EQUATIONS, CHARTS AND TABLES FOR MASS TRANSFER

All equations are in SI units, unless differently stated below the equations

LIST OF SYMBOLS
(meaning of symbols are the following unless stated differently below the equation)

A	surface area, m^2
a	activity, -
c	concentration, mol/m^3
c_p	specific heat at constant pressure, $J/molK$ or J/kgK
$c_{p,h}$	specific heat of humid air at constant pressure, $J/kg_{d.a.}K$
d	diameter, m
D_{AB}	diffusion coefficient between components A and B, m^2/s
D_{AK}	Knudsen diffusion coefficient of component A, m^2/s
$D_{AK,eff}$	effective Knudsen diffusion coefficient of component A, m^2/s
D_{eff}	effective diffusion coefficient, m^2/s
Gr	Grashof number, -
g	acceleration due to gravity = 9.807 m/s^2
H	enthalpy, J
$\dot{H}$	enthalpy flow rate, W
h	specific enthalpy, J/kgK or J/molK
h_h	specific enthalpy of humid air, $J/kg_{d.a.}$
J	molar flux, mol/m^2s mol/m^2s
j	molar diffusion flux, mol/m^2s
Kn	Knudsen number, -
k	mass transfer coefficient, m/s
k'	mass transfer coefficient corresponding to equimolar diffusion ($J_A=-J_B$), m/s
k_B	Bolzmann’s constant = $1.381 \cdot 10^{-23}$ J/K
k_p	permeability (Darcy’s law), m^2
Le	Lewis number, -
l	1. heat of evaporation, J/mol or J/kg 2. length or characteristic length, m
l_0	heat of evaporation of non-bound liquid, J/mol or J/kg
M	molar mass, kg/mol
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
N	mass flux, kg/m^2s
n	amount of substance, mol,
Pe	Péclet number, -
Pr	Prandtl number, -
p	pressure, Pa or bar
p_A	partial pressure of component A, Pa or bar
p_A'	partial pressure of saturated component A, Pa or bar
q	heat flux, W/m^2
R	universal gas constant = 8.314 J/molK
Ra	Rayleigh number, -

Re	Reynolds number, -
r	1. sorption heat, J/mol; J/kg
	2. radius,m
	3. mass transfer resistance, m^{2}sPa/kg
s	real path length, m
S	term for formation of a component, kg/m^{3}s or mol/m^{3}s
Sc	Schmidt number, -
Sh	Sherwood, -
T	temperature, K
t	1. time, s
	2. temperature, °C
t_{wb}	wet bulb temperature, °C
V	volume, m^3
v	velocity, m/s
w_r	moisture content/ratio for porous materials, $kg_{H_2O} / kg_{d.a.}$
x	1. molar fraction, -
	2. humidity of wet air/gas, $kg_{H_2O} / kg_{d.a.}$
y	molar fraction in gas phase, -
z	coordinate, m

α	convective heat transfer coefficient, $\mathrm{W / m^2 K}$
γ	surface tension, J/m^2, N/m
η	dynamic viscosity, kgm^{-1}s^{-1}
φ	relative vapor pressure, -
λ	thermal conductivity, W/mK
λ_m	mean free path, m
ν	kinematic viscosity, $\mathrm{m^2 / s}$
ρ	density, kg/m^3
σ_{ii}	collision diameter, m
τ	tortuosity, -
ξ	activity coefficient, -
$\varnothing$	heat transfer rate/power, W
Φ	porosity (void fraction, volume fraction), -

Subscripts

A, B	components (usually binary mixture)
i	component (when the number of components is not limited of defined)
d.a.	dry air
eff	effective
h	vapor
ref	reference
wg	wet gas

MIXTURE THERMODYNAMICS

Ideal gases

$$p_iV = n_iRT \qquad n_i = \frac{m_i}{M_i} \qquad \rho_i = \frac{p_iM_i}{RT} \qquad \rho = \sum_i \rho_i \;\; p = \sum_i p_i \;\; \rho = \sum_i \rho_i \qquad p = \sum_i p_i$$

$$y_i = \frac{p_i}{p}.$$

Wet ideal gases (subscript wg, component A is volatile and B non-volatile)

$$x = \frac{m_A}{m_B} = \frac{\rho_A}{\rho_B} = \frac{M_A}{M_B}\frac{p_A}{p - p_A} \qquad p_A = \frac{x}{\frac{M_A}{M_B} + x}p$$

$$h_{wg} \equiv \frac{H}{m_B} \qquad h_{wg} = h_B + xh_A \qquad h_{wg} = c_{pB}(T - T_{ref}) + x\left(l_{A,ref} + c_{pA}(T - T_{ref})\right)$$

$$\dot{H} = \dot{m}_B h_{wg}$$

Humid air (v=water vapor, da = dry air, h = humid air)

$$x = 0.6220\frac{p_v}{p - p_v} \qquad p_v = \frac{x}{0.6220 + x}p \qquad \phi \equiv \frac{p_v}{p_v'(T)}$$

M_{da} = 0.02896 kg/mol ja M_v = 0.01802 kg/mol

,

h_h = 1.006 t + x(2501 + 1.85 t) , kJ/$kg_{d.a.}$

Wet bulb temperature

$$t - t_{wb} = l(t_{wb})\frac{M_v}{\rho c_p}\frac{p}{RT}Le^{1-n}\ln\left(\frac{p - p_v}{p - p_v'(t_{wb})}\right),$$

Solutions

Ideal solution (Raoult law) $p_i = x_i p_i' \; p_i = x_i p_i'$

p_i = the partial pressure of gas component i

p_i' = vapor pressure of pure liquid i

x = molar fraction in solution.

Henry's law: $p_i = K_i x_i$

K_i = Henry law constant, Pa

x = molar fraction in a solution

DIFFUSION AND ADVECTION

Fick's diffusion law $j_A = -D_{AB}\frac{\partial c_A}{\partial z}$ *Fick's 2nd law*: $\frac{\partial c_A}{\partial t} = D_{AB}\frac{\partial^2 c_A}{\partial z^2} + S_A$

$\mathbf{J_i} = c_i \mathbf{v_i}$ $\mathbf{J} = \sum_i \mathbf{J_i} = c\mathbf{v}$ $\mathbf{j_i} = c_i(\mathbf{v}_i - \mathbf{v})$ $\mathbf{J_i} = c_i\mathbf{v} + \mathbf{j_i}$ $c\mathbf{v} = \sum_i c_i \mathbf{v_i}$

$\sum_i \mathbf{j_i} = 0$ $D_{AB} = D_{BA}$ $\mathbf{N}_i = \rho_i \mathbf{v_i}$

Binary mixture when **v** = 0: $\mathbf{J_A} = -\mathbf{J_B}$

Diffusion + advection (1D)

$J_A = c_A v - D_{AB}\frac{dc_A}{dz}$ $J = cv = J_A + J_B$.

Steady state solutions:

$$J_A = v\left(\frac{c_{A2} - c_{A1}e^{\frac{vL}{D_{AB}}}}{1 - e^{\frac{vL}{D_{AB}}}}\right) \qquad J_B = v\left(\frac{c_{B2} - c_{B1}e^{\frac{vL}{D_{AB}}}}{1 - e^{\frac{vL}{D_{AB}}}}\right)$$

Stefan flow $J_B = 0$

$$\mathbf{J_A} = \frac{\mathbf{j_A}}{x_B}$$

steady state solution:

$$J_A = cv = \frac{D_{AB}c}{L}\ln\left(\frac{c_{B2}}{c_{B1}}\right)$$

HEAT AND MASS TRANSFER ANALOGY

$q = -\lambda \left.\frac{\partial T}{\partial z}\right|_{z=0}$ -> $J_A = -D_{AB}\left.\frac{\partial c_A}{\partial z}\right|_{z=0}$

Nu->Sh Pr->Sc Re does not change

DIFFUSION COEFFICIENTS

Gas mixtures: $D_{AB} = 0.0101\frac{T^{1.75}(1/M_A + 1/M_B)^{1/2}}{p\left[(\Sigma v_A)^{1/3} + (\Sigma v_B)^{1/3}\right]^2}$

Note units! M = [g/mol], p = [Pa], T = [K]

	Σv		Σv
H_2	7.07	CO	18.9
He	2.88	CO_2	26.9
N_2	17.9	NH_3	14.9
O_2	16.6	H_2O	12.7
Air	20.1	SO_2	41.1
N_2O	35.9		

Liquid mixtures/solutions: Stokes-Einstein equation $D_{AB} = \frac{k_B T}{6\pi\eta r}$

r = radius of the solute
η = dynamic viscosity of the solvent

HEAT TRANSFER

Conduction $q = -\lambda\frac{\partial T}{\partial z}$

Convection (dry heat transfer) $q = \alpha\Delta T$

Heat transferred due to evaporation ("wet" heat transfer) $q = l \cdot N_V$

MASS TRANSFER COEFFICIENT

General definition: $J_A = k\Delta c_A$

$|J_A| >> |J_B|$: $J_A = ck'\ln\left(\frac{c_{B2} - \frac{c}{r}}{c_{B1} - \frac{c}{r}}\right)$ where $r = \frac{J_A}{J_B}$ $r = \frac{J_A}{J_B}$

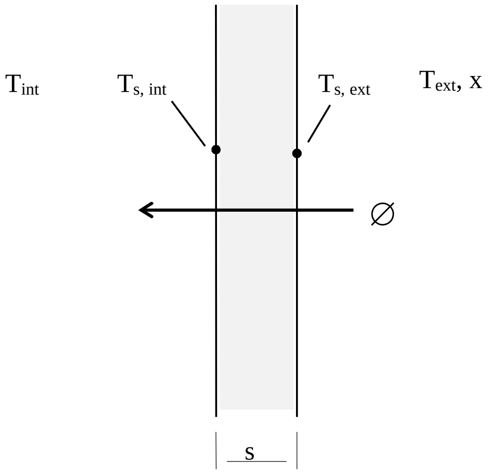
r->∞: $J_A = ck'\ln\left(\frac{c_{B2}}{c_{B1}}\right)$

using analogy and heat transfer coeffcient α

$k' = \frac{\alpha}{\rho c_p}Le^{1-n}$ $\qquad Le = \frac{D_{AB}\rho c_p}{\lambda} = \frac{Pr}{Sc}$

Typically $n \approx 0.33$.

DETERMINATION OF SURFACE TEMPERATURE T_S DURING CONDENSATION OR EVAPORATION ON A WALL THAT SEPARATES TWO FLUIDS



a

$$\eta_{HT}\alpha_{ext}(T_{ext}-T_{s,ext})+\eta_{MT}l(T_{s,ext})M_v\frac{p}{RT_{av}}k'\ln\left(\frac{p-p_v'(T_{s,ext})}{p-p_v}\right)$$

$$-G''(T_{s,ext}-T_{int})=0,$$

$$G''=\frac{A_{int}}{A_{ext}}\cdot\frac{1}{\frac{s}{\lambda}+\frac{1}{\alpha_{int}}}$$

T_{av} = representative temperature at the wet side (as a first approximation, e.g. a dew point can be applied),
λ = thermal conductivity of the wall separating the two fluids
s = thickness of the wall

Subsrcipts: ext = gas at the”wet” side, s = surface, int= fluid at the ”dry” side,

SERIAL RESISTANCES

Heat transfer: $R=\sum_i R_i$ where R_i is a single heat transfer resistance defined as

Ø$=\dfrac{\Delta T_i}{R_i}$

Mass transfer: $r=\sum_i r_i$ where r_i is a single mass transfer resistance defined as

$N_i=\dfrac{\Delta c_i}{r_i}$ or $N_i=\dfrac{\Delta p_i}{r_i}$

THERMAL DIFFUSION

$\mathbf{j_A}=-cD_{AB}\left[\nabla x_A+k_T\dfrac{\nabla T}{T}\right]$ $k_T = D_T/D_{AB}$ $\alpha_T=k_T/x_Ax_B$

D_T = thermal diffusion coefficient (m2/s), k_T = thermal diffusion ratio (-), α_T = thermal diffusion factor

MASS TRANSFER IN POROUS MATERIALS

All fluxes and flows (j,J, N, v') are evaluated per total cross-sectional areas!

No surface effects (modified Fick and diffusion-advection equations)

$$j_A = -D_{eff}\frac{\partial c_A}{\partial z} \qquad D_{eff} = \frac{\Phi}{\tau} D_{AB}$$

$\tau = \frac{s}{z}$, (where s=tortuous path, z = straight distance)

$$J_A = c_A v' - D_{eff}\frac{\partial c_A}{\partial z}$$

Darcy equation for pressure gradient driven flow

$$N = -\frac{k_p}{\nu}\frac{\partial p}{\partial z}$$

ν = kinematic viscosity of fluid

Knudsen diffusion and Dusty gas model

$$Kn = \frac{\lambda_m}{d} \qquad \lambda_m = \frac{k_B T}{\sqrt{2}\,\pi\sigma_{ii}^2 p} \qquad D_{AK} = \frac{d}{3}\sqrt{\frac{8RT}{\pi M_A}}\,.$$

d = radius of a pore or channel, m

σ_{ii} = collision diameter of the molecule (see Table 10), m

$$D_{AK,eff} = \frac{\Phi}{\tau} D_{AK} \qquad j_A = -D_A\frac{\partial c_A}{\partial z} + x_A\left[D_A / D_{eff}\right] j \qquad \frac{1}{D_A} = \frac{1}{D_{AK,eff}} + \frac{1}{D_{eff}}$$

CAPILLARY PRESSURE

$$\Delta p_{kap} = p - p_2 = \frac{2\gamma\cos\theta}{r}$$

p_2 pressure of liquid just below the surface, Pa

p total pressure of gas above the surface, Pa

γ surface tension, J/m^2

θ angle between the liquid and solid surface

R radius of the tube, m

PROPERTIES OF BOUND WATER

Sorption heat for paper

$$r = r_{s0}\left(\frac{T}{T_{cr}}\right)\left(1-\frac{T}{T_{cr}}\right)^{r_T}\exp\left(-r_u\frac{w_r}{w_{r,max}}\right) \qquad w_r \equiv \rho_{2p}/\rho_{1p}\,,$$

$r_{s0} = 6.051 \cdot 10^4 \, \mathrm{kJ/kg}$, $r_u = 30.05$, $r_T = 5.06$ $w_{r,max} = 1.581$.   ,

Relative vapor pressure in paper

$$\ln \varphi = \ln \varphi_o \cdot \left(\frac{w_{r,max}}{w_r} \right) \left(1 - \frac{T}{T_{cr}} \right)^{\varphi_T} \exp\left(-\varphi_w \frac{w_r}{w_{r,max}} \right)$$

$\varphi_T = \varphi_T = 5.144$, $\ln \varphi_o = \ln \varphi_o = -1.856$, $\varphi_w = \varphi_w = 3.475$.

OSMOSIS AND REVERSE OSMOSIS

Osmotic pressure

$$\pi_0 = -\frac{RT}{v} \ln a,$$

π_0 = osmotic pressure, Pa

$a = \xi x$ = activity of solvent, -

ξ activity coefficient, -

v = molar volume of solvent, m^3/mol

If the amount of dissolved substance is small, the solution can be considered as ideal: $\pi_0 = c_s RT$ where c_s is the concentration of dissolved substances (take into account the dissociation of ions!)

Osmotic mass transfer through membranes

Volume flux of solvent (e.g. water) ($m^3/s/m^2_{membrane}$):

$$v' = L_p \left[\Delta p - \sigma \Delta \pi_0 \right]$$

Δp and $\Delta \pi_0$ Δp and $\Delta \pi_0$ are the transmembrane pressure (Pa) and osmotic pressure (Pa) differences, respectively.

σ	reflection coefficient (for an ideal membrane σ=1), -
L_p	filtration coefficient, m/sPa

SOLUTION-DIFFUSION MODEL FOR NON-POROUS MEMBRANES

$$J_i = b_i \frac{\Delta c_i}{s}$$

$$b_i = H_i D_i$$

$$\alpha_{ij} = \frac{b_i}{b_j} = \frac{D_i}{D_j} \frac{H_i}{H_j}$$

b_i = permeability, m^2/s

H_i = solubility of component i in the membrane material, -

s = thickness of the membrane, m

D_i = diffusion coefficient of component i in the membrane, m^2/s

α_{ij} = selectivity of the membrane between components i and j (α_{ij} >1), -

Table 1. Molar masses of elements.

	M (g/mol)		M (g/mol)
Al	26.98	H	1.01
C	12.01	He	4.00
Ca	40.08	N	14.01
Cl	35.45	Na	22.99
Cu	63.55	O	16.00
Fe	55.85	S	32.06

Table 1.3 Henry law constants at 298 K.

Gas	Water as solvent (MPa)	Benzene as a solvent (MPa)
H_2	7120	367
CH_4	41.9	56.9
N_2	8680	239
CO_2	167	11.4
O_2	4400	

Table 1.1. Properties of saturated air at an atmospheric pressure.

Tempera-ture °C	humidity kg_{H2O} / $kg_{dry\ air}$	Partial pressure of water vapor kPa	Partial density of water vapor kg_{H2O} / m^3	Partial density of dry air $kg_{dry\ air}$ /m^3	Specific enthalpy of mixture $kJ/kg_{dry\ air}$	Specific heat of mixture $J/kg_{dry\ air}K$
0	0.003821	0.6108	0.004846	1.285	9.55	1010.8
2	0.004418	0.7054	0.005557	1.275	13.06	1012.0
4	0.005100	0.8129	0.006358	1.264	16.39	1013.4
6	0.005868	0.9346	0.007257	1.254	20.77	1014.9
8	0.006749	1.0721	0.008267	1.243	25.00	1016.7
10	0.007733	1.2271	0.009396	1.232	29.52	1018.6
12	0.008849	1.4015	0.01066	1.221	34.37	1020.8
14	0.010105	1.5974	0.01206	1.211	39.57	1023.3
16	0.011513	1.8168	0.01363	1.199	45.18	1026.0
18	0.013108	2.062	0.01536	1.188	51.29	1029.1
20	0.014895	2.337	0.01729	1.177	57.86	1032.5
22	0.016892	2.642	0.01942	1.165	65.02	1036.4
24	0.019131	2.982	0.02177	1.154	72.60	1040.7
26	0.021635	3.360	0.02437	1.141	81.22	1045.5
28	0.024435	3.778	0.02723	1.129	90.48	1050.9
30	0.027558	4.241	0.03036	1.116	100.57	1056.9
32	0.031050	4.753	0.03380	1.103	111.58	1063.5
34	0.034950	5.318	0.03758	1.090	123.72	1071.0
36	0.039289	5.940	0.04171	1.076	136.99	1079.3
38	0.044136	6.624	0.04622	1.061	151.60	1088.5
40	0.049532	7.375	0.05114	1.046	167.64	1098.9
42	0.055560	8.198	0.05650	1.030	185.40	1110.3
44	0.062278	9.010	0.06233	1.014	204.94	1123.2
46	0.069778	10.085	0.06867	0.997	226.55	1137.5
48	0.078146	11.161	0.07553	0.9791	250.45	1153.4
50	0.087516	12.335	0.08298	0.9606	277.04	1171.3
52	0.098018	13.613	0.09103	0.9411	306.64	1191.3
54	0.10976	15.002	0.09974	0.9207	339.51	1213.7
56	0.12297	16.509	0.1091	0.8999	373.31	1238.9
58	0.13790	18.146	0.1193	0.8768	417.72	1267.3
60	0.15472	19.92	0.1302	0.8532	464.11	1299.4
62	0.17380	21.84	0.1419	0.8283	516.57	1335.7
64	0.19541	23.91	0.1545	0.8021	575.77	1377.0
66	0.22021	26.14	0.1680	0.7746	643.51	1424.1
68	0.24866	28.55	0.1826	0.7456	721.01	1478.2
70	0.28154	31.16	0.1981	0.715	810.36	1541.8
72	0.31966	33.96	0.2146	0.6829	915.57	1613.2
74	0.36468	36.96	0.2324	0.6489	1035.6	1698.6
76	0.41790	40.19	0.2514	0.6132	1179.42	1799.4
78	0.48048	43.65	0.2717	0.5755	1348.40	1919.9
80	0.55931	47.36	0.2933	0.5358	1560.80	2066.4
82	0.65573	51.33	0.3162	0.4939	1820.46	2247.7
84	0.77781	55.57	0.3406	0.4497	2148.92	2476.7
86	0.93768	60.5	0.3666	0.4031	2578.73	2773.9
88	1.15244	64.95	0.3942	0.3542	3155.67	3170.8
90	1.45873	70.11	0.4235	0.3026	3978.42	3730.4
92	1.92718	75.61	0.4545	0.2482	5236.61	4574
94	2.73170	81.46	0.4873	0.1909	7395.49	5987
96	4.42670	87.69	0.5221	0.1305	11944.39	8820
98	10.30306	94.3	0.5588	0.06694	27711.34	17338
100	∞ ∞	101.325	0.5977	0.000	∞ ∞	∞ ∞

Table 1.1 (continues).

Temp °C	Evaporation heat of water kJ/kg	Kinematic viscosity 10^{-6} m^2/s	Diffusion coefficient water-air 10^{-6} m^2/s	Thermal conductivity W/mK
0	2500.8	13.25	22.2	0.02380
2	2495.9	13.43	22.4	0.02413
4	2491.3	13.61	22.6	0.02427
6	2486.6	13.79	22.8	0.02440
8	2481.9	13.97	23.1	0.02454
10	2477.2	14.15	23.3	0.02466
12	2472.5	14.34	23.6	0.02478
14	2467.8	14.52	23.9	0.02490
16	2463.1	14.71	24.2	0.02500
18	2458.4	14.89	24.5	0.02511
20	2453.1	15.08	24.8	0.02520
22	2449.0	15.27	25.2	0.02529
24	2442.0	15.46	25.5	0.02537
26	2439.5	15.65	25.9	0.02544
28	2434.8	15.84	26.3	0.02548
30	2430.0	16.03	26.6	0.02556
32	2425.3	16.22	27.0	0.02561
34	2420.5	16.41	27.4	0.02565
36	2415.8	16.61	27.8	0.02567
38	2411.0	16.80	28.3	0.02569
40	2406.2	17.00	28.7	0.02569
42	2401.4	17.20	29.1	0.02568
44	2396.6	17.39	29.6	0.02566
46	2391.8	17.59	30.0	0.02563
48	2387.0	17.79	30.5	0.02558
50	2382.1	17.99	30.9	0.02552
52	2377.3	18.19	31.4	0.02545
54	2372.4	18.39	31.9	0.02536
56	2367.6	18.59	32.4	0.02526
58	2362.7	18.79	32.9	0.02514
60	2357.9	18.99	33.4	0.02501
62	2353.0	19.19	34.0	0.02487
64	2348.1	19.38	34.5	0.02471
66	2343.1	19.57	35.1	0.02455
68	2338.2	19.76	35.7	0.02437
70	2333.3	19.94	36.3	0.02418
72	2328.3	20.10	36.9	0.02399
74	2323.3	20.28	37.6	0.02379
76	2318.3	20.44	38.3	0.02360
78	2313.3	20.58	39.0	0.02341
80	2308.3	20.71	39.8	0.02323
82	2303.2	20.81	40.7	0.02307
84	2298.1	20.90	41.5	0.02294
86	2293.0	20.96	42.5	0.02285
88	2287.9	20.99	43.6	0.02281
90	2282.8	20.99	44.7	0.02283
92	2277.6	20.94	46.0	0.02295
94	2272.4	20.84	47.4	0.02318
96	2267.1	20.69	49.0	0.02355
98	2261.9	20.47	50.8	0.02409
100	2256.7	20.08	52.8	0.02486

Table 1.2. Thermodynamic properties of dry air at 1 bar.

t °C	ρ kg/m^3	ν 10^{-6} m^2/s	c_p kJ/kgK	h kJ/kg	λ 10^{-3} W/mK	Pr
-180	3.852	1.67	1.073	90.509	8.59	0.804
-160	3.126	2.51	1.037	111.53	10.41	0.782
-140	2.639	3.49	1.021	132.11	12.22	0.770
-120	2.287	4.58	1.014	152.42	14.00	0.759
-100	2.019	5.80	1.011	172.68	15.77	0.751
-80	1.807	7.13	1.009	192.87	17.50	0.743
-60	1.636	6.57	1.008	213.02	19.20	0.564
-40	1.495	10.11	1.007	233.14	20.89	0.729
-20	1.377	11.73	1.006	253.27	22.50	0.722
0	1.275	13.45	1.006	273.41	24.08	0.716
20	1.188	15.27	1.006	293.54	25.61	0.713
40	1.112	17.15	1.007	313.68	27.08	0.709
60	1.045	19.13	1.009	333.84	28.48	0.708
80	0.9859	21.18	1.010	354.02	29.91	0.705
100	0.9329	23.29	1.012	374.23	31.26	0.703
120	0.8854	25.50	1.014	394.48	32.59	0.702
140	0.8425	27.76	1.017	414.78	33.92	0.701
160	0.8035	30.09	1.020	435.14	35.24	0.700
180	0.7681	32.51	1.023	455.55	36.53	0.699
200	0.7356	34.94	1.026	476.03	37.82	0.697
220	0.7058	37.46	1.029	496.58	39.07	0.696
240	0.6783	40.06	1.033	517.2	40.34	0.696
260	0.6528	42.74	1.037	537.9	41.57	0.696
280	0.6292	45.44	1.041	558.69	42.79	0.696
300	0.6072	48.22	1.046	579.56	43.99	0.696
350	0.5585	55.4	1.057	632.13	46.92	0.697
400	0.517	62.9	1.059	685.28	49.83	0.691
450	0.4813	70.7	1.081	739.04	52.50	0.701
500	0.4502	78.8	1.093	793.39	55.45	0.699
550	0.4228	87.2	1.105	848.33	58.20	0.700
600	0.3906	96.0	1.116	903.83	60.93	0.687
650	0.377	105.0		959.88	63.59	
700	0.3577	114.3	1.137	1016.4	65.95	0.705
750	0.3396	124.0		1073.5	68.24	
800	0.3243	133.6	1.155	1131.0	70.5	0.710
850	0.3099	143.6		1188.9	72.7	
900	0.2967	153.7	1.171	1247.3	74.6	0.716
950	0.2846	164.4		1305.9	76.8	
1000	0.2734	175.1	1.185	1355.0	78.7	0.721
1050	0.2631	186.1		1424.4	80.6	
1100	0.2535	197.3	1.198	1484.0	82.5	0.726
1150	0.2446	209		1543.9	84.3	
1200	0.2363	220	1.209	1604.1	86.1	0.730
1250	0.2285	232	-	1664.5	-	-

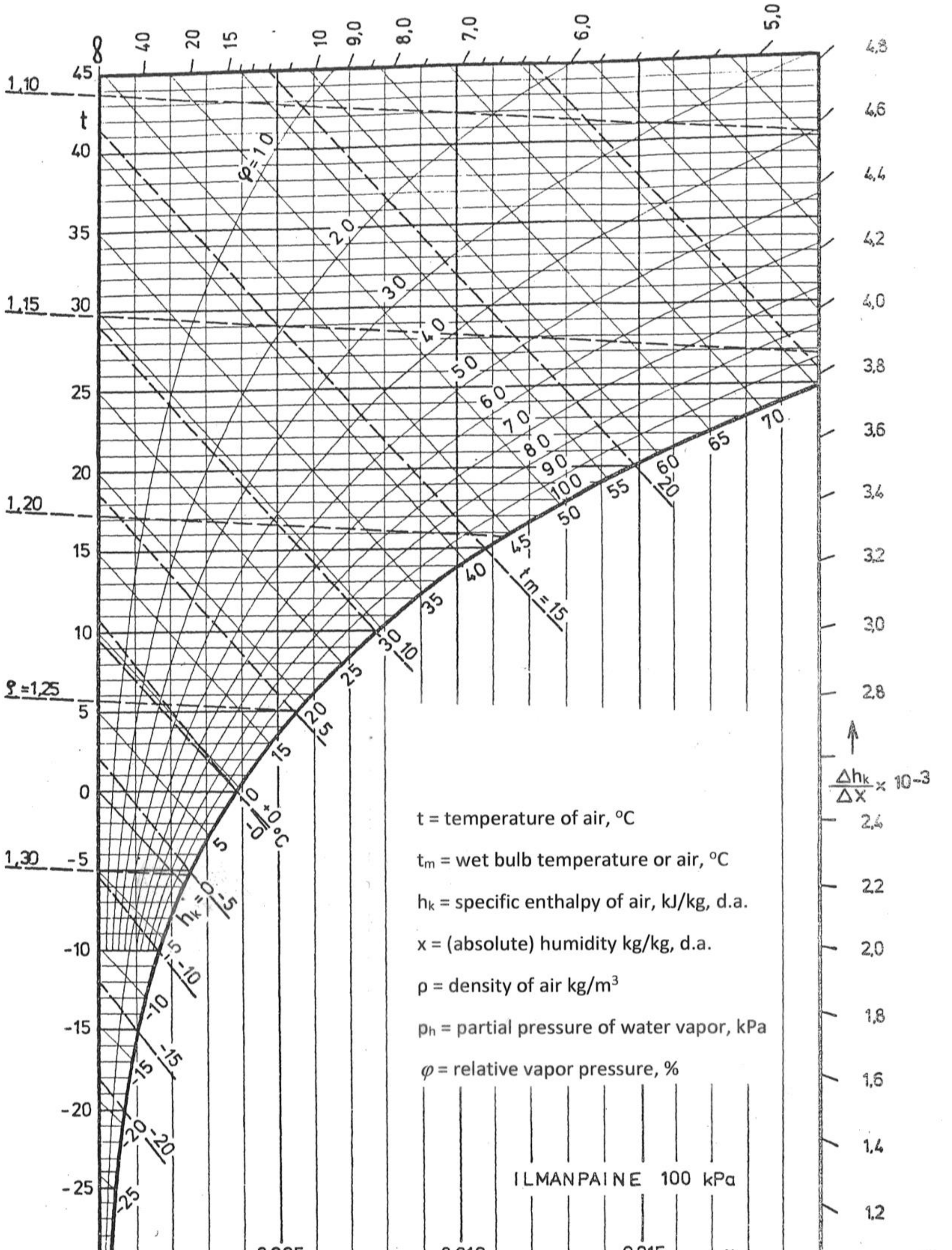
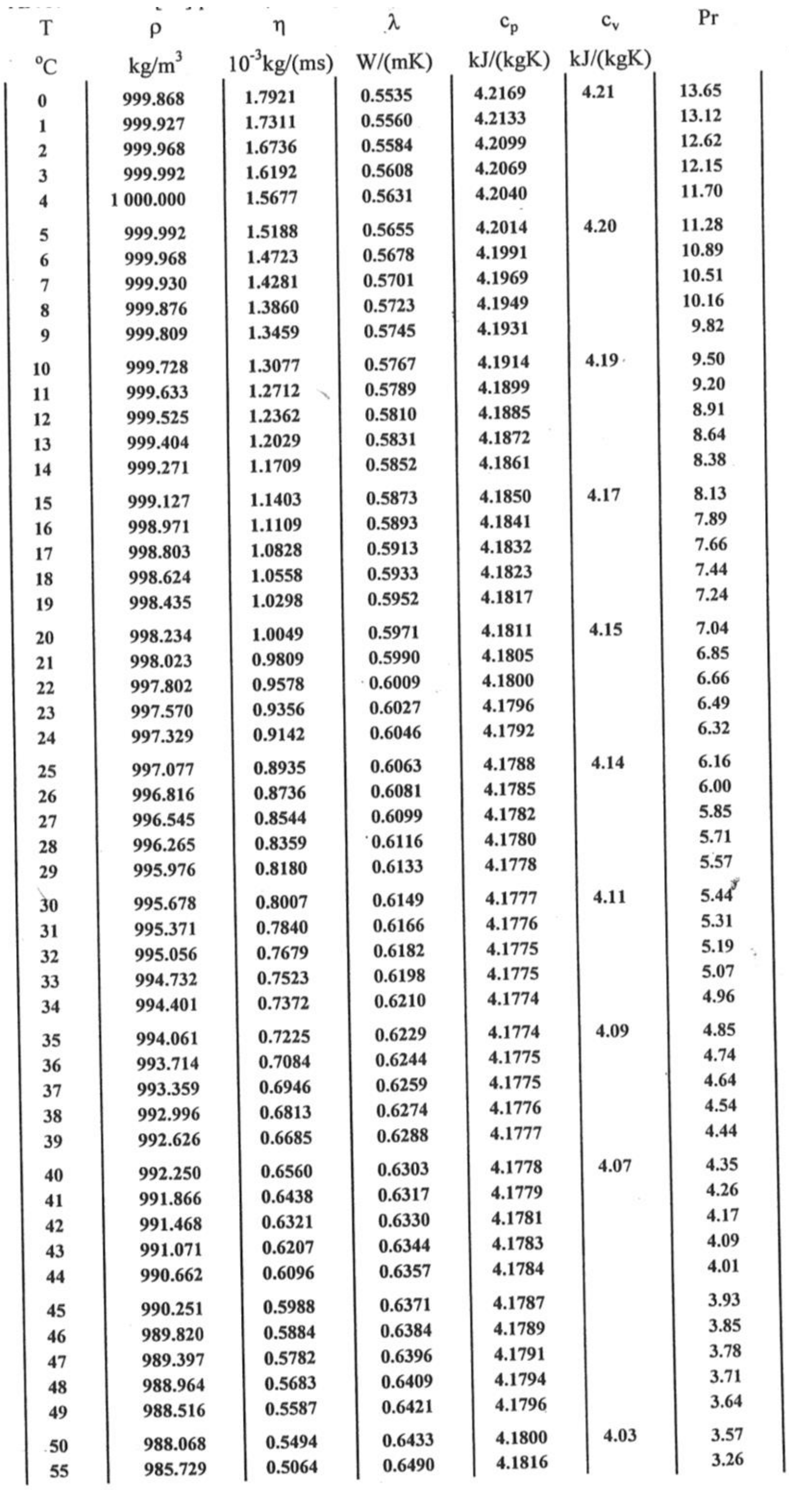


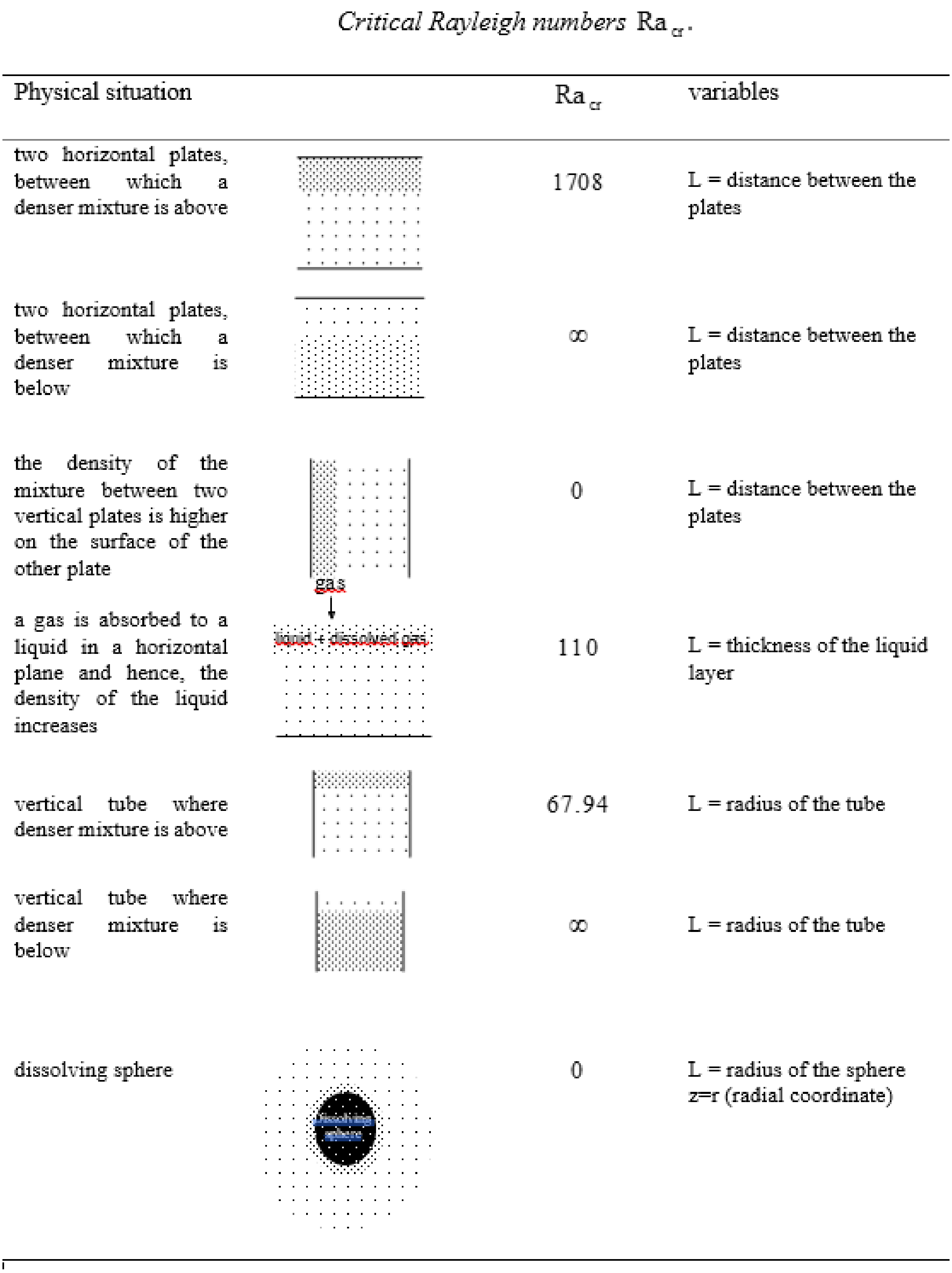
Figure 1.1. Mollier-diagram for humid air at total pressure 100 kPa.

Table 1.3. Properties of water at 1 atm.



T °C	ρ kg/m^3	η 10^{-3}kg/(ms)	λ W/(mK)	c_p kJ/(kgK)	c_v kJ/(kgK)	Pr
0	999.868	1.7921	0.5535	4.2169	4.21	13.65
1	999.927	1.7311	0.5560	4.2133		13.12
2	999.968	1.6736	0.5584	4.2099		12.62
3	999.992	1.6192	0.5608	4.2069		12.15
4	1 000.000	1.5677	0.5631	4.2040		11.70
5	999.992	1.5188	0.5655	4.2014	4.20	11.28
6	999.968	1.4723	0.5678	4.1991		10.89
7	999.930	1.4281	0.5701	4.1969		10.51
8	999.876	1.3860	0.5723	4.1949		10.16
9	999.809	1.3459	0.5745	4.1931		9.82
10	999.728	1.3077	0.5767	4.1914	4.19	9.50
11	999.633	1.2712	0.5789	4.1899		9.20
12	999.525	1.2362	0.5810	4.1885		8.91
13	999.404	1.2029	0.5831	4.1872		8.64
14	999.271	1.1709	0.5852	4.1861		8.38
15	999.127	1.1403	0.5873	4.1850	4.17	8.13
16	998.971	1.1109	0.5893	4.1841		7.89
17	998.803	1.0828	0.5913	4.1832		7.66
18	998.624	1.0558	0.5933	4.1823		7.44
19	998.435	1.0298	0.5952	4.1817		7.24
20	998.234	1.0049	0.5971	4.1811	4.15	7.04
21	998.023	0.9809	0.5990	4.1805		6.85
22	997.802	0.9578	0.6009	4.1800		6.66
23	997.570	0.9356	0.6027	4.1796		6.49
24	997.329	0.9142	0.6046	4.1792		6.32
25	997.077	0.8935	0.6063	4.1788	4.14	6.16
26	996.816	0.8736	0.6081	4.1785		6.00
27	996.545	0.8544	0.6099	4.1782		5.85
28	996.265	0.8359	0.6116	4.1780		5.71
29	995.976	0.8180	0.6133	4.1778		5.57
30	995.678	0.8007	0.6149	4.1777	4.11	5.44
31	995.371	0.7840	0.6166	4.1776		5.31
32	995.056	0.7679	0.6182	4.1775		5.19
33	994.732	0.7523	0.6198	4.1775		5.07
34	994.401	0.7372	0.6210	4.1774		4.96
35	994.061	0.7225	0.6229	4.1774	4.09	4.85
36	993.714	0.7084	0.6244	4.1775		4.74
37	993.359	0.6946	0.6259	4.1775		4.64
38	992.996	0.6813	0.6274	4.1776		4.54
39	992.626	0.6685	0.6288	4.1777		4.44
40	992.250	0.6560	0.6303	4.1778	4.07	4.35
41	991.866	0.6438	0.6317	4.1779		4.26
42	991.468	0.6321	0.6330	4.1781		4.17
43	991.071	0.6207	0.6344	4.1783		4.09
44	990.662	0.6096	0.6357	4.1784		4.01
45	990.251	0.5988	0.6371	4.1787		3.93
46	989.820	0.5884	0.6384	4.1789		3.85
47	989.397	0.5782	0.6396	4.1791		3.78
48	988.964	0.5683	0.6409	4.1794		3.71
49	988.516	0.5587	0.6421	4.1796		3.64
50	988.068	0.5494	0.6433	4.1800	4.03	3.57
55	985.729	0.5064	0.6490	4.1816		3.26

Table 4.1. Critical Rayleighin numbers $\mathrm{Ra}_{\mathrm{cr}}$*.If* $\mathrm{Ra}_{\mathrm{cr}} = \infty$*, free convection cannot occur. If* $\mathrm{Ra}_{\mathrm{cr}} = 0$*, free convection always occurs.*



Critical Rayleigh numbers $\mathrm{Ra}_{\mathrm{cr}}$.

Physical situation		$\mathrm{Ra}_{\mathrm{cr}}$	variables
two horizontal plates, between which a denser mixture is above		1708	L = distance between the plates
two horizontal plates, between which a denser mixture is below		∞	L = distance between the plates
the density of the mixture between two vertical plates is higher on the surface of the other plate		0	L = distance between the plates
a gas is absorbed to a liquid in a horizontal plane and hence, the density of the liquid increases		110	L = thickness of the liquid layer
vertical tube where denser mixture is above		67.94	L = radius of the tube
vertical tube where denser mixture is below		∞	L = radius of the tube
dissolving sphere		0	L = radius of the sphere z=r (radial coordinate)

Table 5.2. Experimental values for gas diffusion coefficients at 1 atm.

Gas mixture	Temperature (K)	Diffusion coefficient (10^{-5} m^2/s)
Air - CH_4	282	1.96
Air - H_2	282	7.1
Air - D_2	296.8	5.65
Air - He	282	6.58
Air - H_2O	298.2	2.6
Air - CO_2	282	1.48
Air- ethanol	273.0	1.02
Air - n-hexane	294	0.80
Air - n-heptane	294	0.71
Air – benzene	298.2	0.96
Air – toluene	299.1	0.86
Air - 2-propanol	299.1	0.99
Air – butanol	299.1	0.87
Air - 2-butanol	299.1	0.89
CH_4 - H_2	298.0	7.26
CH_4 - H_2O	307.7	2.92
CO_2 - O_2	296	1.56
CO_2 - SO_2	263	0.64
H_2 – He	317	17.06
H_2 - D_2	288.2	12.4
H_2 – acetone	296	4.24
H_2 - n-butane	287.9	3.61
H_2 – benzene	311.3	4.04
N_2 - H_2O	298.2	2.93
N_2 - O_2	316	2.3
N_2 - SO_2	263	1.04
O_2 – benzene	311.3	1.01
O_2 – cyclohexane	288.6	0.75
O_2 - n-hexane	288.6	0.75
O_2 - n-octane	303.1	0.71
Freon 12 – benzene	298.2	0.39
Freon 12 - ethanol	298.2	4.75

Table 5.3. Diffusion coefficients at inifinite dilution in water at 25 ^{o}C. Note! concentration c_1 is in unit mol/liter.

Solute	Diffusion coefficient (10^{-9} m^2/s)	Solute	Diffusion coefficient (10^{-9} m^2/s)
Argon	2.00	Benzene	1.02
Air	2.00	Sulphur acid	1.73
CO2	1.92	Nitric acid	2.60
CO	2.03	Acetylene	0.88
Ethane	1.2	Methanol	0.84
Ethyleni	1.87	Ethanol	0.84
Helium	6.28	Formic acid	1.50
Hydrohen	4.5	Acetic acid	1.21
Methane	1.49	Benzoic acid	1.00
N2	1.88	Acetone	1.16
O2	2.10	Urea	$(1380 - 78.2c_1 + 4.64c_1^2)/1000$
Chlorine	1.25	Sucrose	$(0.5228 - 0.265c_1)$
Propane	0.97	Hemoglobin	0.069

Table 6.1. Dimensionless variables.

Sherwoodi number $\mathrm{Sh} = \frac{\mathrm{k}l}{\mathrm{D}_{\mathrm{AB}}}$

Schmidt number $\mathrm{Sc} = \frac{\nu}{\mathrm{D}_{\mathrm{AB}}}$

Prandtl number $\mathrm{Pr} = \frac{\eta \mathrm{c}_{\mathrm{p}}}{\lambda}$

Lewis number $\mathrm{Le} = \frac{\mathrm{D}_{\mathrm{AB}}\rho \mathrm{c}_{\mathrm{p}}}{\lambda} = \frac{\mathrm{Pr}}{\mathrm{Sc}}$

Reynolds number $\mathrm{Re} = \frac{ul}{\nu}$

Grashof number $\mathrm{Gr} = \frac{l^3 \mathrm{g}\Delta\rho}{\rho\nu^2}$

Rayleigh number $\mathrm{Ra} = \frac{l^4 \mathrm{g}}{\eta \mathrm{D}_{\mathrm{AB}}} \frac{\mathrm{d}\rho}{\mathrm{dz}}$

Nusselt number $\mathrm{Nu} = \frac{\alpha l}{\lambda}$

Péclet number $\mathrm{Pe} = \frac{\mathrm{u}l}{\mathrm{D}_{\mathrm{AB}}}$

c_{p} = specific heat at constant pressure, D_{AB} = diffusion coefficient, g = acceleration due to gravity =9.807m/s^2, k = mass transfer coefficient, l = characteristic length, u = flow velocity, z = coordinate in direction to the flow, α =convection heat transfer coefficient, λ = thermal conductivity, ν = kinematic viscosity, η = dynamic viscosity, ρ = density.

Table 7.1. Mass transfer correlations.

Case	Correlation equation	Notice!
Large liquid drops rising in stirred solution	$Sh = 0.13\left(\frac{(P/V)/d^4}{\rho\nu^3}\right)^{1/4} Sc^{1/3}$	*l*=d = bubble diameter P/V = stirrer power per volume
Pure gas bubbles in an unstirred liquid	$\mathrm{Sh} = 0.31\mathrm{Gr}^{1/3}\mathrm{Sc}^{1/3}$	For small swarms of bubbles ri liquid *1* = drop diameter $\Delta\rho =$ density difference betwe drops and surrounding fluid
Large liquid drops rising in unstirred solution.	$\mathrm{Sh} = 0.42\mathrm{Gr}^{1/3}\mathrm{Sc}^{1/2}$	*1* = drop diameter ≥ 3 mm $\Delta\rho =$ density difference betw drops and surrounding fluid
Small liquid drops rising in unstirred solution	$\mathrm{Sh} = 1.13(\mathrm{Re\,Sc})^{4/5}$	*1* = drop diameter u = drop velocity
Falling films	$\mathrm{Sh}_z = 0.69(\mathrm{Re}_z\,\mathrm{Sc})^{1/2}$	*1* = z = position along film me from the top of the film u = average film velocity
Turbulent flow through circular tube.	$\mathrm{Sh} = 0.026\,\mathrm{Re}^{4/5}\,\mathrm{Sc}^{1/3}$	*1* = tube diameter
Free convection around a solid sphere.	$\mathrm{Sh} = 2 + 0.6\mathrm{Gr}^{1/4}\mathrm{Sc}^{1/3}$	*1* = sphere diameter
Spinning disc	$\mathrm{Sh} = 0.62\,\mathrm{Re}_\omega^{1/2}\,\mathrm{Sc}^{1/3}$	Valid: $100 \leq \mathrm{Re}_\omega \leq 20\,000$ $\mathrm{Re}_\omega = \frac{l^2\omega}{\nu}$, l = disc diamete disc rotation (rad/s)

$$\mathrm{Re} = \frac{\mathrm{u}l}{\nu}, \mathrm{Sh} = \frac{\mathrm{k}l}{\mathrm{D}}, \mathrm{Sc} = \frac{\nu}{\mathrm{D}}, Gr = \frac{l^3 g\Delta\rho/\rho}{\nu^2}$$

l = characteristic size, D = diffusion coefficient, g = acceleration due gravity, u= velocity, ν = kinematic viscosity, ρ = density

Table 9.1. Thermal diffusion factors (α_T) for mixtures.

Mixtue[1]	Temperature range K	α_T
Gases		
(A) 50% D_2 - (B) 50% H_2	290-370	+0.17
(A) 50% He - (B) 50% H_2	273-700	+0.15
(A) 50% CH_4 - (B) 50% H_2	300-500	+0.29
(A) 50% O_2 - (B) 50% N_2	293	+0.02
(A) 50% CO_2 - (B) 50% N_2	290-400	+0.05
Liquids		
(A) 80% CCl_4 - (B) 20% cyclohexane	313	+1.3
(A) 50% CCl_4 - (B) 50% cyclohexane	313	+1.3
(A) 20% CCl_4 - (B) 80% cyclohexane	313	+1.3
(A) 80% benzene - (B) 20% cyclohexane	313	-0.1
(A) 50% benzene - (B) 50% cyclohexane	313	-0.4
(A) 20% benzene - (B) 80% cyclohexane	313	-0.6
(A) 75% ethanol - (B) 25% water	298	-0.9
(A) 40% ethanol - (B) 60% water	298	-1.5
(A) 10% ethanol - (B) 90% water	298	+0.3
(A) water - (B) 0.01-M KCl	303	-0.6
(A) water - (B) 0.01-M NaCl	303	-0.9

[1] All in molar fractions except KCl and NaCl solutions.

Table 10. Collision diameters of molecules σ_{ii}*. 1 pm =*10^{-12} *m.*

	σ_{ii} (pm)		σ_{ii} (pm)
H_2	289	N_2	364
He	260	CO	376
CH_4	380	CO_2	330
H_2O	265		

Table 10.2. Surface tension (γ*) of water.*

T/K	γ (J/m^2)	$T\frac{\partial\gamma}{\partial T}$ (J/m^2)
273	$75.5\cdot10^{-3}$	$-67.6\cdot10^{-3}$
323	$63.1\cdot10^{-3}$	$-77.8\cdot10^{-3}$
373	$51.5\cdot10^{-3}$	$-86.8\cdot10^{-3}$