

Estimation of Viscosity of 1, 4-dioxane Aqueous Solution and Liquid Structure of Water in the Solution

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Abstract

The complicated concentration dependency of various physical properties of 1, 4-dioxane aqueous solution such as viscosity and density is likely to be due to changes of liquid structure of the water in the solution due to changes in solute concentrations.

In this study, the mole fraction (X_c) and temperature dependency of the kinematic viscosity of 1, 4-dioxane aqueous solution have been determined under atmospheric pressure to formulate a method for estimating these physical properties of the solution that are affected by mole fraction in a complicated manner.

The conclusions are as follows.

- 1) The kinematic viscosity of an aqueous solution at arbitrary mole fraction and temperature can be estimated by making the difference dimensionless between arbitrary kinematic viscosity and the mean mole fraction dependency which connected the measured kinematic viscosity of water with that of 1,4-dioxane.
- 2) The kinematic viscosity of an aqueous solution at arbitrary mole fraction and temperature can be estimated from the regression line of the correlation of kinematic viscosity and density made dimensionless.
- 3) The viscosity of water and the viscosity in an aqueous solution at arbitrary mole fraction and temperature can be estimated by applying the dimensional analysis.
- 4) The relationship between viscosity and liquid structure of water in aqueous solutions have been identified.

Key words: 1, 4-dioxane Aqueous Solution, Viscosity, Mole Fraction Dependency, Temperature Dependency, Liquid Structure of Water

Introduction

The authors¹⁾²⁾ demonstrated that addition of an adequate amount of 1, 4-dioxane to a LiBr aqueous solution is useful for improving the water solubility of LiBr, which is necessary for the design of compact, high-performance absorption-type freezers that use a LiBr aqueous solution and water as the working medium. To apply this finding in the design of absorption-type freezers, physical properties must be identified such as density, viscosity, and evaporation latent heat of 1, 4-dioxane aqueous solution in which the liquid structure of water varies in a complex manner depending on the mixture mole fraction X_c ³⁾⁴⁾. The authors identified a method of

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estimating density and clarifying the liquid structure of water in a solution in a previous report⁵⁾. This paper discusses viscosity that influences the fluidity and thermal conductivity of an evaporation condensation component, or 1,4-dioxane aqueous solution, and methods of estimating viscosity.

The temperature-dependency of viscosity of a pure-component solution can be expressed by the Andrade equation^{6,7)} by approximation but there is no established theoretical or empirical general formula regarding the viscosity of a solution that is strongly affected by molecular structure⁶⁾. Estimating the viscosity of a mixture from the viscosity of pure components and composition is difficult on account of interactions between component molecules⁶⁾. Therefore, the additive method is applied only to non-aqueous mixtures (normal liquid) that are composed of similar components that are supposed to be independent of each other⁶⁾.

Geddes⁸⁾ and Ishikawa et al.⁹⁾ identified the presence of the inflection point in the physical properties of 1,4-dioxane aqueous solution and determined the concentration and composition at the inflection point. The possibility of variation in the liquid structure of both components due to cluster formation among 1,4-dioxane molecules and hydrogen bonds between 1,4-dioxane and water molecules has recently been reported in studies using mass spectrometry and X-ray diffraction¹⁰⁾ and dielectric relaxation¹¹⁾ but neither the types nor strength of binding force has been clarified.

1,4-dioxane aqueous solution has a peculiar evaporation characteristic in that it has an azeotropic composition at the mixture mole fraction (X_c) of 0.625 where water is the primary component and that the vapor phase composition is virtually identical to the azeotropic composition even if the liquid phase composition changes within the X_c value range of 0.625 to 0.825¹²⁾.

These results suggest that the complex dependency of the physical properties of an aqueous solution such as viscosity on the concentration results from changes in the liquid structure of water in the solution that are associated with changes in the solute concentration.

To establish a method of estimating the kinematic viscosity of 1,4-dioxane aqueous solution that varies in a complex manner depending on X_c , this study was conducted in order to determine the mole fraction dependency and temperature dependency of kinematic viscosity under atmospheric pressure to consider the following:

- 1) A method for the estimation of the kinematic viscosity of 1,4-dioxane aqueous solution
- 2) A method for the estimation of viscosity of water in 1,4-dioxane aqueous solution
- 3) Correlation between viscosity and the liquid structure of water in an aqueous solution

1. Experimental equipment and methods

1.1 Materials used

Deionized water made with a purifier (Advantec Toyo, GSH-500) and analytical grade 1,4-dioxane (Kanto Kagaku) were used. The deionized water had pH=5.518, conductivity=0.7715 $\mu\text{S}\cdot\text{cm}^{-1}$ (298 K) and the concentrations of dissolved inorganic salts such as Na^+ , K^+ , NH_4^+ and

Ca²⁺ were below the lower detection limits.

The 1, 4-dioxane aqueous solution used had water as its primary component and determination was performed at the mole fraction X_c of 0.0 to 1.0, which was set to the nearest 0.1.

1.2 Determination of kinematic viscosity

An Ubbelohde viscometer (Sogo Rikagaku Glass Manufacturing Co., Ltd.) was placed in a digital low-temperature water bath (Tokyo Rikakikai Co., Ltd., NCB-2100) and maintained at given temperatures (293, 303, 313, 323, 333 and 343 K) for 15 minutes, and then the time required for discharge was measured. If three successive measurements did not differ from each other by more than 0.2%, the mean of these measurements was calculated and used for the calculation of kinematic viscosity according to equation (1).

$$\text{Kinematic viscosity} = \text{viscometer constant} \times \text{discharge time} \dots\dots\dots (1)$$

The constant of the viscometer used was the measured value ($0.003 \text{ mm}^2 \cdot \text{s}^{-2}$) designated by the manufacturer.

The measured kinematic viscosity of water ($X_c=1.0$) at given temperatures under atmospheric pressure was 1.0114, 0.8018, 0.6636, 0.5576, 0.4786, and $0.4152 \text{ mm}^2 \cdot \text{s}^{-1}$, respectively. The difference in kinematic viscosity between these values and the estimated values of 1.0038, 0.8008, 0.6580, 0.5536, 0.4747, and $0.4136 \text{ mm}^2 \cdot \text{s}^{-1}$, which were calculated by dividing reference viscosity¹³⁾¹⁴⁾ under atmospheric pressure by reference density¹³⁾¹⁴⁾, was within 1%. The kinematic viscosity of 1, 4-dioxane ($X_c=0.0$) measured in a similar manner was 1.2657, 1.0773, 0.9353, 0.8133, 0.7199, and $0.6450 \text{ mm}^2 \cdot \text{s}^{-1}$, respectively, and the difference between these values and the estimated values of 1.2637, 1.0744, 0.9271, 0.8153, and $0.7264 \text{ mm}^2 \cdot \text{s}^{-1}$, which were calculated by dividing reference viscosity¹³⁾¹⁵⁾ by reference density¹⁵⁾ excluding the value for 343 K, was 1% or less.

2. Mole fraction dependency and temperature dependency of the kinematic viscosity of 1, 4-dioxane aqueous solution

2.1 Mole fraction dependency of kinematic viscosity and empirical estimation

Figure 1 indicates the mixture mole fraction dependency of the measured kinematic viscosity $v_m(X_c, T)$ (solid line) of 1, 4-dioxane aqueous solution. Changes in the liquid structure of water and the transitional mole fractions are shown in the upper part of the figure to allow easy comparison of changes in the liquid structure of water and changes in kinematic viscosity. Irrespective of X_c values, the kinematic viscosity of the solution is greater compared with respective single components and has a maximum at $X_c=0.8$. It then decreases to the kinematic viscosity of 1, 4-dioxane ($X_c=0.0$). Because this tendency is quite similar to the density determined in the previous report⁵⁾, estimating the kinematic viscosity of a solution at a certain temperature and X_c is possible by integrating these factors.

Equation (2) represents the difference between the average mole fraction lines that connect

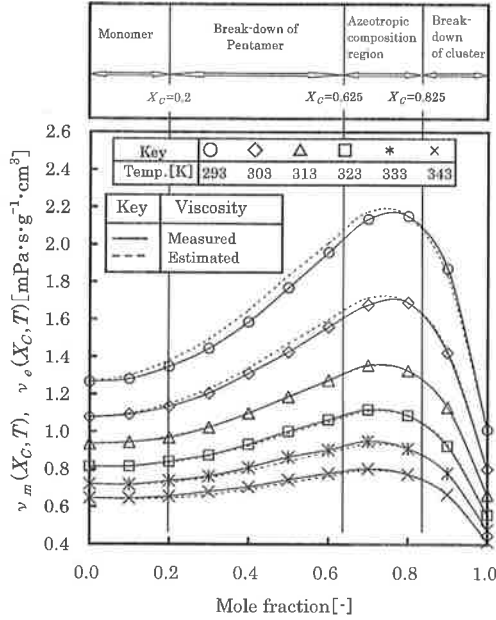


Fig.1 Measured kinematic viscosity and estimated kinematic viscosity of 1, 4-dioxane aqueous solution

measured kinematic viscosity values for water and 1, 4-dioxane at each temperature and the measured kinematic viscosity values at certain X_c values.

$$\begin{aligned} \Delta v_m(X_c, T) &= v_m(X_c, T) - \{v_m(0.0, T) - X_c(v_m(0.0, T) - v_m(1.0, T))\} \\ &= v_m(X_c, T) - \{v_m(1.0, T) + (1 - X_c)(v_m(0.0, T) - v_m(1.0, T))\} \dots \dots \dots (2) \end{aligned}$$

Because kinematic viscosity shows a maximum at $X_c \leq 0.7 - 0.8$ irrespective of temperature, nondimensional values of $\Delta v_m(X_c, T)$ are calculated from equation (3) using $\Delta v_m(0.8, T)$ as the base.

$$\begin{aligned} v_{mR}(X_c, T) &= \frac{\Delta v_m(X_c, T)}{\Delta v_m(0.8, T)} \\ &= \frac{v_m(X_c, T) - \{v_m(1.0, T) + (1 - X_c) \times (v_m(0.0, T) - v_m(1.0, T))\}}{v_m(0.8, T) - \{v_m(1.0, T) + (1 - 0.8) \times (v_m(0.0, T) - v_m(1.0, T))\}} \dots \dots \dots (3) \end{aligned}$$

Figure 2 indicates the mole fraction dependency of nondimensional kinematic viscosity $v_{mR}(X_c, Y)$. The difference in $V_{mR}(X_c, T)$ is:

$$MAX(v_{mR}(0.5, T)) - MIN(v_{mR}(0.5, T)) < 0.114 \dots \dots \dots (4)$$

at the largest, and

$$MAX(v_{mR}(X_c, T)) - MIN(v_{mR}(X_c, T)) \doteq 0.080 \dots \dots \dots (5)$$

on average.

Because the difference in $V_{mR}(X_c, T)$ at individual temperatures is small, $V_{mR}(X_c, T)$ can

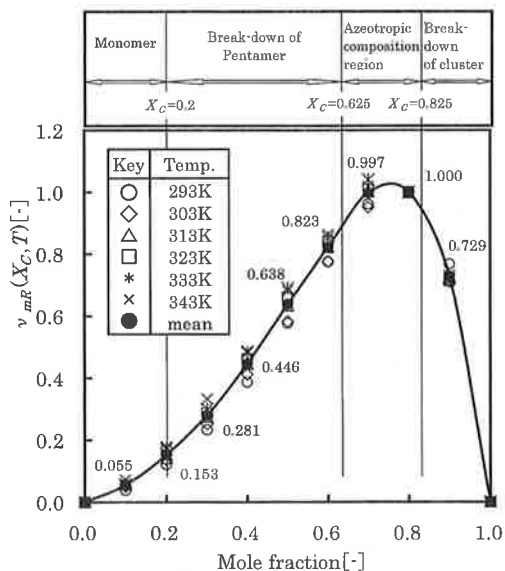


Fig. 2 Non-dimensional measured kinematic viscosity of 1, 4-dioxane aqueous solution

be expressed by a single average curve regardless of temperature.

The average $V_{mR}(X_c, T)$, $V_{HmR}(X_c, T)$, at each mole fraction and temperature is expressed by equation (6).

$$v_{HmR}(X_c, T) = \frac{1}{6} \sum v_{mR}(X_c, T) \dots\dots\dots (6)$$

The difference between $v_{mR}(X_c, T)$ and $v_{HmR}(X_c, T)$ is 0.061 (293 K, $X_c=0.5$) at the largest and 0.025 on average. If $v_{mR}(X_c, T)$ is substituted by $v_{HmR}(X_c, T)$ in equation (3), the kinematic viscosity at each mole fraction and temperature can be estimated by equation (7).

$$v_e(X_c, T) = v_{HmR}(X_c, T) \times \{v(0.8, T) - \{v_m(1.0, T) + 0.2 \times (v_m(0.0, T) - v_m(1.0, T))\} + \{v_m(1.0, T) + (1 - X_c) \times (v_m(0.0, T) - v_m(1.0, T))\} \dots\dots\dots (7)$$

where

$$v(0.8, T) = a \times v_m(0.0, T) = b \times v_m(1.0, T) \dots\dots\dots (8)$$

Because the difference in the sum of $a(T)$ and $b(T)$, both the coefficients calculated by substituting a measured value for $v_m(0.8, T)$ in equation (8), at each temperature is within $\pm 6.885\%$ of the average value, kinematic viscosity can be estimated from equations (8) and (9) by taking the average value as a constant.

$$a + b = \frac{1}{6} \sum \{a(T) + b(T)\} \dots\dots\dots (9)$$

The mole fraction dependency of the estimated kinematic viscosity $v_e(X_c, T)$ (broken line)

was compared with the measured kinematic viscosity of 1, 4-dioxane aqueous solution $v_m(X_c, T)$ (solid line) in **Figure 1**. The difference between them was 4.075% (293 K, $X_c=0.4$) at the largest and 1.336% on average.

2.2 Temperature dependency of kinematic viscosity

Figure 3 indicates the temperature dependency of the viscosity of both components of 1, 4-dioxane aqueous solution, *i.e.* water ($X_c=1.0$) and 1, 4-dioxane ($X_c=0.0$). The temperature axis is expressed in logarithms⁴⁾ to show the difference between 273 K and certain temperatures

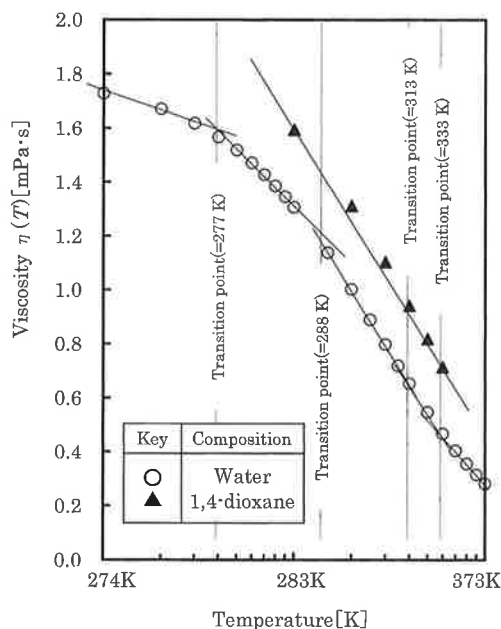


Fig. 3 Temperature dependency of viscosity for water and 1, 4-dioxane

considering the temperature dependency of thermal dissociation of protons.

The temperature dependency of viscosity of 1, 4-dioxane is linear¹³⁾¹⁴⁾ and in accordance with Andrade equation⁹⁾⁷⁾. Thus, 1, 4-dioxane is a normal liquid that has a liquid structure independent of temperature and there is no structural formation of 1, 4-dioxane due to hydrogen bonds. This result is in conformity with the authors results from the ¹⁷O-NMR chemical shift method³⁾ and from the low-frequency Raman analysis¹⁶⁾ by Tominaga *et al.*

Meanwhile, the temperature dependency of viscosity of water¹³⁾¹⁴⁾ shows changes in the slope at 277, 288, 313, and 333 K. These inflection points are in agreement with the transition temperatures⁴⁾¹⁷⁾¹⁸⁻²⁰⁾ of the liquid structure of water. Thus, this figure indicates that water is not a normal liquid but has a liquid structure formed by hydrogen bonds³⁾⁴⁾¹⁷⁾. The liquid structure of water is known to change at 277 K, the point at which water shows the highest density.

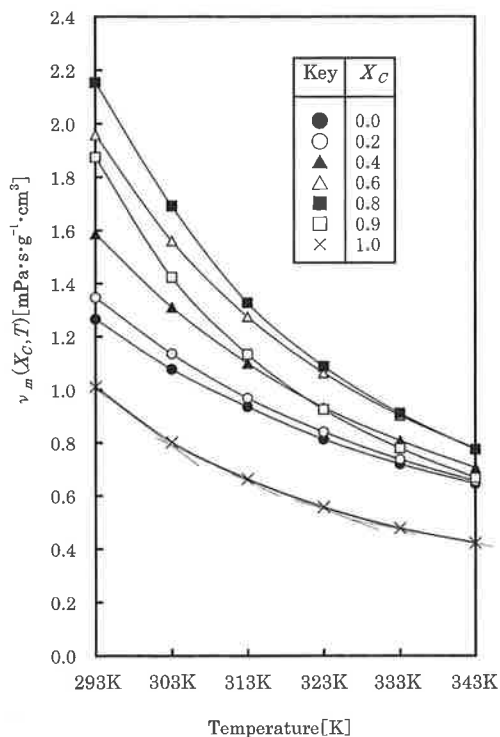


Fig. 4 Temperature dependency of measured kinematic viscosity of 1,4-dioxane aqueous solution

Figure 4 indicates the temperature dependency of the measured kinematic viscosity $v_m(X_c, T)$ of 1,4-dioxane aqueous solution. Irrespective of mole fraction, measured kinematic viscosity decreases as temperature rises showing a slightly concave smooth curve. The slope becomes steep as mole fraction increases and reaches maximum at an X_c of 0.8. As shown in **Figure 3**, the temperature dependency of viscosity of water¹³⁾¹⁴⁾ shows changes in the slope at 277, 288, 313, and 333 K associated with changes in liquid structure. A similar tendency is presented in **Figure 4**. **Table 1** shows the maximum change in the slope of temperature dependency at 303 K. This is in agreement with the secondary transitional temperature of the liquid structure of water as reported by the authors⁴⁾¹⁷⁾ using a chemical shift method and the transitional temperature reported by Drost-Hansen¹⁸⁻²⁰⁾ who measured dielectric constant. The slope change occurred at 313, 323, and 333 K and the slope change was similar among different mole fractions.

3. Correlation between the kinematic viscosity and density of 1,4-dioxane aqueous solution

The viscosity of water, $\eta_m(X_c, T)$, is determined by density $\rho_m(X_c, T)$ ⁵⁾ and kinematic viscosity $v_m(X_c, T)$ as shown in equation (10).

Table 1 Gradient of temperature dependency curve of measured kinematic viscosity

X_c	293 K-303 K	303 K-313 K	313 K-323 K	323 K-333 K	333 K-343 K
0.0	-0.01884	-0.01419	-0.01220	-0.00935	-0.00748
0.1	-0.01898	-0.01479	-0.01297	-0.00965	-0.00733
0.2	-0.02117	-0.01673	-0.01276	-0.01029	-0.00828
0.3	-0.02392	-0.01824	-0.01484	-0.01116	-0.00825
0.4	-0.02753	-0.02116	-0.01670	-0.01241	-0.01028
0.5	-0.03423	-0.02391	-0.01848	-0.01379	-0.01204
0.6	-0.03981	-0.02858	-0.02105	-0.01613	-0.01250
0.7	-0.04575	-0.03221	-0.02391	-0.01679	-0.01470
0.8	-0.04616	-0.03641	-0.02398	-0.01775	-0.01361
0.9	-0.04510	-0.02902	-0.02080	-0.01452	-0.01126
1.0	-0.02096	-0.01382	-0.01061	-0.00790	-0.00634
mean	-0.03113	-0.02264	-0.01712	-0.01270	-0.01019

$$\eta_m(X_c, T) = \rho_m(X_c, T) \cdot v_m(X_c, T) \dots \dots \dots (10)$$

Kinematic viscosity $v_m(X_c, T)$ is in proportion to viscosity $\eta_m(X_c, T)$ but is in inverse proportion to density $\rho_m(X_c, T)$ if $\eta_m(X_c, T)$ is constant.

Figure 5 indicates the relation between measured kinematic viscosity $v_m(X_c, T)$ and density $\rho_m(X_c, T)$. The solid line represents $X_{m(v,\rho)}\{v_m(X_c, T), \rho_m(X_c, T)\}$ at each mole fraction and temperature. The average correlation coefficient by mole fraction is 0.972. A convex curve was generated at all X_c values and a tendency to increase was observed as temperature decreased from 343 K (high) to 293 K (low). Both $v_m(X_c, T)$ and $\rho_m(X_c, T)$ increased slightly when X_c varied from 0.0 (1, 4-dioxane) to 0.7 and so did the slope and degree of convexicity. The slope continued to increase as X_c varied from 0.8 to 1.0 (water) but both $v_m(X_c, T)$ and $\rho_m(X_c, T)$ then rapidly decreased.

Unified expression was attempted to induce a relation equation between $v_m(X_c, T)$ and $\rho_m(X_c, T)$ because of similarities in overall shape.

Thus, the temperature of 343 K at which $v_m(X_c, T)$ and $\rho_m(X_c, T)$ showed the minimum value was used as a base as in equations (11) and (11').

$$v_{mR}(X_c, T) = \frac{v_m(X_c, T) - v_m(X_c, 343)}{v_m(X_c, 293) - v_m(X_c, 343)} \dots \dots \dots (11)$$

$$\rho_{mR}(X_c, T) = \frac{\rho_m(X_c, T) - \rho_m(X_c, 343)}{\rho_m(X_c, 293) - \rho_m(X_c, 343)} \dots \dots \dots (11')$$

Figure 6 presents the correlation between nondimensional kinematic viscosity $v_{mR}(X_c, T)$ and nondimensional density $\rho_{mR}(X_c, T)$. The mean $X_{mR(v,\rho)}\{v_{mR}(X_c, T), \rho_{mR}(X_c, T)\}$, $X_{HmR}(v, \rho)\{v_{HmR}(X_c, T), \rho_{HmR}(X_c, T)\}$ (solid line), at each temperature as expressed in equations (12) and (12') is also shown in the figure.

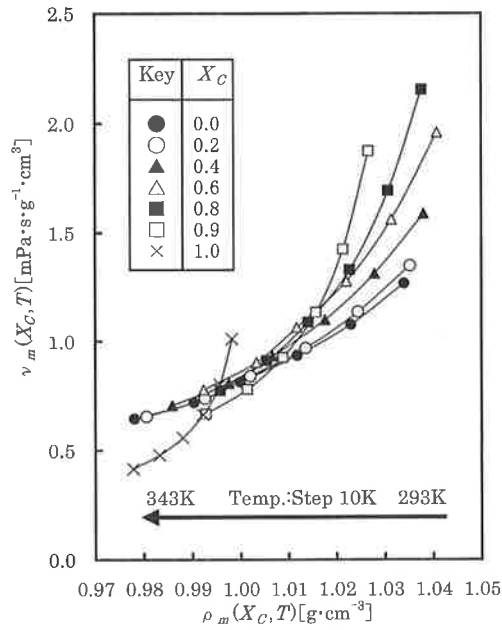


Fig. 5 Correlation of measured kinematic viscosity and measured density

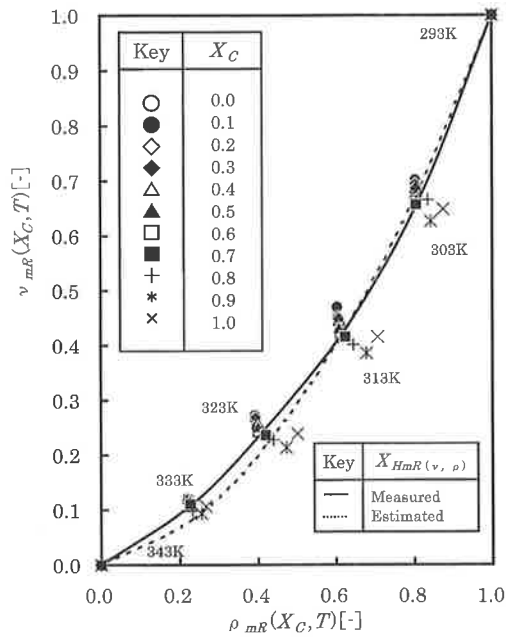


Fig. 6 Correlation of non-dimensional kinematic viscosity and non-dimensional density

$$\nu_{HmR}(X_c, T) = \frac{1}{11} \sum \nu_{mR}(X_c, T) \dots\dots\dots (12)$$

$$\rho_{HmR}(X_C, T) = \frac{1}{11} \sum_i \rho_{mR}(X_C, T) \dots\dots\dots (12')$$

The difference between $v_{mR}(X_C, T)$ and $v_{HmR}(X_C, T)$ and between $\rho_{mR}(X_C, T)$ and $\rho_{HmR}(X_C, T)$ was 0.047 and 0.085, respectively, at the largest and 0.016 and 0.022 on average. The correlation coefficient between $v_{mR}(X_C, T)$ and $\rho_{mR}(X_C, T)$ was 0.969.

Equation (13) was developed on the assumption that $X_{HmR}(v, \rho)$ at each temperature regresses to a parabola.

$$v_{mR}(X_C, T) = a \times (\rho_{mR}(X_C, T))^2 + b \times (\rho_{mR}(X_C, T)) + c \dots\dots\dots (13)$$

If $v_{mR}(X_C, T)$ is substituted by $V_{HmR}(X_C, T)$ and $\rho_{mR}(X_C, T)$ by $\rho_{HmR}(X_C, T)$ in equation (13) to substitute $X_{HmR}(v, \rho) \{v_{HmR}(X_C, T), \rho_{HmR}(X_C, T)\}$, the relation between kinematic viscosity and density is expressed by equation (13').

$$v_{mR}(X_C, T) = 0.834 \times (\rho_{mR}(X_C, T))^2 + 0.166 \times (\rho_{mR}(X_C, T)) \dots\dots\dots (13')$$

Figure 6 compares $X_{HeR}(v, \rho) \{v_{HeR}(X_C, T), \rho_{HmR}(X_C, T)\}$ (broken line), the average of the estimated non-dimensional kinematic viscosity $v_{eR}(X_C, T)$ as deduced from $\rho_{mR}(X_C, T)$ in equation (13'), with $X_{HmR}(v, \rho)$. The difference between $v_{eR}(X_C, T)$ and $v_{mR}(X_C, T)$ was 0.0325 (323 K) at the largest and 0.010 on average and the difference between $v_{eR}(X_C, T)$ and $v_{mR}(X_C, T)$ was 0.135 (303 K, $X_C=1.0$) at the largest and 0.044 on average.

Therefore, estimated kinematic viscosity $v_e(X_C, T)$ at each temperature and certain X_C can be determined from equation (11) as shown in equation (14).

$$v_e(X_C, T) = v_{eR}(X_C, T) \times \{v_m(X_C, 293) - v_m(X_C, 343)\} + v_m(X_C, 343) \dots\dots\dots (14)$$

If the estimated values calculated by equation (7) are substituted for $v_m(X_C, 293)$ and $v_m(X_C, 343)$ in this equation, the difference between $v_e(X_C, T)$ and $v_m(X_C, T)$ is 11.800% (313 K, $X_C=0.9$) at the largest and 3.876% on average. These values are inferior to the maximum difference of 4.075% (293 K, $X_C=0.4$) and the average differences of 1.336% between $v_e(X_C, T)$ and $v_m(X_C, T)$ as calculated in Section 2.1 but it is interesting to know that kinematic viscosity that varies in a complex manner at certain X_C values and temperatures can be estimated from the relation with non-dimensional density with an error of 12% or less.

4. Estimation of the viscosity of 1, 4-dioxane aqueous solution by dimensional analysis

Estimation of the viscosity of water in a solution was attempted using the dimensional analysis used in an equation representing a physical law.

The dimensional equation of viscosity is calculated from equation (10) as in equation (15).

$$\left[\frac{M}{L \cdot H} \right] = \left[\frac{M}{L^3} \right] \left[\frac{L}{H} \right] [L] = \rho UL \dots\dots\dots (15)$$

Thus, viscosity is the product of density, rate, and length. By applying this concept to the viscosity of water according to the normal mixture model that considers changes in the liquid

structure of water as reported previously by the authors⁵⁾, the viscosity $\eta_m(X_c, T)$ of a solution is calculated from the average mole fraction of both components as shown in equation (16).

$$\eta_m(X_c, T) = \rho(X_c, T)UL = \frac{\{M_w X_c + M_D(1 - X_c)\}UL}{V_w(X_c, T)X_c + V_D(T)(1 - X_c)}$$

$$= \frac{\left(\frac{M_w UL}{V_w(X_c, T)}\right)V_w(X_c, T)X_c + \left(\frac{M_D UL}{V_D(T)}\right)V_D(T)(1 - X_c)}{V_w(X_c, T)X_c + V_D(T)(1 - X_c)} \dots\dots\dots (16)$$

The first term of the right side of the equation represents the viscosity of water $\eta_w(X_c, T)$ in a solution and the second term represents the viscosity of 1,4-dioxane $\eta_D(T)$, so the viscosity $\eta_m(X_c, T)$ of the solution is expressed as equation (16').

$$\eta_m(X_c, T) = \frac{\eta_D(X_c, T)V_w(X_c, T)X_c + \eta_D(T)V_D(T)(1 - X_c)}{V_w(X_c, T)X_c + V_D(T)(1 - X_c)} \dots\dots\dots (16')$$

5. Estimation of the viscosity of water in 1, 4-dioxane aqueous solution

The viscosity of water $\eta_w(X_c, T)$ in a solution can be calculated from equation (16') as in equation (17).

$$\eta_w(X_c, T) = \frac{\eta_m(X_c, T)\{V_w(X_c, T)X_c + V_D(T)(1 - X_c)\}}{V_w(X_c, T)X_c}$$

$$- \frac{\eta_D(T)V_D(T)(1 - X_c)}{V_w(X_c, T)X_c} \dots\dots\dots (17)$$

Figure 7 shows the mole fraction dependency of the viscosity of water $\eta_w(X_c, T)$ in a solution as estimated from equation (17).

The viscosity of water in a solution shows similar changes among different temperatures and mole fractions. The viscosity of liquids other than water also decreases as temperature rises. In addition, the viscosity of liquids generally increases as pressure rises as reported in a number of studies²²⁾ concerning the specificity of pressure dependency. However, the viscosity of water decreases as pressure increases at 303 K or less and then increases after reaching a minimum. These phenomena are thought to occur because the viscosity of water strongly depends on intermolecular hydrogen bonds.

Conclusion

The mole fraction dependency of the kinematic viscosity of 1, 4-dioxane aqueous solution was measured under atmospheric pressure and at 293–343 K (at 10-K intervals) to study the method of estimating the kinematic viscosity of a solution and the viscosity of water in a solution, and the liquid structure of water in a solution. The following conclusions were obtained :

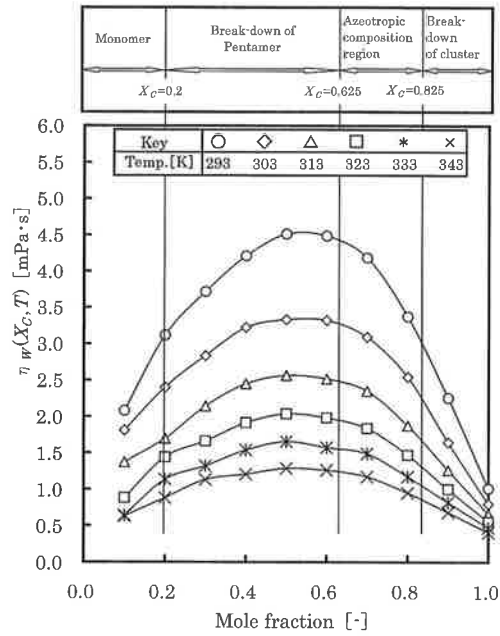


Fig. 7 Estimated viscosity of water in 1,4-dioxane aqueous solution

- 1) The kinematic viscosity of 1,4-dioxane aqueous solution at certain X_c values and temperatures can be estimated from nondimensional differences between the average mole fraction line connecting the measured kinematic viscosity of water and 1,4-dioxane and certain kinematic viscosity values.
- 2) The difference in kinematic viscosity between the values estimated from equation (7) that was deduced from the above idea and measured values was 4.075% (293 K, $X_c=0.4$) at the largest and 1.336% on average.
- 3) The temperature dependency of measured kinematic viscosity was demonstrated.
- 4) The correlation coefficient between nondimensional kinematic viscosity and density was 0.969, so the kinematic viscosity of a solution at certain X_c values and temperatures can be estimated by determining regression curves.
- 5) The viscosity of a solution at certain X_c values and temperatures can be estimated by applying dimensional analysis.
- 6) The viscosity of water in a solution at certain X_c values and temperatures can be estimated from equation (17) deduced from the above estimation equation.
- 7) The viscosity of water in a solution seems to increase until it reaches a maximum at an X_c of 0.5 as 1,4-dioxane is added and hydrogen bonds of the five-membered structure of water are cleaved.

Nomenclature

a : Constant for estimated kinematic viscosity of the solution	[-]
b : Constant for estimated kinematic viscosity of the solution	[-]
$a(T)$: Coefficient of estimated kinematic viscosity of the solution at arbitrary temperature	[-]
$b(T)$: Coefficient of estimated kinematic viscosity of the solution at arbitrary temperature	[-]
H : Dimensional notation of time	[s]
L : Dimensional notation of length	[m]
M : Dimensional notation of mass	[kg]
M_w, M_D : Molar weight of water ($X_c=1.0$) and 1, 4-dioxane ($X_c=0.0$)	[kg • mol ⁻¹]
T : Dimensional notation of temperature	[K]
U : Dimensional notation of velocity	[m • s ⁻¹]
$V_w(T), V_D(T)$: Molar volume of water ($X_c=1.0$) and 1,4-dioxane ($X_c=0.0$) at arbitrary temperature	[m ³ • mol ⁻¹]
$V_w(X_c, T)$: Molar volume of water in 1, 4-dioxane aqueous solution at arbitrary temperature and mole fraction	[m ³ • mol ⁻¹]
X_c : Mole fraction in the liquid phase of 1, 4-dioxane aqueous solution, taking water as the first component.	[-]
$X_{mR}(v,\rho)$: Correlation of non-dimensional kinematic viscosity and non-dimensional density	[-]
$X_{HmR}(v,\rho)$: Correlation of average non-dimensional kinematic viscosity and average non-dimensional density	[-]
η : Dimensional notation of Viscosity	[mPa • s]
$\eta_D(T)$: Viscosity of 1, 4-dioxane at arbitrary temperature	[mPa • s]
$\eta_m(X_c, T)$: Measured viscosity of the solution at arbitrary temperature and mole fraction	[mPa • s]
$\eta_w(X_c, T)$: Viscosity of water in the solution at arbitrary temperature and mole fraction	[mPa • s]
v : Dimensional notation of kinematic viscosity	[m ² • s ⁻¹]
$v_e(X_c, T)$: Estimated kinematic viscosity of the solution at arbitrary temperature and mole fraction	[m ² • s ⁻¹]
$v_{eR}(X_c, T)$: Non-dimensional estimated kinematic viscosity of the solution at arbitrary temperature and mole fraction	[m ² • s ⁻¹]
$v_{HeR}(X_c, T)$: Average non-dimensional estimated kinematic viscosity of the solution at arbitrary temperature and mole fraction	[m ² • s ⁻¹]
$v_{HmR}(X_c, T)$: Average non-dimensional measured kinematic viscosity of the solution at arbitrary temperature and mole fraction	[m ² • s ⁻¹]

$v_m(X_c, T)$: Measured kinematic viscosity of the solution at arbitrary temperature and mole fraction	[m ² · s ⁻¹]
$v_{mR}(X_c, T)$: Non-dimensional measured kinematic viscosity of the solution at arbitrary temperature and mole fraction	[m ² · s ⁻¹]
$\Delta v_m(X_c, T)$: Difference of measured kinematic viscosity of the solution and mean mole fraction dependency at arbitrary temperature and mole fraction	[m ² · s ⁻¹]
ρ : Dimensional notation of density	[kg · m ⁻³]
$\rho_{HmR}(X_c, T)$: Average non-dimensional measured density of the solution at arbitrary temperature and mole fraction	[kg · m ⁻³]
$\rho_m(X_c, T)$: Measured density of the solution at arbitrary temperature and mole fraction	[kg · m ⁻³]
$\rho_{mR}(X_c, T)$: Non-dimensional measured density of the solution at arbitrary temperature and mole fraction	[kg · m ⁻³]

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