



Correlations between density, viscosity, surface tension and ultrasonic velocity of different mono- and di-saccharides



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ABSTRACT

The aim of this study is to correlate the density, viscosity, surface tension and ultrasonic velocity of different concentrations (0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09 and 0.10 mol/L) of mono- (fructose, glucose and galactose) and di- (sucrose, maltose and lactose) saccharide solutions at six different temperatures (298.15, 308.15, 318.15, 328.15, 338.15 and 348.15 K). The correlations between surface tension and viscosity have been investigated using four different models. The suitability of the models was checked using the deviation modulus. The correlation of ultrasonic velocity, density and surface tension leads to a master curve with a high regression coefficient ($R^2 = 0.997$).

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1. Introduction

Viscosity and surface tension are two properties of fluids that are different in nature but whose values need to be known for a wide variety of industrial and physicochemical process (catalysis, adsorption, distillation, extraction, etc.). The surface tension, σ , is a physical property of matter related to the intermolecular interaction potential energy and the liquid interfacial microstructure [1–5]. The surface tension can be measured with high accuracy at low and moderate temperatures and pressures, while at high temperatures and pressures, the values are determined using computer simulations [6,7]. The fluid viscosity, η , is measured with high precision, and the resulting data and its temperature dependence are used as essential properties for the accurate determination of molecular information such as the pair interaction potential function [8].

Density, as the other parameters, is the basic physical parameter frequently used in chemical engineering, and also the indispensable thermodynamic data for chemical researches and computations involving fluid flow, heat transfer and mass transfer [9].

Pelofsky proposed in 1966 [10] an empirical relationship between natural logarithm of surface tension and the inverse of viscosity (usually termed the fluidity). Pelofsky's empirical expression (which we shall denote here as the *P* correlation) can be applied to both the organic and inorganic phases of pure and mixed components [10]. Two adjustable coefficients are needed, whose values may depend in the temperature range being considered. The *P* correlation was later modified by Schonhorn [11] who introduced a correction into the second term of

the right-hand side of the expression to fulfill the requirement that, at the critical point, the surface tension goes to zero while the viscosity tends to a small constant value. This modification introduces new coefficients, and has not subsequently been used [12].

Ghatee et al. [13] applied the Pelofsky model (modified Pelofsky model) to correlate the surface tension and viscosity of some ionic liquids. It was observed that it was necessary to modify it slightly by introducing an exponent into the viscosity term. They initially treated this exponent as an adjustable coefficient but then they found that its value could be fixed at 0.3 without any significant loss of accuracy for the fluids considered. The same observations were observed by Oroian [14] in the case of honeys.

The two model accuracy (Pelofsky and Ghatee), according to Zheng et al. [12], are very limited in terms of performance and accuracy for the calculation of surface tension for selected fluids in a different temperature range. The use of equations with greater number of coefficients can improve the performance of the model for the correlation of surface tension and viscosity [12].

In the case of the physical properties of mono- and di-saccharide solutions, some studies related to hydration behavior at different temperatures [15], the measuring of density, viscosity and ultrasonic velocity at different temperatures [16], and heat capacity in solid state [17] have been reported. To the authors' knowledge no other studies related to the correlation of different physical properties of mono- and di-saccharide solution have been reported.

The aim of this study is to investigate the correlation between surface tension and viscosity of different concentrations (0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09 and 0.10 m) of mono- (fructose, glucose and galactose) and di- (sucrose, maltose and lactose) saccharide solutions at six different temperatures (298.15, 308.15, 318.15, 328.15,

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338.15 and 348.15 K) using four models, and the correlation between surface tension, density and ultrasonic velocity in the same conditions.

2. Materials and methods

2.1. Materials

For this study, six different mono- and di-saccharides: fructose, glucose, galactose, maltose, lactose and sucrose at different molar concentrations (0.01 to 0.10 mol/L) were analyzed. All the mono- and di-saccharides were purchased from Sigma Aldrich (Germany). The solutions were prepared using double deionized water. Double deionized water (18 M Ω cm resistivity) produced by a water purification system (Thermofisher, Germany) was used in all solutions.

2.2. Density measurements

Density (ρ) of the samples was measured using a pycnometer with an accuracy 10^{-4} kg/m 3 . The calibration of a pycnometer was made with ultrapure water. Temperature was kept constant within ± 0.01 K using a PID controller and circulating water using a thermostatic-fluid bath. The density of the samples was measured at 298.15, 308.15, 318.15, 328.15, 338.15 and 348.15 K. The values of parameters were expressed as the mean \pm standard deviation to a confidence interval for mean of 95%.

2.3. Ultrasonic velocity measurement

The ultrasonic velocity measurement was carried out using a flow detector USM 35X (GE Measurement and Control, USA) with a dual-element (TR) probe working at 4 MHz. The measurements were carried out at 298.15, 308.15, 318.15, 328.15, 338.15 and 348.15 K. The values of parameters were expressed as the mean \pm standard deviation to a confidence interval for mean of 95%.

2.4. Viscosity measurement

Viscosity measurements were carried out on the samples at different temperatures (298.15, 308.15, 318.15, 328.15, 338.15 and 348.15 K), with an Ubbelohde viscometer and a temperature controlled water bath (uncertainty 0.26%). The sample was allowed to reach the desired temperature for 20 min. Each measurement was taken in duplicate. The values of parameters were expressed as the mean \pm standard deviation to a confidence interval for mean of 95%.

2.5. Surface tension determination

The surface tension was computed using Auerbach's equation: [18]

$$u = \left(\frac{\sigma}{6.33 \cdot 10^{-10} \cdot \rho} \right)^{2/3} \quad (1)$$

where u is the ultrasonic velocity (m/s), σ is the surface tension in N/m and ρ is the density in kg/m 3 . Therefore, for the calculation of the surface tension, first we measured the ultrasonic velocity and density and later on by using the Auerbach equation we were able to compute the surface tension.

2.6. Prediction accuracy

The mean relative deviation modulus, D , was used to verify the suitability of model for experimental data:

$$D\% = \frac{100}{n} \sum_{i=1}^n \frac{|X_{\text{exp},i} - X_{\text{cal},i}|}{X_{\text{exp},i}} \quad (2)$$

where n is the total number of data. Subscripts exp. and cal. denote experimental and calculated values, respectively. X represents viscosity, η , or surface tension, σ .

3. Results and discussions

The physical parameters (ultrasonic velocity, density, viscosity and surface tension) have been analyzed at different temperatures (298.15, 308.15, 318.15, 328.15, 338.15 and 348.15 K, with a temperature accuracy of 0.01 K). The physical parameter values in function of temperatures and concentrations are presented in Tables 1–4.

3.1. Influence of temperature and concentration on the viscosity

The saccharide solution viscosity has been measured using the Ubbelohde viscometer at different temperatures (298.15, 308.15, 318.15, 328.15, 338.15 and 348.15 K). It can be observed in Fig. 1 that the solution viscosity is influenced positively by the concentration and negatively by the temperature.

Correlations were made to allow the prediction of viscosity of the honey samples. The correlations of viscosity were as a function of temperature or honey concentration using polynomial fitting by means of the experimental data. The following expressions were used for the regression equations of the experimental data:

$$\eta = a + b \cdot T + f \cdot T^2 \quad (3)$$

$$\eta = d + e \cdot c_M + f \cdot c_M^2 \quad (4)$$

where η is the viscosity in N·s·m $^{-2}$, T is the temperature in K, c_M is the molar concentration (mol/L) and a – f are the fitting parameters. The regression coefficients for both models ranged between 0.961 and 0.997.

The values of a ranged between $1.718 \cdot 10^{-3}$ and $1.953 \cdot 10^{-3}$, b ranged between $-0.04289 \cdot 10^{-3}$, and c ranged between $0.00026 \cdot 10^{-3}$ and $0.00029 \cdot 10^{-3}$, respectively. The a and c are positively influenced by the concentration ($r = 0.835^{***}$ and $r = 0.781$, respectively) and b is not influenced significantly by the temperature ($r = -0.044$ ns).

The parameters d of Eq. (4) ranged between $0.245 \cdot 10^{-3}$ and $0.944 \cdot 10^{-3}$, e ranged between $0.180 \cdot 10^{-3}$ and $1.038 \cdot 10^{-3}$ and f ranged between $0.290 \cdot 10^{-3}$ and $1.117 \cdot 10^{-3}$, respectively. The d and e are negatively influenced by the temperature ($r = -0.957^{***}$ and $r = -0.877$, respectively) and f is positively influenced by the temperature ($r = 0.904^{***}$). The mean deviation modulus between the prediction and experimental values and average ranged between 0.172% and 0.564%.

3.2. Influence of temperature and concentration on the surface tension

The solution surface tension (computed using the Auerbach relation) ranged between 0.030 and 0.038 N/m. A linear evolution of the surface tension with temperature (Fig. 2) can be observed. The evolution of the surface tension with temperature was subjected to linear regression to see its prediction using the following equation:

$$\sigma = g + h \cdot T + i \cdot T^2 \quad (5)$$

where σ – surface tension in N/m, g , h and i are constants, and T – temperature (K).

In Fig. 2, the evolution of surface tension and solution concentration for glucose is presented. The g values ranged between 0.040 and 0.041, h ranged between -0.00015 and -0.00016 , while i ranged between $1.96 \cdot 10^{-7}$ and $2.00 \cdot 10^{-7}$. The g and i values are influenced positively by the concentration ($r = 0.977^{***}$ and $r = 0.926^{***}$ respectively), and h is influenced negatively by the concentration ($r = -0.945^{***}$).

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