.65 - 0.79	Tungsten polished	0.04
Nickel, elctroplated	0.03	Water (0 - 100°C)	0.95 - 0.963
Nickel, oxidized	0.59 - 0.86	Wood Beech, planned	0.935
Nickel, polished	0.072	Wood Oak, planned	0.885
Oak, planed	0.89	Wood, Pine	0.95
Oil paints, all colors	0.92 - 0.96	Wrought Iron	0.94
Paint	0.96	Zinc polished	0.045
Paper	0.93	Zinc Tarnished	0.25

Mathematics

error function

x	erf(x)	x	erf(x)	x	erf(x)
0.00	0.0000	1.00	0.8427	2.00	0.9953
0.05	0.0564	1.05	0.8624	2.05	0.9963
0.10	0.1125	1.10	0.8802	2.10	0.9970
0.15	0.1680	1.15	0.8961	2.15	0.9976
0.20	0.2227	1.20	0.9103	2.20	0.9981
0.25	0.2763	1.25	0.9229	2.25	0.9985
0.30	0.3286	1.30	0.9340	2.30	0.9989
0.35	0.3794	1.35	0.9438	2.35	0.9991
0.40	0.4284	1.40	0.9523	2.40	0.9993
0.45	0.4755	1.45	0.9597	2.45	0.9995
0.50	0.5205	1.50	0.9661	2.50	0.9996
0.55	0.5633	1.55	0.9716	2.55	0.9997
0.60	0.6039	1.60	0.9763	2.60	0.9998
0.65	0.6420	1.65	0.9804	2.65	0.9998
0.70	0.6778	1.70	0.9838	2.70	0.9999
0.75	0.7112	1.75	0.9867	2.75	0.9999
0.80	0.7421	1.80	0.9891	2.80	0.9999
0.85	0.7707	1.85	0.9911	2.85	0.9999
0.90	0.7969	1.90	0.9928	2.90	1.0000
0.95	0.8209	1.95	0.9942	2.95	1.0000

Basic integrals

$$\int x^n\,dx = \frac{x^{n+1}}{n+1} + C \quad (n \neq -1)$$

$$\int \frac{1}{x}\,dx = ln(x) + C$$

$$\int e^x\,dx = e^x + C$$

$$\int e^{ax}\,dx = \frac{1}{a}e^{ax} + C$$

$$\int a\,dx = ax + C$$

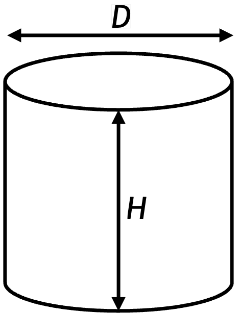
$$\int a^x\,dx = \frac{a^x}{ln(a)} + C$$

$$\int (ax+b)^n = \frac{(ax+b)^{n+1}}{a(n+1)} + C$$

$$\int \frac{c}{ax+b}\,dx = \frac{c}{a}ln(ax+b) + C$$

Geometrical Measures

Cylinder

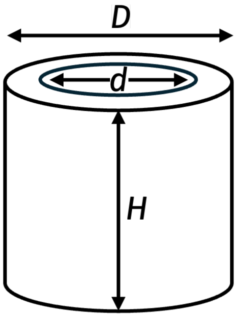


Outer surface = $\pi D\left(\frac{1}{2}D + H\right)$

Curved surface = πHD

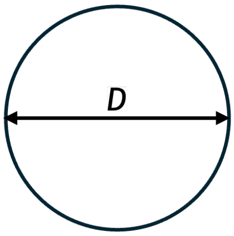
Volume = $\frac{1}{4}\pi HD^2$

Tube



Volume = $\frac{1}{4}\pi H\left(D^2 - d^2\right)$

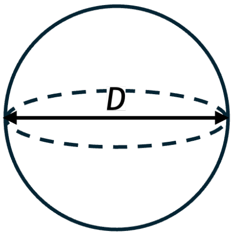
Circle



Surface = $\frac{1}{4}\pi D^2$

Circumference = πD

Sphere



Surface = πD^2

Volume = $\frac{1}{6}\pi D^3$

Properties of materials

water at $p = 10^5 \ Pa$

T	ρ	η	ν	λ	C_p	α	Pr	β
$(^\circ C)$	(kg/m^3)	$(Pa.s)$	(m^2/s)	(W/mK)	$J/(kgK)$	(m^2/s)	-	$(m^3/(m^3K))$
0.0	999.8	1.792e-03	1.792e-06	5.557e-01	4219.4	1.317e-07	13.6	-6.771e-05
5.0	1000.0	1.518e-03	1.518e-06	5.678e-01	4205.0	1.350e-07	11.2	1.608e-05
10.0	999.7	1.306e-03	1.306e-06	5.788e-01	4195.2	1.380e-07	9.5	8.797e-05
15.0	999.1	1.137e-03	1.139e-06	5.888e-01	4188.5	1.407e-07	8.1	1.509e-04
20.0	998.2	1.002e-03	1.003e-06	5.980e-01	4184.1	1.432e-07	7.0	2.068e-04
25.0	997.0	8.900e-04	8.926e-07	6.065e-01	4181.3	1.455e-07	6.1	2.573e-04
30.0	995.6	7.972e-04	8.007e-07	6.144e-01	4179.8	1.476e-07	5.4	3.034e-04
35.0	994.0	7.191e-04	7.234e-07	6.217e-01	4179.3	1.497e-07	4.8	3.459e-04
40.0	992.2	6.527e-04	6.578e-07	6.285e-01	4179.4	1.516e-07	4.3	3.855e-04
45.0	990.2	5.957e-04	6.016e-07	6.348e-01	4180.1	1.534e-07	3.9	4.227e-04
50.0	988.0	5.465e-04	5.531e-07	6.406e-01	4181.3	1.551e-07	3.6	4.578e-04
55.0	985.7	5.036e-04	5.109e-07	6.460e-01	4183.0	1.567e-07	3.3	4.912e-04
60.0	983.2	4.660e-04	4.740e-07	6.510e-01	4185.0	1.582e-07	3.0	5.233e-04
65.0	980.5	4.329e-04	4.415e-07	6.556e-01	4187.3	1.597e-07	2.8	5.541e-04
70.0	977.8	4.035e-04	4.127e-07	6.598e-01	4190.1	1.610e-07	2.6	5.840e-04
75.0	974.8	3.774e-04	3.871e-07	6.636e-01	4193.2	1.623e-07	2.4	6.130e-04
80.0	971.8	3.540e-04	3.643e-07	6.670e-01	4196.8	1.635e-07	2.2	6.414e-04
85.0	968.6	3.331e-04	3.439e-07	6.701e-01	4200.7	1.647e-07	2.1	6.692e-04
90.0	965.3	3.142e-04	3.255e-07	6.728e-01	4205.2	1.657e-07	2.0	6.966e-04
95.0	961.9	2.971e-04	3.088e-07	6.752e-01	4210.2	1.667e-07	1.9	7.237e-04

air at $p = 10^5\ Pa$

T	ρ	η	ν	λ	C_p	C_v	α	β
$(^\circ C)$	(kg/m^3)	$(Pa.s)$	(m^2/s)	(W/mK)	$J/(kgK)$	$J/(kgK)$	(m^2/s)	$(m^3/(m^3 K))$
0.0	1.276	1.722e-05	1.349e-05	2.436e-02	1005.7	716.9	1.898e-05	3.674e-03
10.0	1.231	1.772e-05	1.439e-05	2.512e-02	1005.9	717.3	2.029e-05	3.543e-03
20.0	1.189	1.821e-05	1.531e-05	2.587e-02	1006.1	717.7	2.163e-05	3.421e-03
30.0	1.149	1.869e-05	1.626e-05	2.662e-02	1006.5	718.1	2.301e-05	3.307e-03
40.0	1.113	1.917e-05	1.722e-05	2.735e-02	1006.9	718.6	2.442e-05	3.201e-03
50.0	1.078	1.964e-05	1.821e-05	2.808e-02	1007.4	719.2	2.585e-05	3.101e-03
60.0	1.046	2.010e-05	1.922e-05	2.880e-02	1008.0	719.9	2.732e-05	3.007e-03
70.0	1.015	2.056e-05	2.025e-05	2.952e-02	1008.7	720.7	2.882e-05	2.919e-03
80.0	0.986	2.101e-05	2.130e-05	3.023e-02	1009.4	721.5	3.035e-05	2.836e-03
90.0	0.959	2.146e-05	2.237e-05	3.093e-02	1010.3	722.4	3.191e-05	2.758e-03
100.0	0.933	2.190e-05	2.346e-05	3.162e-02	1011.2	723.4	3.350e-05	2.683e-03
110.0	0.909	2.233e-05	2.457e-05	3.231e-02	1012.2	724.4	3.511e-05	2.613e-03
120.0	0.886	2.276e-05	2.569e-05	3.299e-02	1013.3	725.6	3.675e-05	2.546e-03
130.0	0.864	2.319e-05	2.684e-05	3.367e-02	1014.5	726.8	3.841e-05	2.483e-03
140.0	0.843	2.361e-05	2.801e-05	3.434e-02	1015.8	728.1	4.010e-05	2.423e-03
150.0	0.823	2.403e-05	2.919e-05	3.500e-02	1017.1	729.5	4.181e-05	2.365e-03
160.0	0.804	2.444e-05	3.039e-05	3.566e-02	1018.5	730.9	4.354e-05	2.310e-03
170.0	0.786	2.485e-05	3.162e-05	3.631e-02	1020.0	732.5	4.530e-05	2.258e-03
180.0	0.769	2.525e-05	3.285e-05	3.696e-02	1021.6	734.1	4.708e-05	2.208e-03
190.0	0.752	2.565e-05	3.411e-05	3.761e-02	1023.2	735.7	4.888e-05	2.160e-03
200.0	0.736	2.605e-05	3.539e-05	3.825e-02	1025.0	737.5	5.070e-05	2.115e-03

other fluids and gases at $p = 10^5\ Pa, T = 20\ ^{\circ}C$

Fluid	ρ	η	ν	λ	C_p	α	β
	(kg/m^3)	$(Pa.s)$	(m^2/s)	(W/mK)	$J/(kgK)$	(m^2/s)	$(m^3/(m^3K))$
1-Butene	2.371				1544.6		3.785e-03
Acetone	790.265				2131.0		1.404e-03
Air	1.189	1.821e-05	1.531e-05	2.587e-02	1006.1	2.163e-05	3.421e-03
Ammonia	0.707	9.911e-06	1.403e-05	2.449e-02	2162.2	1.603e-05	3.569e-03
Argon	1.640	2.231e-05	1.360e-05	1.750e-02	521.6	2.045e-05	3.422e-03
Benzene	878.832	6.468e-04	7.360e-07	1.429e-01	1722.2	9.440e-08	1.209e-03
CarbonDioxide	1.815	1.467e-05	8.085e-06	1.625e-02	846.0	1.058e-05	3.471e-03
CarbonMonoxide	1.150				1042.0		3.422e-03
CarbonylSulfide	2.494				697.3		3.536e-03
CycloHexane	778.673	9.724e-04	1.249e-06		1835.6		1.207e-03
CycloPropane	1.756				1334.2		3.616e-03
Cyclopentane	745.388	3.240e-04	4.347e-07	1.285e-01	1786.6	9.651e-08	1.316e-03
Deuterium	0.165				7247.3		3.410e-03
Dichloroethane	1252.628				1298.9		1.144e-03
DiethylEther	713.587				2317.1		1.601e-03
DimethylCarbonate	1069.892				1826.1		1.233e-03
DimethylEther	1.927	9.065e-06	4.704e-06		1455.1		3.657e-03
Ethane	1.243	9.207e-06	7.404e-06	2.036e-02	1737.7	9.421e-06	3.495e-03
Ethanol	789.418	1.194e-03	1.512e-06	1.645e-01	2396.0	8.697e-08	1.084e-03
EthylBenzene	866.895	6.476e-04	7.471e-07	1.290e-01	1730.1	8.603e-08	1.005e-03
Ethylene	1.158				1520.9		3.475e-03
EthyleneOxide	1.859				1138.8		3.808e-03
Fluorine	1.560				822.4		3.420e-03
HFE143m	4.214				928.5		3.756e-03
HeavyWater	1105.334	1.246e-03	1.127e-06	5.887e-01	4199.6	1.268e-07	1.247e-04

other fluids and gases at $p = 10^5\ Pa$, $T = 20\,^{\circ}C$ (cont'd)

Fluid	ρ (kg/m^3)	η $(Pa.s)$	ν (m^2/s)	λ (W/mK)	C_p $J/(kgK)$	α (m^2/s)	β $(m^3/(m^3K))$
Helium	0.164	1.962e-05	1.195e-04	1.535e-01	5193.2	1.801e-04	3.409e-03
Hydrogen	0.083	8.797e-06	1.064e-04	1.834e-01	14287.8	1.553e-04	3.410e-03
HydrogenChloride	1.505				810.3		3.480e-03
HydrogenSulfide	1.409	1.186e-05	8.418e-06		1013.1		3.498e-03
IsoButane	2.452	7.375e-06	3.007e-06	1.637e-02	1670.7	3.995e-06	3.735e-03
IsoButene	2.371				1612.5		3.789e-03
Isohexane	653.174				2211.6		1.395e-03
Isopentane	620.059	2.025e-04	3.266e-07	1.032e-01	2248.0	7.407e-08	1.628e-03
Krypton	3.445				249.2		3.435e-03
Methane	0.659	1.104e-05	1.674e-05	3.345e-02	2220.5	2.284e-05	3.434e-03
Methanol	791.311	5.864e-04	7.410e-07	2.013e-01	2501.4	1.017e-07	1.189e-03
MethylLinoleate	885.430				2306.0		8.399e-04
MethylLinolenate	899.230				2115.8		8.304e-04
MethylOleate	873.817				2239.4		8.390e-04
Neon	0.827				1030.4		3.410e-03
Neopentane	3.079				1691.4		3.891e-03
Nitrogen	1.150	1.757e-05	1.529e-05	2.547e-02	1041.3	2.128e-05	3.420e-03
NitrousOxide	1.816				878.2		3.473e-03
Novec649	1617.509				1099.2		1.840e-03
OrthoDeuterium	0.165				7250.4		3.410e-03
OrthoHydrogen	0.083				14086.2		3.410e-03
Oxygen	1.314	2.027e-05	1.543e-05	2.595e-02	918.9	2.149e-05	3.423e-03
ParaDeuterium	0.165				7247.5		3.410e-03
ParaHydrogen	0.083			1.906e-01	14892.2	1.548e-04	3.410e-03
Propylene	1.753	8.410e-06	4.799e-06	1.663e-02	1533.8	6.185e-06	3.577e-03

other fluids and gases at $p = 10^5\ Pa, T = 20\,^{\circ}C$ (cont'd)

Fluid	ρ (kg/m^3)	η ($Pa.s$)	ν (m^2/s)	λ (W/mK)	C_p $J/(kgK)$	α (m^2/s)	β ($m^3/(m^3K)$)
Propyne	1.673				1538.6		3.630e-03
R11	1488.101	4.556e-04	3.061e-07	8.824e-02	876.0	6.769e-08	1.584e-03
R113	1575.097				913.1		1.505e-03
R114	7.243				694.5		3.767e-03
R115	6.462				713.8		3.632e-03
R116	5.725	1.388e-05	2.425e-06	1.441e-02	768.0	3.277e-06	3.541e-03
R12	5.061	1.160e-05	2.292e-06	9.701e-03	607.7	3.154e-06	3.636e-03
R123	1476.668	4.427e-04	2.998e-07	7.783e-02	1013.5	5.201e-08	1.718e-03
R1233zd(E)	5.588	1.090e-05	1.951e-06		812.7		3.960e-03
R1234yf	4.790	1.216e-05	2.538e-06	1.342e-02	896.3	3.126e-06	3.699e-03
R1234ze(E)	4.798	1.214e-05	2.530e-06	1.336e-02	881.9	3.159e-06	3.717e-03
R1234ze(Z)	4.887				852.8		4.023e-03
R124	5.757	1.267e-05	2.201e-06	1.276e-02	735.7	3.013e-06	3.761e-03
R1243zf	4.036				939.2		3.705e-03
R125	5.004	1.275e-05	2.548e-06	1.364e-02	789.1	3.455e-06	3.609e-03
R13	4.327	1.413e-05	3.265e-06	1.201e-02	639.8	4.339e-06	3.522e-03
R134a	4.278	1.162e-05	2.717e-06	1.299e-02	843.5	3.600e-06	3.694e-03
R13I1	8.231				349.0		3.698e-03
R14	3.625	1.699e-05	4.688e-06	1.561e-02	689.2	6.251e-06	3.460e-03
R141b	1243.487	4.318e-04	3.472e-07	9.230e-02	1147.3	6.470e-08	1.546e-03
R142b	4.238				845.4		3.762e-03
R143a	3.511	1.094e-05	3.115e-06	1.443e-02	937.4	4.386e-06	3.635e-03
R152A	2.772	1.094e-05	3.946e-06	1.367e-02	1041.1	4.737e-06	3.706e-03
R161	2.004				1244.2		3.602e-03
R21	4.357				615.7		3.820e-03

other fluids and gases at $p = 10^5\ Pa$, $T = 20\,^{\circ}C$ (cont'd)

Fluid	ρ (kg/m^3)	η $(Pa.s)$	ν (m^2/s)	λ (W/mK)	C_p $J/(kgK)$	α (m^2/s)	β $(m^3/(m^3K))$
R218	7.891	1.214e-05	1.539e-06	1.209e-02	789.6	1.941e-06	3.698e-03
R22	3.603	1.355e-05	3.761e-06	1.118e-02	656.8	4.724e-06	3.596e-03
R227EA	7.183	1.137e-05	1.583e-06	1.295e-02	806.1	2.237e-06	3.794e-03
R23	2.896	1.467e-05	5.066e-06	1.335e-02	729.9	6.316e-06	3.508e-03
R236EA	6.471	1.070e-05	1.654e-06	1.408e-02	860.6	2.528e-06	3.900e-03
R236FA	6.459	1.075e-05	1.665e-06	1.225e-02	831.1	2.282e-06	3.871e-03
R245ca	1399.792				1371.7		1.777e-03
R245fa	5.722	1.161e-05	2.030e-06	1.529e-02	880.7	3.035e-06	3.972e-03
R32	2.163	1.314e-05	6.076e-06	1.325e-02	842.0	7.277e-06	3.580e-03
R365MFC	1267.722				1367.0		1.668e-03
R40	2.110				833.5		3.646e-03
R404A	4.076	1.202e-05	2.948e-06	1.308e-02	869.2	3.693e-06	3.634e-03
R407C	3.598	1.203e-05	3.345e-06	1.286e-02	830.3	4.306e-06	3.633e-03
R41	1.409				1111.3		3.512e-03
R410A	3.020	1.265e-05	4.190e-06	1.296e-02	816.4	5.257e-06	3.590e-03
R507A	4.128	1.197e-05	2.900e-06	1.310e-02	864.1	3.674e-06	3.630e-03
RC318	8.472				783.7		3.789e-03
SES36	1384.757				1068.0		1.791e-03
SulfurDioxide	2.676				648.3		3.652e-03
SulfurHexafluoride	6.064	1.499e-05	2.472e-06	1.262e-02	661.0	3.147e-06	3.545e-03
Toluene	866.888	5.871e-04	6.773e-07	1.317e-01	1685.4	9.016e-08	1.072e-03
Water	998.206	1.002e-03	1.003e-06	5.980e-01	4184.1	1.432e-07	2.068e-04
Xenon	5.416				160.2		3.467e-03
cis-2-Butene	2.379				1477.3		3.840e-03

other fluids and gases at $p = 10^5\ Pa$, $T = 20\,^{\circ}C$ (cont'd)

Fluid	ρ (kg/m^3)	η $(Pa.s)$	ν (m^2/s)	λ (W/mK)	C_p $J/(kgK)$	α (m^2/s)	β $(m^3/(m^3K))$
m-Xylene	864.208	6.176e-04	7.146e-07	1.311e-01	1695.6	8.948e-08	9.903e-04
n-Butane	2.462	7.279e-06	2.957e-06	1.607e-02	1712.3	3.813e-06	3.797e-03
n-Decane	730.407	9.134e-04	1.251e-06	1.308e-01	2174.2	8.236e-08	1.064e-03
n-Dodecane	749.433	1.488e-03	1.986e-06	1.365e-01	2196.4	8.293e-08	9.897e-04
n-Heptane	683.812	4.121e-04	6.026e-07	1.237e-01	2221.9	8.140e-08	1.231e-03
n-Hexane	659.380	3.132e-04	4.749e-07	1.215e-01	2252.0	8.185e-08	1.369e-03
n-Nonane	718.027	6.983e-04	9.725e-07	1.281e-01	2189.6	8.149e-08	1.097e-03
n-Octane	702.609	5.441e-04	7.744e-07	1.262e-01	2209.8	8.126e-08	1.146e-03
n-Pentane	626.189	1.891e-04	3.020e-07	1.138e-01	2293.7	7.925e-08	1.583e-03
n-Propane	1.840	8.012e-06	4.354e-06	1.776e-02	1663.7	5.802e-06	3.599e-03
n-Undecane	740.298				2198.6		1.032e-03
o-Xylene	880.230	8.112e-04	9.216e-07	1.319e-01	1750.0	8.563e-08	9.551e-04
p-Xylene	861.068	6.447e-04	7.487e-07	1.279e-01	1700.5	8.735e-08	1.005e-03
trans-2-Butene	2.379				1596.3		3.838e-03

Composition of air

Component	Volume %	Weight %
Nitrogen	78.09	75.53
Oxygen	20.95	23.14
Argon	0.93	1.28
CO2	3.00E-02	5.00E-02
Neon	1.80E-03	1.30E-03
Helium	5.00E-04	7.00E-05
Krypton	1.00E-04	3.00E-04
Xenon	8.00E-06	4.00E-05
Hydrogen	5.00E-05	3.00E-06
Ozon	1.00E-06	2.00E-06

Henry's law constant for solubility of gases in water, $H_s = \frac{p_i}{x_i}$

	Nitrogen	Oxygen	Air	Hydrogen	CO_2
$T\,^{\circ}C$	10^9 Pa	10^9 Pa	10^9 Pa	10^9 Pa	10^7 Pa
0	5.36	2.58	4.38	5.87	7.62
5	6.05	2.95	4.95	6.16	9.61
10	6.77	3.31	5.59	6.44	10.9
15	7.48	3.69	6.15	6.7	12.8
20	8.15	4.06	6.73	6.92	14.8
25	8.77	4.44	7.3	7.16	17.1
30	9.36	4.81	7.81	7.38	19.5
35	9.98	5.14	8.34	7.52	
40	10.5	5.42	8.82	7.61	24.5
45	11	5.71	9.23	7.7	
50	11.5	5.96	9.59	7.75	29.8
60	12.2	6.37	10.2	7.75	35.7
80	12.8	6.96	10.8	7.65	
90	12.8	7.08	10.9	7.61	
100	12.8	7.1	10.8	7.55	

Diffusion coefficients of gases in water

Gas	Temperature ($^{\circ}C$)	Diffusion coefficient (10^{-9} m^2/s)
Ammonia	20	1.46
CO_2	21.7	1.60
Nitrogen	25	2.34
Oxygen	21	2.33

Diffusion coefficients of gases and vapors in air

Gas	Diffusion coefficient (10^{-9} m^2/s)
Ammonia	28
CO_2	16.4
Ethanol	11.9
Oxygen	20.6
Water	25.6

metals

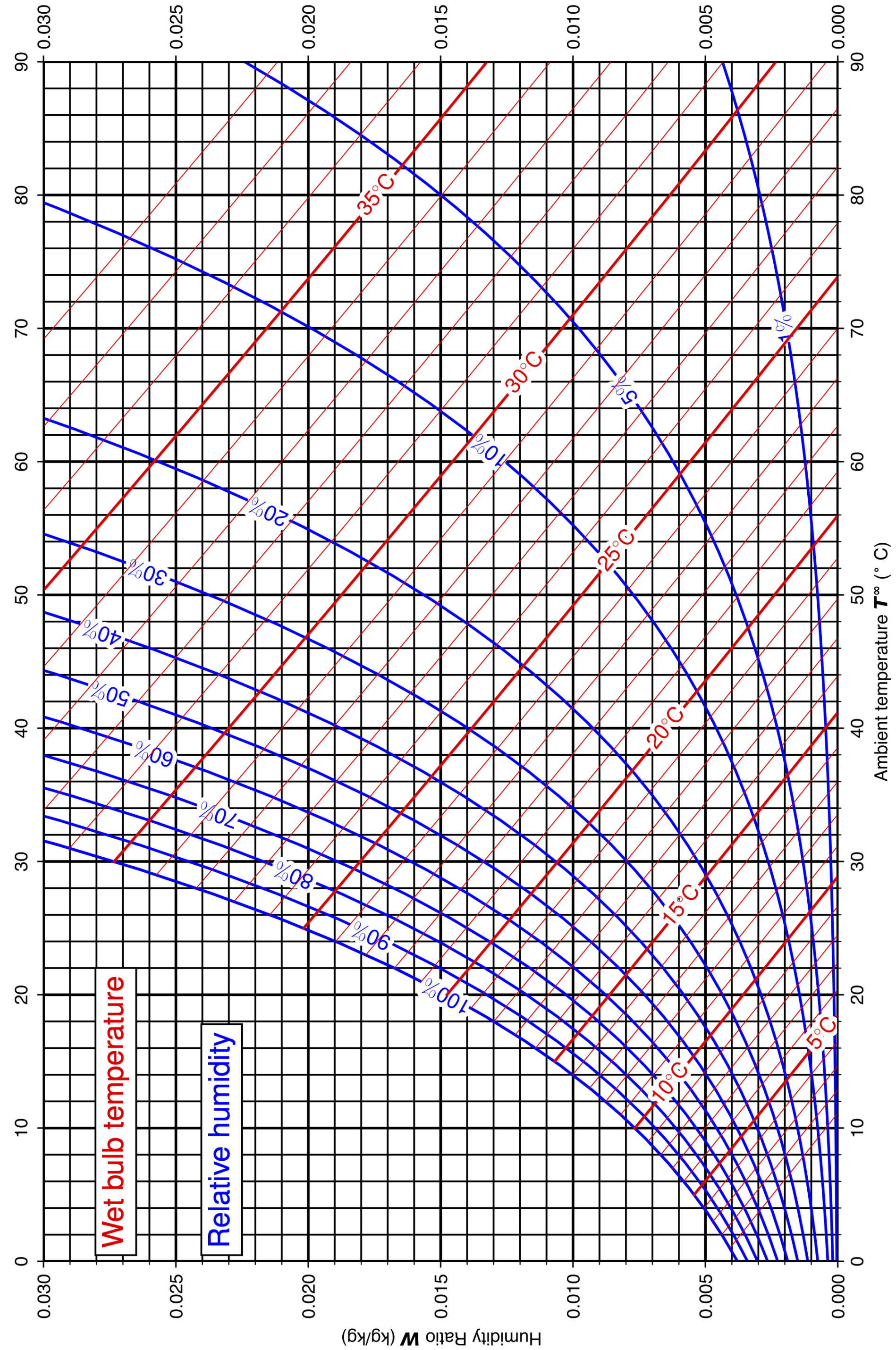
Name	T $(^{\circ}C)$	ρ (kg/m^3)	C_p $(J/(kg.K))$	λ $(W/(m.K))$	a $(10^{-6} m^2/s)$	α $(10^{-6} m/(m.K))$	T_{melt} $(^{\circ}C)$
Aluminium	20	2700	945	238	93.4	24	660
Austenitic steel	20	7900	470	14.5	3.9	15.6	1350 - 1400
Beryllium	20	1848	1780	180	54.7	12	1287
Bismuth	20	9800	129	8.4	6.6	13.3	271
Bronze	20	8800	377	61.7	18.6	17.8	870 - 950
Cadmium	100	8640	246	94.2	44.3	30	321
Carbon steel	20	7860	483	52	13.7	12	1425 - 1460
Cesium	20	1870	242	35.9	79.3	97	28
Chromium	20	7100	474	88.6	26.3	7	1907
Cobalt	20	8780	427	69.1	18.4	12	1495
Constantan	20	8900	410	22.6	6.19	15	1225 - 1300
Copper	20	8960	385	401	116	16.2	1085
Duralumin	20	2790	912	165	64.8	23	500 - 650
Gallium	20	5910	371	41	18.7	18	29.8
Gold	20	19290	128	310	125	14.2	1064
Indium	20	7280	239	81.8	47	33	157
Iridium	20	22400	133	147	49.3	6.4	2446
Iron	20	7870	456	75	20.9	12	1538
Lead	20	11340	127	35	24.3	28.9	327
Lithium	20	534	3570	85	44.5	46	180.5
pearlitic steel	20	7800	486	10.6	10.6	12.5	1400 - 1450
Magnesium	20	1740	1050	159	87	26	650
Manganese	20	7476	477	7.8	2.2	23.6	1246
Mercury	20	13545	139	8.7	4.6	60.4	-39
Molybdenum	20	10200	272	147	53	5	2623
Nickel	20	8900	450	92	23	13.2	1455
Niobium	20	8570	267	52.3	22.9	7	2477
Palladium	20	11970	242	71.2	24.6	11.8	1554
Platinum	20	21500	133	71.2	24.9	8.9	1768
Plutonium	20	19840	130	6.7	2.6	54	639
Potassium	20	860	760	100	153	83	63.5
Rhenium	20	21020	138	48.1	16.6	6.7	3186
Rhodium	20	12500	246	151	49.1	8	1964
Silver	20	10500	235	429	174	19.3	961.8
Sodium	20	970	1234	130	112	70	97.8
Tantalum	20	16500	142	57.5	24.5	6.5	3017
Thorium	25	11720	118	37	26.7	6.5	1750
Tin	20	7290	221	62.8	39	29	232
Titanium	20	4500	522	21.9	9.32	8.5	1668
Tungsten	20	19000	138	174	66.4	4.5	3422
Uranium	500	18600	174	30	9.26	13.4	1132
Vanadium	50	6120	498	31	10.2	8	1910
Wood’s metal	20	9730	147	12.8	8.96	20	70 - 80
Zinc	20	7130	385	113	41.2	30	419.5
Zirconium	70	6500	290	22.7	12	5.7	1855

other solid materials

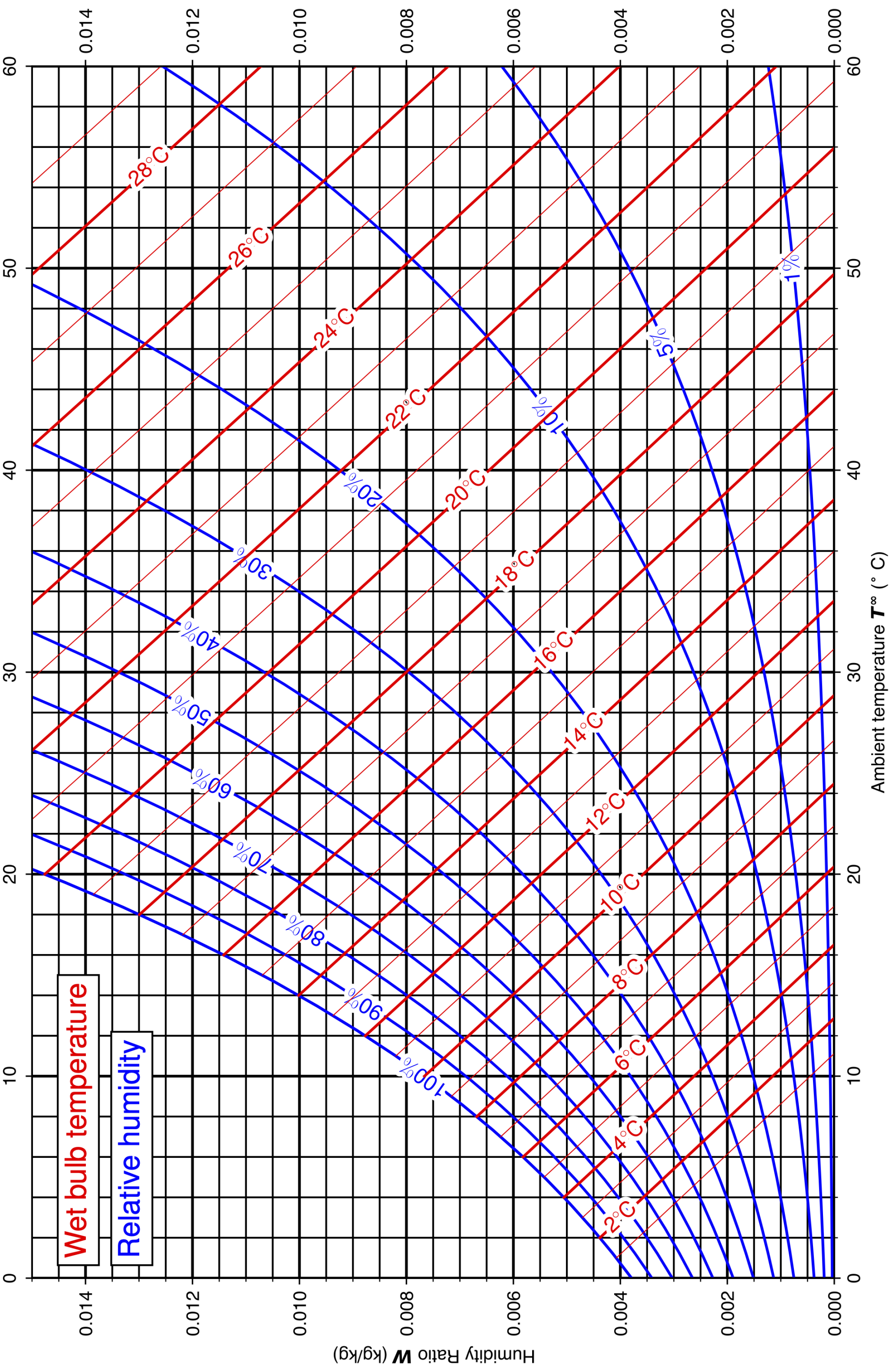
Name	T $(^{\circ}C)$	ρ (kg/m^3)	C_p $(J/(kg.K))$	λ $(W/(m.K))$	a $(10^{-6} m^2/s)$
Asbestos cardboard	20	900	816	0.16	0.22
Asbestos fiber	50	470	820	0.11	0.29
Asphalt	20	2120	-	0.7	0.19
Bakelite	20	1270	1590	0.23	0.114
Cement	20	1900	1130	0.3	0.14
Cement mortar	20	1900	800	0.93	0.61
Chalk stone	20	2000	880	0.93	0.53
Coal (brown)	20	1200	1260	0.26	0.18
Concrete	20	2200	879	1.28	0.66
Cotton	30	80	1150	0.059	0.63
Glass-wool	0	200	660	0.037	0.28
Granite	20	2750	890	2.9	1.2
Graphite (natural)	20	1700	710	100	0.83
Ground (compact)	20	1900	1150	1.5	0.69
Ice	0	917	2040	2.25	1.2
Laminated cloth	20	1350	1500	0.28	1.38
Lead glass	20	2890	680	0.8	0.4
Lime-sand brick	20	1900	840	0.81	0.51
Mineral wool	50	200	920	0.046	0.25
Paper	20	700	1200	0.12	0.14
Paper laminate	25	1350	1420	0.23	0.12
Paraffin	30	925	2260	0.27	0.13
Polyethylene	25	930	2500	0.28	0.12
Polystyrene	20	1050	1250	0.14	0.107
Polyurethane	20	1200	2090	0.32	0.128
Polyvinyl chloride	20	1380	960	0.15	0.113
Porcelain ware	25	2200	900	1	0.5
Quartz	20	2500	780	1.4	0.72
Quartz glass	20	2210	730	1.4	0.87
Red brick	20	1800	890	0.77	0.49
Reinforced concrete	20	2200	840	1.5	0.81
Sand	20	1500	1020	0.5	0.33
Slag concrete	0	1500	750	0.87	0.77
Slag-wool	25	200	800	0.05	0.31
Snow (dense)	0	350	2100	0.35	0.48
Snow (recent)	0	200	2100	0.1	0.24
Sponge rubber	20	250	2050	0.06	0.12
Sulfur	20	2070	720	0.27	0.18
White rubber	20	1100	1670	0.16-0.23	0.087-0.095
Window glass	20	2480	800	1.16	0.58
Wood (pine)	20	550	2700	0.16	0.1

Mollier Diagrams

Large range



Detailed range



Other

Physical constants

Name	Symbol	Value	Unit
Gas constant	R	8.314463	$J/(mol.K)$
Avogadro number	N_A	6.022045×10^{23}	mol^{-1}
Gravitational acceleration	g	9.81	m/s^2
Stefan Boltzmann constant	σ	5.67032×10^{-8}	$W/(m^2 K^4)$
Boltzmann constant	k	1.380662×10^{-23}	J/K

Unit conversions

Symbol	Quantity	Expressed in	→	Values	←	SI unit
p	Pressure	psi	×	6.89×10^3	÷	Pa or N/m^2
		atm	×	1.1013×10^5	÷	
		bar	×	10^5	÷	
		$mm\ Hg$	×	1.33×10^2	÷	
μ	Dynamic viscosity	cP (centiPoise)	×	10^{-3}	÷	$Pa.s$
T	Temperature	^oC	+	273.15	-	K
		^oF	$\div 1.8 + A$	$A = 255.37$	$\times 1.8 + B$	
				$B = -459.67$		

References

The majority of the information presented in this reference book consists of very general knowledge. Some information, however, is more specific and can be attributed to the references provided below.

The following sections use data from: *Handbook of hydraulic resistance, I.E. Idel'chik, Israel Program for Scientific Translations Ltd. (1966)*:

page 10	**sharp and smooth bends (**$Re > 3 \times 10^5$**)**
page 11	**sudden expansion and contraction**
page 12	**sharp-edged orifices (thickness <1.5% of** D_h**)**
page 14	**diffusors and contractions (**$Re \equiv w_0 D_h / \nu > 10^4$**)**
page 15	**circular or square pipe entrances and exits**

The following sections use formulas as proposed in: *Energy losses at 90° pipe junctions, Itō, H. and Imai, K., Journal of the Hydraulics Division, vol. 99, pages 1353–1368 (1973)*:

page 13	**converging and diverging T-junctions (**$Re \equiv w_3 D / \nu > 10^5$**)**

The following sections contain fluid and gas properties calculated by the CoolProp library (`www.coolprop.org`). Details of this library can be found in *Pure and Pseudo-pure Fluid Thermophysical Property Evaluation and the Open-Source Thermophysical Property Library CoolProp, Bell, I. H., Wronski, J., Quoilin, S. and Lemort, V., Industrial & Engineering Chemistry Research, vol. 53, pages 2498–2508 (2014)*

page 27	**water at** $p = 10^5\ Pa$
page 28	**air at** $p = 10^5\ Pa$
page 29	**other fluids and gases at** $p = 10^5\ Pa$**,** $T = 20\,^{\circ}C$
page 37	**Mollier Diagrams**

Graphs, Formulas and Tables relevant to Transport Phenomena

Martin Rohde

This book provides relevant information required during BSc-level courses on Transport Phenomena, encompassing micro- and macroscopic balances, correlations for friction, heat transfer and species transport and material properties. The information comes in handy during exercise classes and written exams.

Martin Rohde
Delft University of Technology
Faculty of Applied Sciences

Martin Rohde studied Chemical Engineering at the University of Groningen. In 2004 he earned his PhD at the Kramers Laboratory of the Delft University of Technology, a renowned institution where the field of Transport Phenomena was pioneered in the late 1950s by Prof. Hans Kramers and visiting professor Robert B. Bird. After completing his PhD, Martin Rohde joined the Delft University of Technology as a scientific staff member where he has been teaching and performing research in the field of Transport Phenomena in energy and health applications.

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