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# Viscosities of Solutions of Interest for Studies of Absorption Processes

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We report the viscosities of solutions of glycerin, sucrose, glucose, or fructose in water or in 0.5 M sodium carbonate + 0.5 M sodium bicarbonate buffer at concentrations from 0 to 150 g·L$^{-1}$ and temperatures from 288.1 to 323.1 K. An equation gave the dependence of kinematic viscosity on concentration and temperature with a deviation of less than 1.2%.

## Introduction

The rate at which gas–liquid absorption processes occur depends on mass transfer coefficients, interfacial areas, and, if the gas reacts chemically with the liquid, the corresponding kinetic constants. Calculation or determination of these variables requires knowledge of certain physical properties: the density, surface tension, and viscosity of the liquid phase and the diffusivity and solubility of the gas in the liquid. Danckwerts' method for determining interfacial area, for example, which is based on the dissolution of $CO_2$ in buffer solutions (often sodium carbonate + bicarbonate buffers), assumes knowledge of the viscosity of these solutions (*1*). In our previous studies (*2*, *3*) of the influence of viscosity on gas–liquid absorption, we have controlled this variable by addition of sugars or glycerin. We found, however, that neither published experimental data nor the scope of existing models for the viscosities of sugar or glycerin solutions as a function of temperature and concentration was sufficient for our needs (*4*, *5*). As a necessary preliminary to further work on mass transfer, we therefore undertook the experimental determination of the kinematic viscosities of the solutions of interest over the appropriate ranges of temperature and concentration. This paper reports our measurements, which were performed with greater accuracy than would normally be required for application to mass transfer.

## Experimental Section

Solutions of glycerin, sucrose, glucose, or fructose in water or 0.5 M sodium carbonate + 0.5 M sodium bicarbonate buffer (concentrations at 298.1 K) were made up at concentrations ranging from 0 to 150 g·L$^{-1}$ at 25 g·L$^{-1}$ intervals, and their viscosities measured at temperatures ranging from 288.1 to 323.1 K at 5 K intervals. Sucrose, glucose anhydride, and fructose (all >99.95% pure) and glycerin (>99.5% pure) were Merck products and were desiccated to constant mass prior to use. Sodium carbonate and sodium bicarbonate, Probus products, were both >99.9% pure; the carbonate was desiccated prior to use to remove any bicarbonate. Water was distilled and degassed. Solutions were made up with known masses of solutes and solvent, and in what follows their concentrations are expressed as mass fractions. All solutions were filtered before use.

Kinematic viscosities were calculated from the transit time of the liquid meniscus through a capillary, measured to a precision of ±0.01 s in a Schott-Geräte AVS 350 automatic Ubbelohde viscosimeter. Temperature was thermostated to within ±0.02 K in a bath. Several determinations were carried out for each experimental condition; in no case did the maximum deviation from the mean exceed 0.4%.

**Table 1. Kinematic Viscosities $\nu$ of Water and 0.5 M Sodium Carbonate + 0.5 M Sodium Bicarbonate Buffer at Various Temperatures**

| $T$/K | $10^6\nu$/(m$^2$·s$^{-1}$) | $T$/K | $10^6\nu$/(m$^2$·s$^{-1}$) |
|---|---|---|---|
| | Water | | |
| 288.1 | 1.138 | 308.1 | 0.722 |
| 293.1 | 1.001 | 313.1 | 0.655 |
| 298.1 | 0.892 | 318.1 | 0.595 |
| 303.1 | 0.799 | 323.1 | 0.546 |
| | 0.5 M Sodium Carbonate + 0.5 M Sodium Bicarbonate | | |
| 288.1 | 1.551 | 308.1 | 0.980 |
| 293.1 | 1.361 | 313.1 | 0.885 |
| 298.1 | 1.211 | 318.1 | 0.808 |
| 303.1 | 1.091 | 323.1 | 0.743 |

**Table 2. Kinematic Viscosities of Aqueous Solutions of Sucrose at Various Mass Fractions $w$ and Temperatures $T$**

| | $10^6\nu$/(m$^2$·s$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| $T$/K | $w$ = 0.0269 | $w$ = 0.0528 | $w$ = 0.0749 | $w$ = 0.0981 | $w$ = 0.1207 | $w$ = 0.1428 |
| 288.1 | 1.211 | 1.298 | 1.386 | 1.474 | 1.582 | 1.723 |
| 293.1 | 1.065 | 1.143 | 1.212 | 1.289 | 1.383 | 1.494 |
| 298.1 | 0.946 | 1.021 | 1.076 | 1.141 | 1.222 | 1.317 |
| 303.1 | 0.848 | 0.909 | 0.959 | 1.018 | 1.086 | 1.170 |
| 308.1 | 0.766 | 0.821 | 0.865 | 0.914 | 0.975 | 1.045 |
| 313.1 | 0.697 | 0.745 | 0.784 | 0.828 | 0.880 | 0.941 |
| 318.1 | 0.637 | 0.678 | 0.713 | 0.754 | 0.801 | 0.857 |
| 323.1 | 0.587 | 0.622 | 0.657 | 0.689 | 0.731 | 0.780 |

**Table 3. Kinematic Viscosities of Aqueous Solutions of Glucose at Various Mass Fractions $w$ and Temperatures $T$**

| | $10^6\nu$/(m$^2$·s$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| $T$/K | $w$ = 0.0249 | $w$ = 0.0493 | $w$ = 0.0733 | $w$ = 0.0969 | $w$ = 0.1209 | $w$ = 0.1439 |
| 288.1 | 1.207 | 1.291 | 1.362 | 1.451 | 1.559 | 1.688 |
| 293.1 | 1.063 | 1.132 | 1.190 | 1.268 | 1.361 | 1.468 |
| 298.1 | 0.945 | 1.003 | 1.054 | 1.122 | 1.199 | 1.290 |
| 303.1 | 0.846 | 0.896 | 0.938 | 1.000 | 1.067 | 1.145 |
| 308.1 | 0.764 | 0.810 | 0.846 | 0.899 | 0.960 | 1.024 |
| 313.1 | 0.695 | 0.734 | 0.767 | 0.812 | 0.866 | 0.925 |
| 318.1 | 0.635 | 0.670 | 0.701 | 0.742 | 0.787 | 0.836 |
| 323.1 | 0.584 | 0.613 | 0.643 | 0.680 | 0.718 | 0.763 |

## Results

The measured kinematic viscosities of degassed distilled water at the working temperatures, all of which were within 0.2% of published values (*4*), are listed in Table 1 together with analogous measurements for 0.5 M sodium carbonate + 0.5 M sodium bicarbonate buffer. Tables 2–5 list the measured viscosities of solutions of sucrose, glucose, fructose and glycerin in water (all values measured at 293.1 K are within 1% of the published data (*4*)), and Tables 6–9 list the analogous data for the same solutes in 0.5 M sodium carbonate + 0.5 M sodium bicarbonate buffer.

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**Table 4. Kinematic Viscosities of Aqueous Solutions of Fructose at Various Mass Fractions $w$ and Temperatures $T$**

| | $10^6\nu/(\mathrm{m^2{\cdot}s^{-1}})$ | | | | | |
|---|---|---|---|---|---|---|
| $T$/K | $w$ = 0.0249 | $w$ = 0.0495 | $w$ = 0.0733 | $w$ = 0.0967 | $w$ = 0.1197 | $w$ = 0.1421 |
| 288.1 | 1.211 | 1.284 | 1.341 | 1.463 | 1.562 | 1.653 |
| 293.1 | 1.067 | 1.125 | 1.175 | 1.258 | 1.361 | 1.442 |
| 298.1 | 0.946 | 1.006 | 1.042 | 1.113 | 1.211 | 1.268 |
| 303.1 | 0.848 | 0.886 | 0.930 | 0.991 | 1.073 | 1.124 |
| 308.1 | 0.766 | 0.807 | 0.839 | 0.892 | 0.949 | 1.078 |
| 313.1 | 0.696 | 0.729 | 0.760 | 0.807 | 0.858 | 0.921 |
| 318.1 | 0.637 | 0.667 | 0.694 | 0.733 | 0.780 | 0.831 |
| 323.1 | 0.585 | 0.610 | 0.635 | 0.670 | 0.710 | 0.760 |

**Table 5. Kinematic Viscosities of Aqueous Solutions of Glycerin at Various Mass Fractions $w$ and Temperatures $T$**

| | $10^6\nu/(\mathrm{m^2{\cdot}s^{-1}})$ | | | | | |
|---|---|---|---|---|---|---|
| $T$/K | $w$ = 0.0253 | $w$ = 0.0532 | $w$ = 0.0748 | $w$ = 0.0986 | $w$ = 0.1224 | $w$ = 0.1486 |
| 288.1 | 1.232 | 1.295 | 1.378 | 1.455 | 1.565 | 1.672 |
| 293.1 | 1.078 | 1.137 | 1.204 | 1.272 | 1.362 | 1.455 |
| 298.1 | 0.960 | 1.009 | 1.066 | 1.126 | 1.199 | 1.284 |
| 303.1 | 0.865 | 0.902 | 0.954 | 1.004 | 1.067 | 1.136 |
| 308.1 | 0.778 | 0.812 | 0.859 | 0.902 | 0.958 | 1.018 |
| 313.1 | 0.706 | 0.737 | 0.777 | 0.816 | 0.865 | 0.917 |
| 318.1 | 0.642 | 0.671 | 0.709 | 0.743 | 0.785 | 0.828 |
| 323.1 | 0.586 | 0.618 | 0.650 | 0.679 | 0.720 | 0.757 |

**Table 6. Kinematic Viscosities of Solutions of Sucrose in 0.5 M Sodium Carbonate + 0.5 M Sodium Bicarbonate Buffer at Various Mass Fractions $w$ and Temperatures $T$**

| | $10^6\nu/(\mathrm{m^2{\cdot}s^{-1}})$ | | | | | |
|---|---|---|---|---|---|---|
| $T$/K | $w$ = 0.0231 | $w$ = 0.0458 | $w$ = 0.0685 | $w$ = 0.0900 | $w$ = 0.1116 | $w$ = 0.1328 |
| 288.1 | 1.675 | 1.817 | 1.967 | 2.146 | 2.350 | 2.584 |
| 293.1 | 1.466 | 1.587 | 1.710 | 1.865 | 2.031 | 2.233 |
| 298.1 | 1.297 | 1.404 | 1.514 | 1.639 | 1.783 | 1.948 |
| 303.1 | 1.158 | 1.255 | 1.348 | 1.452 | 1.572 | 1.711 |
| 308.1 | 1.041 | 1.121 | 1.199 | 1.301 | 1.402 | 1.523 |
| 313.1 | 0.946 | 1.014 | 1.083 | 1.168 | 1.262 | 1.360 |
| 318.1 | 0.865 | 0.924 | 0.982 | 1.059 | 1.139 | 1.227 |
| 323.1 | 0.789 | 0.845 | 0.892 | 0.965 | 1.035 | 1.112 |

**Table 7. Kinematic Viscosities of Solutions of Glucose in 0.5 M Sodium Carbonate + 0.5 M Sodium Bicarbonate Buffer at Various Mass Fractions $w$ and Temperatures $T$**

| | $10^6\nu/(\mathrm{m^2{\cdot}s^{-1}})$ | | | | | |
|---|---|---|---|---|---|---|
| $T$/K | $w$ = 0.0231 | $w$ = 0.0458 | $w$ = 0.0681 | $w$ = 0.0900 | $w$ = 0.1116 | $w$ = 0.1370 |
| 288.1 | 1.688 | 1.815 | 1.958 | 2.129 | 2.336 | 2.596 |
| 293.1 | 1.473 | 1.584 | 1.711 | 1.850 | 2.015 | 2.233 |
| 298.1 | 1.315 | 1.401 | 1.505 | 1.622 | 1.761 | 1.945 |
| 303.1 | 1.179 | 1.247 | 1.341 | 1.445 | 1.557 | 1.710 |
| 308.1 | 1.060 | 1.122 | 1.201 | 1.290 | 1.386 | 1.518 |
| 313.1 | 0.959 | 1.014 | 1.081 | 1.167 | 1.244 | 1.358 |
| 318.1 | 0.874 | 0.922 | 0.981 | 1.054 | 1.125 | 1.222 |
| 323.1 | 0.802 | 0.844 | 0.896 | 0.959 | 1.027 | 1.108 |

**Table 8. Kinematic Viscosities of Solutions of Fructose in 0.5 M Sodium Carbonate + 0.5 M Sodium Bicarbonate Buffer at Various Mass Fractions $w$ and Temperatures $T$**

| | $10^6\nu/(\mathrm{m^2{\cdot}s^{-1}})$ | | | | | |
|---|---|---|---|---|---|---|
| $T$/K | $w$ = 0.0231 | $w$ = 0.0458 | $w$ = 0.0681 | $w$ = 0.0899 | $w$ = 0.1115 | $w$ = 0.1329 |
| 288.1 | 1.677 | 1.815 | 1.967 | 2.123 | 2.287 | 2.491 |
| 293.1 | 1.469 | 1.588 | 1.719 | 1.842 | 1.978 | 2.158 |
| 298.1 | 1.310 | 1.405 | 1.515 | 1.619 | 1.735 | 1.890 |
| 303.1 | 1.173 | 1.255 | 1.343 | 1.435 | 1.534 | 1.652 |
| 308.1 | 1.058 | 1.127 | 1.207 | 1.284 | 1.370 | 1.470 |
| 313.1 | 0.962 | 1.023 | 1.090 | 1.156 | 1.232 | 1.307 |
| 318.1 | 0.878 | 0.930 | 0.991 | 1.049 | 1.114 | 1.177 |
| 323.1 | 0.805 | 0.852 | 0.904 | 0.956 | 1.013 | 1.065 |

**Table 9. Kinematic Viscosities of Solutions of Glycerin in 0.5 M Sodium Carbonate + 0.5 M Sodium Bicarbonate Buffer at Various Mass Fractions $w$ and Temperatures $T$**

| | $10^6\nu/(\mathrm{m^2{\cdot}s^{-1}})$ | | | | | |
|---|---|---|---|---|---|---|
| $T$/K | $w$ = 0.0299 | $w$ = 0.0461 | $w$ = 0.0692 | $w$ = 0.0916 | $w$ = 0.1133 | $w$ = 0.1359 |
| 288.1 | 1.652 | 1.804 | 1.922 | 2.080 | 2.278 | 2.414 |
| 293.1 | 1.453 | 1.576 | 1.675 | 1.811 | 1.962 | 2.082 |
| 298.1 | 1.285 | 1.383 | 1.489 | 1.584 | 1.725 | 1.822 |
| 303.1 | 1.149 | 1.241 | 1.311 | 1.412 | 1.525 | 1.627 |
| 308.1 | 1.034 | 1.111 | 1.175 | 1.264 | 1.350 | 1.446 |
| 313.1 | 0.938 | 1.004 | 1.062 | 1.138 | 1.212 | 1.283 |
| 318.1 | 0.856 | 0.913 | 0.960 | 1.025 | 1.074 | 1.162 |
| 323.1 | 0.785 | 0.834 | 0.876 | 0.934 | 0.963 | 1.058 |

**Table 10. Parameters of Equation 3 for the Temperature and Mass Fraction Dependence of the Kinematic Viscosities of Aqueous Solutions of Various Sugars and Glycerin**[a]

| solution | $F \times 10^7/(\mathrm{m^2{\cdot}s^{-1}})$ | $G \times 10^{-7}/\mathrm{K^3}$ |
|---|---|---|
| sucrose | 2.6170 | 7.6336 |
| glucose | 2.2018 | 7.8860 |
| fructose | 2.1219 | 7.9216 |
| glycerine | 1.7933 | 8.4196 |

[a] $\nu_0 = \nu_{\mathrm{H_2O}}/(\mathrm{m^2{\cdot}s^{-1}}) = 9.7734 \times 10^{-8}\mathrm{e}^{5.8662\times10^7/(T/\mathrm{K})^3}$.

**Table 11. Parameters of Equation 3 for the Temperature and Concentration Dependence of the Kinematic Viscosities of Solutions of Various Sugars and Glycerin in 0.5 M Sodium Carbonate + 0.5 M Sodium Bicarbonate Buffer**[a]

| solution | $F \times 10^7/(\mathrm{m^2{\cdot}s^{-1}})$ | $G \times 10^{-7}/\mathrm{K^3}$ |
|---|---|---|
| sucrose + buffer | 3.7453 | 8.4059 |
| glucose + buffer | 3.2645 | 8.6466 |
| fructose + buffer | 2.7940 | 8.8937 |
| glycerine + buffer | 2.7446 | 8.7379 |

[a] $\nu_0 = \nu_{\mathrm{buffer}}/(\mathrm{m^2{\cdot}s^{-1}}) = 12.5477 \times 10^{-8}\mathrm{e}^{6.0084\times10^7/(T/\mathrm{K})^3}$.

The Cornelissen–Waterman equation for the dependence of kinematic viscosity $\nu$ on absolute temperature $T$ at constant solute concentration (*6*),

$$\nu = A\mathrm{e}^{B/T^m} \tag{1}$$

was fitted to the experimental data (with deviations of less than 0.2%) by the Nelder–Mead method, which gave a value of 3 for $m$ when the whole data set was considered. The equations so obtained for water and buffer with no solute are shown in Tables 10 and 11, respectively.

The variation of viscosity with solute concentration (mass fraction, $w$) was expressed by an empirical equation of the form

$$\nu = D + Ew^n \tag{2}$$

where $n = 1.25$ was optimized using the whole data set, and the standard deviations of the fits were less than 1%.

The dependence of kinematic viscosity on both temperature and solute concentration was modeled by treating $D$ and $E$ in eq 2 as functions of $T$ of the same form as eq 1:

$$\nu = \nu_0 + F\mathrm{e}^{G/T^m}w^n \tag{3}$$

where $\nu_0$ is the kinematic viscosity in the absence of solute (given, for water and sodium carbonate + bicarbonate buffer as solvents, by the functions shown in Tables 10 and 11, respectively), $m$ and $n$ are taken to have the values 3 and 1.25 determined for eqs 1 and 2, and the parameters $F$ and $G$, optimized by the Nelder–Mead method, are listed for each system in Tables 10 and 11. Equation 3 fitted the measurements to within 1.2%.

In conclusion, the results reported here allow the calculation of the kinematic viscosities of aqueous solutions commonly employed in laboratory studies of gas–liquid absorption. As far as we are aware, there has been no previous report of systematic determination of such data, the few scattered values that have been published hitherto having been obtained by a variety of different methods in various absorption studies.

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