2p. Diffusion in Liquids

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Symbols

- c concentration of solution in moles per liter
- D diffusion coefficient
- F Faraday
- k Boltzmann's gas constant
- p concentration in grams per 100 milliliters
- r_s Stokes radius
- R gas constant
- T Kelvin temperature
- Z valence
- η viscosity
- λ ionic conductance

The diffusion coefficient in liquid solutions is defined as the coefficient D in Fick's equation

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} \qquad \text{(2p-1)}$$

in which c is the concentration of the solution and D is a function of the concentration. This coefficient is sometimes called the differential value of the diffusion. In the tables of this section it is always these values which are tabulated. The units of D throughout are cm^2/sec multiplied by 10^5, and all values refer to a pressure of 1 atm. Moreover all values are *mutual* coefficients; i.e., in the absence of a volume change on mixing, the one value describes the diffusion of either solute or solvent. A recent compilation of *self-* and *tracer*-diffusion coefficients and the effect of pressure on diffusion in liquids has been made by P. A. Johnson and A. L. Babb, *Chem. Rev.* **56**, 387 (1956). In the tables that follow, the methods employed and the average deviations of the reported data from smooth interpolation curves are indicated by the following abbrevation scheme:

- C conductance ($\pm 0.2\%$)
- D diaphragm cell ($\pm 0.2\%$)
- G Gouy interference ($\pm 0.1\%$)
- L layer analysis ($\pm 0.2\%$)
- M Mach-Zehnder interference
- R Rayleigh interference ($\pm 0.1\%$)

In binary liquid systems, Table 2p-7, the reported uncertainty is about 1 per cent. Values for which no reference is given are previously unpublished results of the compiler.

TABLE 2p-1. DIFFUSION COEFFICIENTS OF DILUTE AQUEOUS SOLUTIONS OF ELECTROLYTES AT 25°C
(Concentration, moles/liter)

Electrolyte	0.000	0.0006	0.001	0.002	0.003	0.005	0.007	0.010	Ref.	Method
LiCl	1.366	1.349	1.345	1.337	1.331	1.323	1.318	1.312	10	C
NaCl	1.612	.....	1.586	1.576	1.570	1.561	1.554	1.545	10	C
KCl	1.994	.....	1.964	1.952	1.944	1.933	1.924	1.915	10	C
RbCl	2.057	.....	2.024	2.012	2.003	1.991	1.983	1.972	10	C
CsCl	2.046	.....	2.013	2.001	1.992	1.978	1.969	1.958	10	C
KNO_3	1.931	.....	1.899	1.887	1.879	1.866	1.856	1.844	10	C
$AgNO_3$	1.767	.....	.....	.....	1.720	1.708	1.699	.....	10	C
$MgCl_2$	1.251	.....	1.189	1.172	1.161	.....	.....	.....	9	C
$CaCl_2$	1.335	.....	1.249	1.224	1.206	1.180	.....	.....	1	C
$SrCl_2$	1.336	.....	1.269	1.249	1.236	1.219	1.210	.....	8	C
$BaCl_2$	1.387	1.332	1.320	1.299	1.285	1.264	.....	.....	9	C
Li_2SO_4	1.041	1.000	990	0.975	0.965	0.950	.....	.....	2	C
Na_2SO_4	1.230	.....	1.175	1.159	1.145	1.124	.....	.....	2	C
Cs_2SO_4	1.569	.....	1.487	1.460	1.442	1.418	.....	.....	7	C
$MgSO_4$	0.849	0.784	0.767	0.741	0.726	0.708	0.700	.....	6	C
$ZnSO_4$	0.849	.....	0.741	0.734	0.723	0.706	.....	.....	3	C
$LaCl_3$	1.294	.....	1.173	1.144	1.125	1.102	1.087	.....	4	C
$K_4Fe(CN)_6$	1.473	.....	.....	.....	1.211	1.183	.....	.....	5	C

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TABLE 2p-2. DIFFUSION COEFFICIENTS OF CONCENTRATED AQUEOUS SOLUTIONS OF ELECTROLYTES AT 25°C
(Concentration, moles/liter)

Electrolyte	0.00	0.05	0.1	0.2	0.3	0.5	0.7	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0	6.0	8.0	Ref.	Method
HCl	3.337	3.073	3.050	3.054	3.093	3.184	3.286	3.436	3.743	4.046	4.337	4.658	4.920	5.17	.....	.....	.....	4	D
LiCl	1.366	1.280	1.269	1.267	1.269	1.278	1.288	1.302	1.331	1.363	1.397	1.430	1.464	.....	.....	.....	.....	4	D
NaCl	1.612	1.506	1.484	1.478	1.477	1.474	1.475	1.483	1.495	1.514	1.529	1.544	1.559	1.584	.....	.....	.....	4	D
KCl	1.994	1.863	1.848	1.835	1.826	1.835	1.846	1.876	1.951	2.011	2.064	2.110	2.152	.....	.....	.....	.....	4	D
KCl	.....	1.864	1.847	1.839	1.839	1.850	1.865	1.892	1.943	1.999	2.057	2.112	2.160	2.204	.....	.....	.....	2	G
NH_4Cl	.....	.....	1.838	1.836	1.841	1.861	1.883	1.921	1.986	2.051	2.113	2.164	2.203	2.235	2.264	.....	.....	3	G
HBr	3.402	3.156	3.146	3.190	3.249	3.388	3.552	3.869	.....	.....	.....	.....	.....	.....	.....	.....	.....	4	D
LiBr	1.377	1.300	1.279	1.285	1.295	1.328	1.360	1.404	1.473	1.542	1.597	1.650	1.693	.....	.....	.....	.....	4	D
NaBr	1.627	1.533	1.517	1.507	1.515	1.542	1.569	1.596	1.629	1.668	1.702	.....	.....	.....	.....	.....	.....	4	D
KBr	2.017	1.892	1.874	1.870	1.872	1.885	1.917	1.975	2.062	2.132	2.199	2.280	2.354	2.434	.....	.....	.....	4	D
NaI	1.616	1.527	1.520	1.532	1.547	1.580	1.612	1.662	1.751	1.846	1.925	1.992	.....	.....	.....	.....	.....	1	D
KI	2.000	1.891	1.865	1.859	1.881	1.955	2.001	2.065	2.166	2.254	2.347	2.440	2.533	.....	.....	.....	.....	1	D
$LiNO_3$	1.337	.....	1.240	1.243	.....	1.260	.....	1.293	1.317	1.332	1.336	1.332	.....	1.292	1.238	1.157	.....	5	G
NH_4NO_3	1.928	.....	1.769	1.749	.....	1.724	.....	1.690	1.661	1.633	1.605	1.578	.....	1.524	1.472	1.421	1.320	5	G
$(NH_4)_2SO_4$	1.527	0.802	0.825	0.867	.....	0.938	.....	1.011	1.047	1.069	1.088	1.106	.....	.....	.....	.....	.....	5	G
$CaCl_2$	1.335	.....	1.110	1.111	1.118	1.140	1.166	1.203	1.263	1.307	1.306	1.265	1.195	.....	.....	.....	.....	3	G

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TABLE 2p-3. DIFFUSION COEFFICIENTS OF AQUEOUS SOLUTIONS OF NONELECTROLYTES
(Gouy interference method)

Concn. p, g/100 ml	Nonelectrolyte								
	Urea 25°C	Glycolamide 25°C	Glycine		*n*-Butyl alcohol		α-Alanine 25°C	Sucrose	
			1°C	25°C	1°C	25°C		1°C	25°C
0.00	1.3817	1.1423	0.5200	1.0635	0.4523	0.9720	0.9145	0.2424	0.5233
0.25	.....	.....	0.5158	1.0571	0.4395	0.9610	0.9105	.....	.....
0.50	.....	1.1359	0.5120	1.0507	0.4313	0.9500	0.9065	0.2403	0.5194
0.75	1.3720	1.1328	0.5083	1.0443	0.4242	0.9390	0.9026	0.2393	0.5175
1.00	1.3688	1.1296	0.5048	1.0379	0.4182	0.9282	0.8987	0.2383	0.5155
2	1.3561	1.1171	0.4914	1.0122	0.3968	0.8854	0.8834	0.2342	0.5078
3	1.3437	1.1047	0.4793	0.9866	0.3780	9.8436	0.8686	0.2302	0.5001
5	1.3197	1.0804	0.4590	0.9353	0.3462	0.7629	0.8405	0.2221	0.4846
10	1.2642	1.0222	.....	.....	.....	.....	0.7787		
15	1.2151	0.9676	.....	.....	.....	.....	0.7292		
20	1.1725	0.9167							
25	1.1363	0.8694							
30	.....	0.8257							
Ref.	3	1	5	5	6	6	4	2	2

At 25°C the data from which this table was prepared may be represented analytically as follows:

Urea: $D \times 10^5 \pm 0.05\% = 1.3817 - 0.0130p + 0.0001288p^2$ for $p \leq 25$

Glycolamide: $D \times 10^5 \pm 0.08\% = 1.1423 - 0.01274p + 0.0000729p^2$ for $p \leq 30$

Glycine: $D \times 10^5 \pm 0.08\% = 1.0635 - 0.02563p$ for $p \leq 5$

n-Butyl alcohol: $D \times 10^5 \pm 0.03\% = 0.9720 - 0.0443p + 0.000490p^2$ for $p \leq 5$

α-Alanine: $D \times 10^5 \pm 0.09\% = 0.9145 - 0.01603p + 0.0002449p^2$ for $p \leq 15$

Sucrose: $D \times 10^5 \pm 0.04\% = 0.5233 - 0.007745p$ for $p \leq 5$

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TABLE 2p-4. DIFFUSION OF ORGANIC COMPOUNDS IN DILUTE AQUEOUS SOLUTION AT 1° AND 25°C*

Compound	Wt. %	$D_1 \times 10^5$	$D_{25} \times 10^5$	Compound	Wt. %	$D_1 \times 10^5$	$D_{25} \times 10^5$
Methyl alcohol	0.00	0.76$_6$	1.58$_7$†	Glycylglycylglycine	0.29	0.3175	0.6652
Ethyl alcohol	0.00	.....	1.24$_8$†	Leucylglycylglycine	0.30	.....	0.5507
n-Propyl alcohol	0.59	.....	1.02$_2$†	*o*-Aminobenzoic acid	0.24	.....	0.840
Isopropyl alcohol	0.59	.....	1.02$_0$†	*m*-Aminobenzoic acid	0.24	.....	0.774
				p-Aminobenzoic acid	0.23	.....	0.842
n-Butyl alcohol	0.49	.....	0.95$_2$†				
Isobutyl alcohol	0.49	.....	0.93$_8$†	Proline	0.32	0.4187	0.8789
sec-Butyl alcohol	0.49	.....	0.92$_2$†				
tert-Butyl alcohol	0.47	.....	0.87$_9$†	Hydroxyproline	0.32	0.3930	0.8255
Glycine	0.30	0.5151	1.0554				
Glycolamide	0.30	.....	1.1385	Histidine	0.28	0.3452	0.7328
α-Alanine	0.32	0.4317	0.9097	Phenylalanine	0.25	0.3244	0.7047
β-Alanine	0.31	0.4500	0.9327				
Sarcosine	0.32	.....	0.9674	Tryptophane	0.23	0.3042	0.6592
Serine	0.31	0.4195	0.8802				
				d(−)Ribose	0.41	.....	0.7769
α-Aminobutyric acid	0.31	0.3891	0.8288	l(+)Arabinose	0.39	.....	0.7599
β-Aminobutyric acid	0.32	.....	0.8367	*d*(−)Lyxose	0.40	.....	0.7591
γ-Aminobutyric acid	0.32	.....	0.8259	*d*(+)Xylose	0.40	.....	0.7462
α-Amino isobutyric acid	0.32	.....	0.8130	*d*(−)Levulose	0.39	0.3230	0.6944
				d(+)Mannose	0.39	.....	0.6875
Threonine	0.32	.....	0.7984	l(−)Sorbose	0.39	.....	0.6791
				d(+)Dextrose	0.39	0.3137	0.6728
Valine	0.30	0.3566	0.7725	*d*(+)Galactose	0.38	0.3131	0.6655
Norvaline	0.32	.....	0.7682				
				d(+)Sucrose	0.39	0.2414	0.5209
Leucine	0.32	0.3333	0.7255	*d*(+)Lactose·H_2O	0.40	.....	0.5076
Norleucine	0.32	0.3328	0.7249	*d*(+)Cellobiose	0.38	.....	0.5039
				d(+)Melibiose·$2H_2O$	0.41	.....	0.5022
Asparagine	0.29	.....	0.8300	*d*(+)Maltose·H_2O	0.40	.....	0.4929
Glycylglycine	0.29	0.3790	0.7909				
				d(+)Melezitose·$2H_2O$	0.40	.....	0.4478
Glutamine	0.34	.....	0.7623	*d*(+)Raffinose·$5H_2O$	0.45	0.2011	0.4339
Glycylalanine	0.36	.....	0.7221				
Alanylglycine	0.30	.....	0.7207	Cycloheptaamylose	0.39	.....	0.3224
Glycylleucine	0.29	0.2869	0.6231	Bovine plasma albumin	0.25	.....	0.0670‡
Leucylglycine	0.31	0.2831	0.6129				

Isomers are in groups. Rayleigh interference method.
* L. G. Longsworth, *J. Am. Chem. Soc.* **74**, 4155 (1952); **75**, 5075 (1953).
† D strongly concentration-dependent.
‡ Extrapolated to salt-free solution.

TABLE 2p-5. DIFFUSION COEFFICIENTS IN AQUEOUS SOLUTION AT DIFFERENT TEMPERATURES

Solute	Wt. %	5 °C	15 °C	25 °C	35 °C	45 °C	55 °C	Ref.	Method
H^+	0.00	6.208	7.737	9.313	10.919	12.538	14.150	2	*
Li^+	0.00	0.5654	0.7769	1.0286	1.3197	1.6483	2.0142	2	
Na^+	0.00	0.7524	1.0218	1.3349	1.6928	2.0959	2.5439	2	
K^+	0.00	1.1604	1.5335	1.9565	2.4265	2.9403	3.4943	2	
Cl^+	0.00	1.1796	1.5801	2.0324	2.5368	3.0935	3.7031	2	
Br^+	0.00	1.2233	1.6259	2.0808	2.5869	3.1426	3.7465	2	
I^-	0.00	1.2066	1.6007	2.0457	2.5409	3.0850	3.6762	2	
Ca^{++}	0.00	.....	0.6043	0.7919	1.0078	1.2528	.....	1	
$H^1H^2O^{16}$	0.00	1.294	1.743	2.261	.....	.....	.....	3	R
Urea	0.38	0.790	1.063	1.377	1.731	.....	.....	3	R
Glycolamide	0.46	0.637	0.869	1.140	1.451	1.794	.....	...	R
Glycine	0.30	0.593	0.806	1.054	1.337	.....	.....	3	R
Alanine	0.32	0.500	0.688	0.909	1.164	.....	.....	3	R
Dextrose	0.38	0.3640	0.5038	0.6713	0.867	.....	.....	3	R
Cyclohepta-amylose	0.38	0.1738	0.2418	0.3225	0.4160	.....	.....	3	R
Bovine plasma albumin	0.25	0.0356	0.0493	0.0657	.....	.....	.....	3	R

* D for ions computed from ionic conductances λ with the aid of the relation $D = RT\lambda/zF^2$, where R = 8.3144 joules/(deg)(mole), T = °Kelvin = 273.13 + t, z = valence, and F = 96,500 coulombs/equivalent.

$$D_{salt} = \frac{(z_+ + z_-)D_+D_-}{z_+D_+ + z_-D_-}$$

Since the Stokes radius $r_s = kT/6\pi\eta D$ varies but little with temperature, a plot of r_s vs. t affords precise interpolation. Here k = 1.3803 × 10^{-16} erg/(deg)(mole), and η is the viscosity of the solvent in poises.

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TABLE 2p-6. DIFFUSION COEFFICIENTS IN NONAQUEOUS SOLVENTS

Solvent Solute	t, °C	$D \times 10^5$	Ref.
Hexane			
Iodine	25.0	4.05	7
n-Heptane			
Iodine	25.0	3.42	7
Carbon tetrachloride	25.0	3.17	2
iso-Octane			
Carbon tetrachloride	25.0	2.57	2
Benzene			
Iodine	25.0	2.13	7
Diphenyl	25.0	1.558	6
Diphenyl	35.0	1.847	6
Toluene			
Iodine	25.0	2.13	7
m-Xylene			
Iodine	25.0	1.89	7
Mesitylene			
Iodine	25.0	1.49	7
Dioxane			
Iodine	25.0	1.07	7
Carbon tetrachloride	25.0	1.02	2
sym-Tetrachlorethane*			
sym-Tetrabromethane	0.4	0.351	1
sym-Tetrabromethane	7.7	0.479	1
sym-Tetrabromethane	15.0	0.497	1
sym-Tetrabromethane	25.0	0.611	1
sym-Tetrabromethane	35.6	0.741	1
sym-Tetrabromethane	51.1	0.954	1
Carbon tetrachloride			
Hydrogen	0.0	6.28	5
Hydrogen	25.0	9.75	5
Deuterium	25.0	7.71	5
Nitrogen	0.0	2.44	5
Nitrogen	25.0	3.42	5
Oxygen	25.0	3.82	4
Carbon tetrachloride			
Argon	0.0	2.44	5
Argon	25.0	3.63	5
Methane	0.0	2.05	5
Methane	25.0	2.89	5
Carbon tetrafluoride	25.0	2.04	4
Silicon hexafluoride	25.0	1.71	4
Heptane	25.0	1.349	3
Dodecane	25.0	0.954	3
Hexadecane	25.0	0.780	3
Eicosane	25.0	0.664	3
Docosane	25.0	0.620	3
Octacosane	25.0	0.528	3
Dotriacontane	25.0	0.479	3
Tetrahydrofuran	25.0	1.468	3
Naphthalene	25.0	1.200	3
Anthracene	25.0	1.026	3
Diphenyl	25.0	1.074	3
Diphenylmethane	25.0	0.985	3
Triphenylmethane	25.0	0.694	3
Hexadecanol	25.0	0.741	3
Phenol	25.0	1.370	3
Benzohydrol	25.0	0.918	3
Triphenylmethanol	25.0	0.687	3
Benzoic acid†	25.0	0.882	3
Palmitic acid†	25.0	0.448	3
Hexachloroethane	25.0	1.007	3
Hexachlorobenzene	25.0	0.922	3
Hexachlorocyclohexane	25.0	0.843	3
N,N-dimethylacetamide	25.0	1.228	3
N,N-dimethylpropionamide	25.0	1.135	3

* Values in this solvent are at a concentration of 0.03 mole/liter. All other values in the table are limiting diffusion coefficients at zero concentration of solute.
† Dimer.

References for Table 2p-6

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TABLE 2p-7. DIFFUSION COEFFICIENTS OF BINARY LIQUID SYSTEMS

System	t, °C	$D \times 10^5$					
Mole % A		0.0	20.0	40.0	60.0	80.0	100.0
Hexane(A)-dodecane[6]*	25.1	1.43	1.61	1.80	2.02	2.33	2.73
Hexane(A)-hexadecane[5]	25.1	0.852	1.050	1.256	1.48	1.74	2.20
Heptane(A)-hexadecane[6]	25.1	0.745	0.888	1.05	1.23	1.46	1.78
Acetone(A)-benzene[1]	25.2	2.75	2.55	2.70	2.97	3.40	4.17
Cyclohexane(A)-benzene[14]	25.0	2.104	1.903	1.813	1.796	1.834	1.880
Hexane(A)-CCl_4†[6]	25.1	1.47	1.85	2.26	2.73	3.26	3.87
Cyclohexane(A)-CCl_4[12]	25.0	1.283	1.311	1.350	1.393	1.443	1.484
Toluene(A)-CCl_4[13]	25.0	1.404	1.538	1.682	1.838	2.003	2.180
Mesitylene(A)-CCl_4[13]	25.0	1.193	1.353	1.493	1.615	1.718	1.802
Acetone(A)-CCl_4[1]	25.2	1.71	1.45	1.66	2.08	2.65	3.60
Methyl ethyl ketone(A)-CCl_4[3]	25.0	1.57	1.44	1.68	2.04	2.49	3.02
Methyl alcohol(A)-CCl_4[4,13]	25.0	2.61	0.556	0.489	0.799	1.278	2.258
Ethyl alcohol(A)-CCl_4[4,10,13]	25.0	1.95	0.67	0.60	0.84	1.17	1.50
Benzyl alcohol(A)-CCl_4[13]	25.0	1.280	0.386	0.349	0.344	0.342	0.324
Acetic acid(A)-CCl_4[3,13]	25.0	1.42‡	1.19	0.92	0.82	0.88	1.28
Acetone(A)-chloroform[1]	25.2	2.34	2.95	3.30	3.45	3.55	3.63
Acetone(A)-chloroform[1]	40.0	2.88	3.58	4.05	4.23	4.26	4.31
Diethyl ether(A)-chloroform[2]	25.0	2.14	2.90	3.67	4.21	4.44	4.51
Water(A)-ethyl alcohol[9]	25.0	1.132	0.930	0.625	0.415	0.409	1.240
Mole % A		3.04	19.64	51.07	76.08	91.69	99.78
Water(A)-acetone[1]	25.0	4.56	2.39	0.819	0.635	0.854	1.28
Mole % A		0.48	11.43	25.48	50.32	75.17	99.82
Methyl alcohol(A)-benzene[11]	27.1	3.839	1.327	0.949	0.901	1.533	2.762
Methyl alcohol(A)-benzene[1]	40.0	4.67	1.85	1.30	1.28	1.98	3.16
Mole % A		0.37	9.57	20.34	34.15	70.22	99.61
Ethyl alcohol(A)-benzene[1]	25.2	2.93	1.30	0.993	0.901	1.35	1.81
Ethyl alcohol(A)-benzene[1]	40.0	3.74	1.89	1.46	1.30	1.76	2.37

TABLE 2p-7. DIFFUSION COEFFICIENTS OF BINARY LIQUID SYSTEMS (*Continued*)

System	t, °C	$D \times 10^5$					
		2.15	25.02	50.51	74.98	98.15	
Mole % A							
Benzene(A)–CCl_4[8]	10.0	1.085	1.093	1.230	1.344	1.466	
Benzene(A)–CCl_4[8]	25.3	1.419	1.519	1.651	1.759	1.912	
Benzene(A)–CCl_4[8]	40.0	1.775	1.970	2.077	2.284	2.432	
		1.34	25.01	49.92	74.92	98.62	
Mole % A							
Toluene(A)–chlorobenzene[8]	10.0	1.346	1.404	1.556	1.652	1.759	
Toluene(A)–chlorobenzene[8]	27.0	1.756	1.852	1.985	2.123	2.264	
Toluene(A)–chlorobenzene[8]	40.0	2.113	2.277	2.435	2.585	2.714	
		3.32	26.42	51.22	76.17	96.52	
Mole % A							
Chlorobenzene(A)–bromobenzene[8]	10.0	1.007	1.069	1.146	1.226	1.291	
Chlorobenzene(A)–bromobenzene[8]	26.8	1.342	1.380	1.506	1.596	1.708	
Chlorobenzene(A)–bromobenzene[8]	40.0	1.584	1.691	1.806	1.902	1.996	

* Reference no.
† Carbon tetrachloride.
‡ Acetic acid dimer.

References for Table 2p-7

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