Acoustical and thermodynamic investigations of L-serine in aqueous solutions of carbohydrates at different temperatures

Ashwani Kumar[1], Asha Sharmhal[2] and Rajinder K. Bamezai*[1]

[1]: Department of Chemistry, University of Jammu, Jammu, India

[2]: Department of Chemistry, Govt. Degree College Basohli, Kathua, India

ABSTRACT

Density and speed of sound of L-serine (0.025 to 0.2 mol kg^{-1}) in water and in aqueous saccharides viz 0.1 M glucose, 0.1 M sucrose and 0.1 M lactose were obtained at T = (293.15, 298.15, 303.15, 308.15 and 313.15) K. From the density and speed of sound data, the limiting apparent molar volume, limiting apparent molar compressibility and their corresponding transfer parameters have been evaluated. Positive values of transfer parameters suggest the predominance of solute-solvent (hydrophilic-ionic group and hydrophilic-hydrophilic group) interactions over solute-solute (hydrophobic-hydrophilic group) interactions in the solution. The results have been discussed in terms of solute-solute and solute-solvent interactions in these systems. Moreover, modulation of volumetric properties of L-serine in aqueous saccharides solutions has also been discussed in relation to the increase in the complexity of saccharides and temperature.

Keywords: Carbohydrates, Density, L-serine, Speed of sound, Transfer compressibility, Transfer volume

1. INTRODUCTION

The interactions of saccharides with proteins have been an intense field of research as it finds applications in number of biochemical processes like immunology, biosynthesis, medicine, pharmacology, etc. Amino acids, being the basic structural units of proteins, make up the major content of human body in playing a vital role. So, the thermodynamic study of these compounds in aqueous and mixed aqueous saccharide solutions can provide valuable information on solute-solute and solute-solvent interactions [1-4]. The physiological importance of amino acids can also be gauzed from the fact that they are delicate to the gustatory system, therefore, every amino acid makes a contribution of varying degree towards the taste of foods [5,6]. L-serine has α-amino and carboxyl groups. Apart from it, L-serine has a side chain isopropyl variable group, making it a non-polar and essential amino acid. It cannot be synthesized in human body and thus must be obtained from the diet. Saccharide solutions are often used in various food related industries to control the water activity, pH and to monitor the growth of microorganisms that are contaminated [7,8]. The addition of cosolute (saccharide) to the system (amino acid + water) can drastically affect the interactions between amino acids and water molecules and, accordingly, the structural order of the water molecule may increase or decrease. Further, a better understanding of the mechanism of taste chemoreception can be monitored by studying the parameters on solute-water interactions and particularly, the changes involved in the hydration layer of the solute, through a number of studies on the molar volumes of savor molecules [9-16]. Therefore, physicochemical data determining the hydration behavior of saccharides is required for a better understanding of protein stabilization, taste chemoreception and antidesiccation mechanisms [17].

Although, a detailed study of thermophysical properties of amino acids are known [18-22], however, volumetric and compressibility studies along with taste behavior of L-serine with some saccharides (glucose, sucrose and lactose) in the aqueous medium seem to be scarce. This led us to study the thermodynamic behavior of L-serine in the concentration range (0.0 to 0.2) mol kg^{-1} in water and in various aqueous solution of saccharides (0.1 glucose, 0.1 sucrose and 0.1 lactose) mol dm^{-3} at T = (293.15, 298.15, 303.15, 308.15 and 313.15) K, i.e., as a function of concentration and temperature, from density and speed of sound data. The derived parameters like apparent molar volume, limiting apparent molar volume, transfer volume, as well as apparent molar compressibility, limiting apparent molar compressibility, transfer compressibility, partial molar expansibilities and thermal expansion coefficient are obtained from the experimental results. These evaluated parameters are found to be helpful to understand the interactions between aqueous saccharides and the L-serine.

2. EXPERIMENTAL

2.1. Source and purity of chemicals

The chemicals along with their mass fraction purity used in the present work are: L-serine, α-lactose monohydrate (all >99.8%), D-(+)-glucose, sucrose (both >99.5%). All these chemicals are obtained from Sigma Aldrich, India and used after keeping them over anhydrous calcium chloride in a vacuum desiccator overnight at room temperature, except α-lactose monohydrate which was used as such. All the solutions are prepared in freshly prepared triple distilled water on molality basis. Specific conductance of the triple distilled water used for the preparation of aqueous solutions was found to be less than 1×10^{-6} S cm^{-1}.

2.2. Apparatus and procedure

The stock solutions of glucose, sucrose and lactose (each being 0.1 mol dm^{-3}) were used as solvent to prepare L-serine solutions of nine different molal concentrations (ranging from 0.0 to 0.2) mol kg^{-1}. An electronic single pan five digit analytical balance (Model: Mettler AE-240) with a precision of ±0.01 mg was used to measure the mass. All the solutions were prepared with precaution and stored in special airtight bottles to avoid their exposure to air and evaporation. A vibrating-tube density meter (Model: DMA 5000M, Anton Paar, Austria) with an uncertainty of $\pm 5 \times 10^{-2}$ kg m^{-3} was used to measure the density of solutions. A density calibration was performed first with triply distilled water followed by dry air at 293.15 K at atmospheric pressure before each series of measurement. The density, being extremely sensitive to temperature, was controlled to $\pm 1 \times 10^{-3}$ K by built-in Peltier system. The speed of sound of solutions was measured using a single-crystal variable-path multi-frequency ultrasonic interferometer (Model: M-82S, Mittal Enterprises, India) having stainless steel sample cell (with a digital micrometer) operating at a fixed frequency of 2 MHz. The uncertainty in speed measurement was found to be within ±0.5 m s^{-1}. The temperature of solutions was maintained to an accuracy of ±0.02 K using an electronic controlled thermostatic water bath (Model: TIC-4000N, Thermotech, India).

3. RESULTS AND DISCUSSION

3.1. Volumetric studies

The experimental values of density and speeds of sound of L-serine in the concentration range (0.000, 0.025, 0.050, 0.075, 0.100, 0.125, 0.150, 0.175 and 0.200) mol kg^{-1} in water and aqueous solution of saccharides (0.1

glucose, 0.1 sucrose and 0.1 lactose) mol dm^{-3} at T = (293.15, 298.15, 303.15, 308.15 and 313.15) K are listed in Table 1. The density of L-serine in solutions (representative 3-D plot, shown in Fig 1, of density versus molality of L-serine in aqueous solution of 0.1 mol dm^{-3} lactose) increase with the increase in the concentration of L-serine but decreases with the rise of temperature.

The apparent molar volume (V_ϕ) has been obtained from the density values using Equation 1.

$$V_\phi = \frac{1000(\rho_o - \rho)}{m\rho\rho_o} + \frac{M}{\rho} \qquad (1)$$

where M and m are the molar mass and molality of solute (L-serine), ρ and ρ_o are the densities of the solution (amino acid + saccharide + water) and solvent (saccharide + water), respectively. The data presented in Table 2 reveals that apparent molar volume increases as the temperature and concentration of L-serine increase. A plot of V_ϕ against molality of L-serine in water as well as aqueous solution of saccharides at different temperatures has been found to be linear (Fig. 2 is for L-serine in one of the saccharides, namely, 0.1 mol dm^{-3} glucose). The limiting apparent molar volume of solute, also known as partial molar volume (V^o_ϕ), is then obtained using the least square fitting of V_ϕ values through the following relation:

$$V_\phi = V^o_\phi + S_v m \qquad (2)$$

where S_v , the experimental slope, is characteristic of interactions between solute molecules.

The values of V^o_ϕ and S_v along with the standard deviation, σ, for L-serine in water as well as aqueous solution of saccharides at different temperatures are presented in Table 3. Our values of V^o_ϕ in water are found to be in good agreement with those reported in literature [23,24]. An introspection of this Table shows that V^o_ϕ values of L-serine in water and cosolute (aqueous solution of saccharides) are positive at all temperatures which are an indicative of strong solute–solvent interactions. The greater V^o_ϕ values for L-serine in aqueous glucose/sucrose/lactose solutions in comparison to aqueous solution may be attributed to its hydration behaviour. The values also increase with the increase in temperature from aqueous to aqueous saccharides. This may be ascribed on the basis of the size of primary and secondary solvation layers around the zwitterions of L-serine in aqueous saccharides. An increase in temperature allows the solvent molecule from the secondary solvation layer of L-serine zwitterions to get released into the bulk of the solvent rather than binding to the charged end groups which results in the expansion of the solution [25].

The limiting apparent molar transfer volume ($\Delta_{tr}V°_\phi$ Table 3) of L-serine from water to aqueous saccharides was calculated using the following relation:

$$\Delta_{tr}V°_\phi = V°_{\phi,aq\text{-}saccharides} - V°_{\phi,water} \qquad (3)$$

where $V°_{\phi,water}$ is the limiting apparent molar volume of the L-serine in water. The $\Delta_{tr}V°_\phi$ values are positive which increases with increase in the complexity of saccharides, i.e., in the order lactose > sucrose > glucose but decreases with increase in temperature.

The limiting apparent molar volume of L-serine can also be expressed in the following way [26,27]:

$$V°_\phi = \mathrm{V_{vdW}} + V_{void} - V_s \qquad (4)$$

Where $\mathrm{V_{vdW}}$ is the van der Waals volume [28] occupied by the solute, V_{void} is the volume linked with the void and vacant spaces present therein and V_s is shrinkage in the volume due to hydrogen bonding between the solute and water molecules. It has been well documented that the contribution due to $\mathrm{V_{vdW}}$ and V_{void} experimentally remain same in both water as well as aqueous glucose/sucrose/lactose solutions [29]. Hence, positive $\Delta_{tr}V°_\phi$ values for the L-serine can be ascribed due to decrease in the shrinkage volume in presence of aqueous saccharide solutions.

The interactions between solute and cosolute in aqueous solution can be explained using a co-sphere overlap model [30]. When two molecules come closer to each other, their hydration co-spheres overlap. This results in the displacement of co-sphere material accompanied by change in thermodynamic properties of solutions which may be used as one of the tools to explain $\Delta_{tr}V°_\phi$ values. As per this model, the main interactions between amino acid (solute) and three saccharides (cosolute) may be classified as: (a) hydrophilic-ionic interactions between OH groups of saccharides and zwitterions of amino acid, (b) hydrophilic-hydrophobic interactions between the OH groups of saccharides and non-polar (-CH_2) in side chain of amino acid and (c) hydrophobic-hydrophobic interactions between hydrophobic groups of solute and cosolute [31]. The $V°_\phi$ values increase due to reduction in the electrostriction at terminals by positive contribution from the interactions of type (a) leading to positive $\Delta_{tr}V°_\phi$ values. On the contrary, $V°_\phi$ values may decrease due to disruption of side group hydration by that of the charged end by negative contribution from the interactions of type (b) and (c) leading to negative $\Delta_{tr}V°_\phi$ values. Our positive $\Delta_{tr}V°_\phi$ results justify dominance of interactions of type (a). The $\Delta_{tr}V°_\phi$ values of solute in aqueous cosolute at all temperatures follow the order: lactose > sucrose > glucose. Glucose molecule is a monosaccharide, whereas both sucrose and lactose has two monosaccharide units with the difference that the lactose molecule has galactose and glucose subunits whereas the sucrose molecule consists of glucose and fructose subunits. The above trend is due to the strong hydrophilic-ionic interactions of solute in aqueous lactose and sucrose solutions due to the presence of higher number of OH groups than in glucose one.

In order to evaluate the limiting apparent molar expansibility (ϕ^o_E), one makes use of variation of $V°_\phi$ with T using the following general polynomial equation:

$$V°_\phi = a + bT + cT^2 \qquad (5)$$

where a, b and c are coefficients whose values are listed in Table 4. The limiting apparent molar expansibility, reported in Table 5, can now be evaluated as:

$$\phi^o_E = (\partial V°_\phi/\partial T)_p = b + 2cT \qquad (6)$$

It is evident that ϕ^o_E values are positive and decrease with temperature, which is also shown by negative $(\partial^2 V°_\phi/\partial T^2)_p$ values. This means that molecular motions get swifter and the disagreement in water structure becomes little between hydration shell and bulk water resulting into the feeble overlap of hydration shell. Another parameter, the temperature derivative of apparent molar expansibility at infinite dilution, which gives pivotal judgment regarding the solvation of a solute and its structure making or structure breaking ability in a solvent, can be determined using the following relation:

$$(\partial\phi^o_E/\partial T)_p = (\partial^2 V°_\phi/\partial T^2)_p = 2c \qquad (7)$$

For structure making and structure breaking solutes, $(\partial^2 V°_\phi/\partial T^2)_p$ values should be positive and negative, respectively [32]. Our observation (Table 4) suggests that L-serine act as structural breaker in water and aqueous saccharides.

The thermal expansion coefficient, α, has been calculated using the following relation:

$$\alpha = 1/V°_\phi\,(\partial V°_\phi/\partial T)_p \qquad (8)$$

A general observation which arises from Table 5 is that α values decrease with increasing temperature. This trend shows that the structure plays an important part in deciding the magnitude of α, which further supports the chaotropic behaviour of the L-serine in aqueous solution of various saccharides. In general, it has observed that thermal expansion coefficient in conjunction with limiting apparent volume may be used as a tool to explain the solute-solvent interactions [33].

3.2. Compressibility studies

The isentropic compressibility (κ_s) is given by the following equation:

$$\kappa_s = (u^2\rho)^{-1} \qquad (9)$$

The isentropic compressibility of L-serine in water and aqueous saccharides shows a decrease with increase in molality of the L-serine as well as temperature (values not given). The decreasing κ_s values indicate that the water molecules around the solute (L-serine) associated with ionic groups of zwitterion/hydrophilic groups are less compressible than water molecules in the bulk solution [34], which is imperative due to strong attractive interactions. The observed κ_s values in water and 0.1 mol dm^{-3} aqueous solutions each of lactose, sucrose and glucose are 4.47187, 4.37862, 4.38680 and 4.42884 (10^{-10} m^2 N^{-1}), respectively at 298.15 K. The trend lactose < sucrose < glucose is obeyed at other temperatures as well.

Apparent molar compressibility ($K_{s,\phi}$) is evaluated from density and speed of sound values using Eqn. (10).

$$K_{s,\phi} = \frac{1000(\kappa_s\rho_0 - \kappa^o{}_s\rho)}{m\rho\rho_0} + \frac{M}{\rho} \qquad (10)$$

where κ_s and $\kappa^o{}_s$ are isentropic compressibilities of solution and solvent (aqueous saccharides), respectively.

The values of apparent molar compressibility of L-serine are presented in Table 2. Its variation with molality of L-serine in water as well as aqueous saccharides at different temperatures has been found to be linear (Fig. 3 is for L-serine in one of the saccharides, namely, 0.1 mol dm^{-3} glucose). The variation of apparent molar compressibility ($K_{s,\phi}$) with the molality can be represented using the following relation.

$$K_{s,\phi} = K^o{}_{s,\phi} + S_k m \qquad (11)$$

where $K^o{}_{s,\phi}$ is the limiting apparent molar compressibility or partial molar compressibility of solute and S_k is the experimental slope. Both these values, obtained using linear regression of $K^o{}_{s,\phi}$ against m, along with the standard deviation, σ, are given in Table 3. An examination of this table suggests that $K^o{}_{s,\phi}$ and S_k values, at all temperatures, are negative and positive, respectively. The negative values of $K°_{s,\phi}$ reaffirm that the water molecules surrounding the ionic charged groups of L-serine provide great resistance to compression than water molecules present in the bulk of the solution, thereby, advocating the existence of strong solute-solvent interactions than weak solute-solvent interactions. The more negative values at lower temperature may be due to the strong attractive interactions between solute and solvent molecules. As the temperature is raised, $K°_{s,\phi}$ values becomes less negative which indicates that electrostriction is reduced and some water molecules from the secondary solvation layer of zwitterions from the L-serine are released into the bulk, thus, making the solutions more compressible.

The limiting apparent molar transfer compressibility ($\Delta_{tr}K°_{s,\phi}$) of L-serine from water to aqueous saccharides is calculated using the following expression:

$$\Delta_{tr}K°_{s,\phi} = K°_{s,\phi,aq.\ saccharides} - K°_{s,\phi,water} \qquad (12)$$

where $K°_{s,\phi,water}$ is the limiting apparent molar compressibility of the L-serine in water. The $\Delta_{tr}K°_{s,\phi}$ values of the L-serine from water to aqueous saccharides, shown in Table 3, are positive which decreases with increase in temperature but increase as we move from glucose to lactose. The positive $\Delta_{tr}K°_{s,\phi}$ values signify the importance of the charged end groups of L-serine. The interactions among zwitterionic centres of L-serine and saccharides increase with the increase in the complexity of saccharides. With the increasing complexity of saccharides, electrostriction increases and structure making tendency of ions increase, making electrostricted water much less compressible than bulk water. The decrease in $\Delta_{tr}K^{\circ}_{s,\phi}$ values with increase in temperature indicate that release of water molecules from the secondary solvation layer of zwitterions into the bulk becomes difficult as compared to aqueous medium. The observed trends in $K^{\circ}_{s,\phi}$ and $\Delta_{tr}K^{\circ}_{s,\phi}$ support the conclusions drawn from V°_{ϕ} and $\Delta_{tr}V^{\circ}_{\phi}$.

4. CONCLUSIONS

The densities and speeds of sound of solutions of L-serine in water and in aqueous saccharides (0.1 mol dm^{-3} glucose, 0.1 mol dm^{-3} sucrose and 0.1 mol dm^{-3} lactose) are measured at different temperatures. From the experimental density and speed of sound results, several thermodynamic parameters are calculated. The degree of interactions increases with an increase in the molar mass of L-serine and an increase in the complexity of saccharides. The positive values of $\Delta_{tr}V^{\circ}_{\phi}$ and $\Delta_{tr}K^{\circ}_{s,\phi}$ show that solute-solvent interactions are prominent over solute-solute interactions and this overpowering effect decreases with the increase in temperature for all the systems under study.

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Table 1. Density (ρ) and speeds of sound (u) of L-serine of different molalities in water and aqueous saccharides solutions at different temperatures.

m (mol kg^{-1})	*T* (K)									
	293.15				293.15				293.15	
	ρ (kg m^{-3})		ρ (kg m^{-3})		ρ (kg m^{-3})		ρ (kg m^{-3})		ρ (kg m^{-3})	
L-serine + water										
0.000	998.212	0.000	998.212	0.000	998.212	0.000	998.212	0.000	998.212	0.000
0.025	999.337	0.025	999.337	0.025	999.337	0.025	999.337	0.025	999.337	0.025
0.050	1000.454	0.050	1000.454	0.050	1000.454	0.050	1000.454	0.050	1000.454	0.050
0.075	1001.562	0.075	1001.562	0.075	1001.562	0.075	1001.562	0.075	1001.562	0.075
0.100	1002.661	0.100	1002.661	0.100	1002.661	0.100	1002.661	0.100	1002.661	0.100
0.125	1003.751	0.125	1003.751	0.125	1003.751	0.125	1003.751	0.125	1003.751	0.125
0.150	1004.832	0.150	1004.832	0.150	1004.832	0.150	1004.832	0.150	1004.832	0.150
0.175	1005.904	0.175	1005.904	0.175	1005.904	0.175	1005.904	0.175	1005.904	0.175
0.200	1006.966	0.200	1006.966	0.200	1006.966	0.200	1006.966	0.200	1006.966	0.200
L-serine + 0.1 mol dm^{-3} aqueous-glucose										
0.000	1005.255	0.000	1005.255	0.000	1005.255	0.000	1005.255	0.000	1005.255	0.000
0.025	1006.336	0.025	1006.336	0.025	1006.336	0.025	1006.336	0.025	1006.336	0.025
0.050	1007.409	0.050	1007.409	0.050	1007.409	0.050	1007.409	0.050	1007.409	0.050
0.075	1008.471	0.075	1008.471	0.075	1008.471	0.075	1008.471	0.075	1008.471	0.075
0.100	1009.525	0.100	1009.525	0.100	1009.525	0.100	1009.525	0.100	1009.525	0.100
0.125	1010.570	0.125	1010.570	0.125	1010.570	0.125	1010.570	0.125	1010.570	0.125
0.150	1011.607	0.150	1011.607	0.150	1011.607	0.150	1011.607	0.150	1011.607	0.150
0.175	1012.633	0.175	1012.633	0.175	1012.633	0.175	1012.633	0.175	1012.633	0.175
0.200	1013.651	0.200	1013.651	0.200	1013.651	0.200	1013.651	0.200	1013.651	0.200
L-serine + 0.1 mol dm^{-3} aqueous-sucrose										

0.000	1011.404	0.000	1011.404	0.000	1011.404	0.000	1011.404	0.000	1011.404	0.000
0.025	1012.448	0.025	1012.448	0.025	1012.448	0.025	1012.448	0.025	1012.448	0.025
0.050	1013.482	0.050	1013.482	0.050	1013.482	0.050	1013.482	0.050	1013.482	0.050
0.075	1014.506	0.075	1014.506	0.075	1014.506	0.075	1014.506	0.075	1014.506	0.075
0.100	1015.521	0.100	1015.521	0.100	1015.521	0.100	1015.521	0.100	1015.521	0.100
0.125	1016.525	0.125	1016.525	0.125	1016.525	0.125	1016.525	0.125	1016.525	0.125
0.150	1017.520	0.150	1017.520	0.150	1017.520	0.150	1017.520	0.150	1017.520	0.150
0.175	1018.508	0.175	1018.508	0.175	1018.508	0.175	1018.508	0.175	1018.508	0.175
0.200	1019.486	0.200	1019.486	0.200	1019.486	0.200	1019.486	0.200	1019.486	0.200
L-serine + 0.1 mol dm^{-3} aqueous-lactose										
0.000	1011.810	0.000	1011.810	0.000	1011.810	0.000	1011.810	0.000	1011.810	0.000
0.025	1012.850	0.025	1012.850	0.025	1012.850	0.025	1012.850	0.025	1012.850	0.025
0.050	1013.880	0.050	1013.880	0.050	1013.880	0.050	1013.880	0.050	1013.880	0.050
0.075	1014.900	0.075	1014.900	0.075	1014.900	0.075	1014.900	0.075	1014.900	0.075
0.100	1015.911	0.100	1015.911	0.100	1015.911	0.100	1015.911	0.100	1015.911	0.100
0.125	1016.911	0.125	1016.911	0.125	1016.911	0.125	1016.911	0.125	1016.911	0.125
0.150	1017.902	0.150	1017.902	0.150	1017.902	0.150	1017.902	0.150	1017.902	0.150
0.175	1018.880	0.175	1018.880	0.175	1018.880	0.175	1018.880	0.175	1018.880	0.175
0.200	1019.850	0.200	1019.850	0.200	1019.850	0.200	1019.850	0.200	1019.850	0.200

Table 2. Apparent molar volume (V_ϕ) and apparent molar compressibility ($K_{s,\phi}$) of L-serine of different molalities in water and aqueous saccharides solutions at different temperatures.

m (mol kg^{-1})	*T* (K)									
	293.15		293.15		293.15		293.15		293.15	
	$10^6 \times V_\phi$ (m^{3}mol^{-1})									
L-serine + water										
0.025	60.05	0.025	60.05	0.025	60.05	0.025	60.05	0.025	60.05	0.025
0.050	60.14	0.050	60.14	0.050	60.14	0.050	60.14	0.050	60.14	0.050
0.075	60.25	0.075	60.25	0.075	60.25	0.075	60.25	0.075	60.25	0.075
0.100	60.36	0.100	60.36	0.100	60.36	0.100	60.36	0.100	60.36	0.100
0.125	60.47	0.125	60.47	0.125	60.47	0.125	60.47	0.125	60.47	0.125
0.150	60.58	0.150	60.58	0.150	60.58	0.150	60.58	0.150	60.58	0.150
0.175	60.70	0.175	60.70	0.175	60.70	0.175	60.70	0.175	60.70	0.175
0.200	60.82	0.200	60.82	0.200	60.82	0.200	60.82	0.200	60.82	0.200
L-serine + 0.1 mol dm^{-3} aqueous-glucose										
0.025	61.69	0.025	61.69	0.025	61.69	0.025	61.69	0.025	61.69	0.025
0.050	61.78	0.050	61.78	0.050	61.78	0.050	61.78	0.050	61.78	0.050
0.075	61.91	0.075	61.91	0.075	61.91	0.075	61.91	0.075	61.91	0.075
0.100	62.02	0.100	62.02	0.100	62.02	0.100	62.02	0.100	62.02	0.100
0.125	62.14	0.125	62.14	0.125	62.14	0.125	62.14	0.125	62.14	0.125
0.150	62.24	0.150	62.24	0.150	62.24	0.150	62.24	0.150	62.24	0.150
0.175	62.36	0.175	62.36	0.175	62.36	0.175	62.36	0.175	62.36	0.175
0.200	62.48	0.200	62.48	0.200	62.48	0.200	62.48	0.200	62.48	0.200
L-serine + 0.1 mol dm^{-3} aqueous-sucrose										
0.025	63.02	0.025	63.02	0.025	63.02	0.025	63.02	0.025	63.02	0.025
0.050	63.15	0.050	63.15	0.050	63.15	0.050	63.15	0.050	63.15	0.050
0.075	63.28	0.075	63.28	0.075	63.28	0.075	63.28	0.075	63.28	0.075

0.100	63.40	0.100	63.40	0.100	63.40	0.100	63.40	0.100	63.40	0.100
0.125	63.53	0.125	63.53	0.125	63.53	0.125	63.53	0.125	63.53	0.125
0.150	63.66	0.150	63.66	0.150	63.66	0.150	63.66	0.150	63.66	0.150
0.175	63.77	0.175	63.77	0.175	63.77	0.175	63.77	0.175	63.77	0.175
0.200	63.89	0.200	63.89	0.200	63.89	0.200	63.89	0.200	63.89	0.200
L-serine + 0.1 mol dm^{-3} aqueous-lactose										
0.025	63.16	0.025	63.16	0.025	63.16	0.025	63.16	0.025	63.16	0.025
0.050	63.29	0.050	63.29	0.050	63.29	0.050	63.29	0.050	63.29	0.050
0.075	63.43	0.075	63.43	0.075	63.43	0.075	63.43	0.075	63.43	0.075
0.100	63.55	0.100	63.55	0.100	63.55	0.100	63.55	0.100	63.55	0.100
0.125	63.68	0.125	63.68	0.125	63.68	0.125	63.68	0.125	63.68	0.125
0.150	63.81	0.150	63.81	0.150	63.81	0.150	63.81	0.150	63.81	0.150
0.175	63.95	0.175	63.95	0.175	63.95	0.175	63.95	0.175	63.95	0.175
0.200	64.09	0.200	64.09	0.200	64.09	0.200	64.09	0.200	64.09	0.200

Table 3. Limiting apparent molar volume (V°_ϕ), standard deviation (σ), slope (S_v), transfer volume ($V^\circ_{\phi,tr}$), limiting apparent molar compressibility ($K^\circ_{s,\phi}$), standard deviation (σ), slope (S_k) and transfer compressibility, ($K^\circ_{s,\phi,tr}$) of L-serine in water and aqueous saccharides solutions at different temperatures.

Property	T (K)				
	293.15	298.15	303.15	308.15	313.15
L-serine + water					
$10^6 \times V^\circ_\phi$ (m^{3}mol^{-1})	59.92(±0.01)	60.29(±0.01)	60.61(±0.01)	60.80(±0.01)	61.07(±0.01)
	(60.06)[23]	(60.56)[23]	(60.96)[23]	(61.34)[23]	(61.63)[23]

σ	0.01	0.01	0.01	0.01	0.01
$10^6\times S_v$ (m^{3}mol^{-2} kg)	4.42(±0.05)	3.92(±0.04)	3.51(±0.02)	3.19(±0.04)	2.94(±0.04)
$10^{14}\times K°_{s,\phi}$ (Pa^{-1}m^{3}mol^{-1})	-3.48(±0.02)	-3.12(±0.02)	-2.77(±0.01)	-2.46(±0.02)	-2.22(±0.02)
σ	0.03	0.02	0.02	0.03	0.03
$10^{14}\times S_k$ (Pa^{-1}m^{3}mol^{-2} kg)	9.97(±0.17)	9.26(±0.12)	8.69(±0.10)	8.22(±0.16)	8.98(±0.19)
L-serine + 0.1 mol dm^{-3} aqueous glucose					
$10^6\times V°_\phi$ (m^{3}mol^{-1})	61.56(±0.01)	61.85(±0.01)	62.07(±0.01)	62.20(±0.01)	62.40(±0.01)
σ	0.01	0.01	0.01	0.01	0.01
$10^6\times S_v$ (m^{3}mol^{-2} kg)	4.56(±0.04)	4.21(±0.06)	3.88(±0.04)	3.58(±0.03)	3.32(±0.04)
$10^6\times \Delta_{tr}V°_\phi$ (m^3 mol^{-1})	1.64	1.56	1.46	1.40	1.33
$10^{14}\times K°_{s,\phi}$ (Pa^{-1}m^{3}mol^{-1})	-2.54(±0.02)	-2.42(±0.02)	-2.12(±0.02)	-2.01(±0.03)	-2.00(±0.02)
σ	0.03	0.02	0.03	0.03	0.03
$10^{14}\times S_k$ (Pa^{-1}m^{3}mol^{-2} kg)	9.77(±0.19)	9.46(±0.15)	9.17(±0.21)	8.84(±0.20)	8.33(±0.17)
$10^{14}\times \Delta_{tr}K°_{s,\phi}$ (Pa^{-1}m^{3}mol^{-1})	0.94	0.70	0.65	0.45	0.22
L-serine + 0.1 mol dm^{-3} aqueous sucrose					
$10^6\times V°_\phi$ (m^{3}mol^{-1})	62.90(±0.01)	63.12(±0.01)	63.28(±0.01)	63.40(±0.01)	63.57(±0.01)
σ	0.01	0.01	0.01	0.01	0.01
$10^6\times S_v$ (m^{3}mol^{-2} kg)	5.01(±0.05)	4.67(±0.03)	4.36(±0.03)	4.07(±0.03)	3.79(±0.04)
$10^6\times \Delta_{tr}V°_\phi$ (m^3 mol^{-1})	2.98	2.83	2.67	2.60	2.50
$10^{14}\times K°_{s,\phi}$ (Pa^{-1}m^{3}mol^{-1})	-2.09(± 0.04)	-2.01(±0.04)	-1.71(±0.05)	-1.66(±0.04)	-1.62(±0.03)
σ	0.06	0.05	0.07	0.05	0.04
$10^{14}\times S_k$ (Pa^{-1}m^{3}mol^{-2} kg)	10.21(±0.35)	9.70(±0.29)	9.25(±0.41)	8.80(±0.21)	8.41(±0.27)
$10^{14}\times \Delta_{tr}K°_{s,\phi}$ (Pa^{-1}m^{3}mol^{-1})	1.39	1.11	1.06	0.80	0.60
L-serine + 0.1 mol dm^{-3} aqueous lactose					
$10^6\times V°_\phi$ (m^{3}mol^{-1})	63.03(±0.01)	63.24(±0.01)	63.39(±0.01)	63.48(±0.01)	63.63(±0.01)
σ	0.01	0.01	0.01	0.01	0.01
$10^6\times S_v$ (m^{3}mol^{-2} kg)	5.26(±0.04)	4.78(±0.07)	4.41(±0.03)	4.13(±0.07)	3.93(±0.03)
$10^6\times \Delta_{tr}V°_\phi$ (m^3 mol^{-1})	3.11	2.95	2.78	2.68	2.56
$10^{14}\times K°_{s,\phi}$ (Pa^{-1}m^{3}mol^{-1})	-1.71(±0.09)	-1.66(±0.08)	-1.43(±0.08)	-1.39(±0.05)	-1.35(±0.04)

σ	0.12	0.10	0.10	0.06	0.05
$10^{14}\times S_k$ (Pa^{-1}m^{3}mol^{-2} kg)	10.11(±0.70)	9.64(±0.62)	8.94(±0.60)	8.09(±0.37)	7.70(±0.32)
$10^{14}\times\Delta_{tr}K^{\circ}_{s,\phi}$ (Pa^{-1}m^{3}mol^{-1})	1.77	1.46	1.34	1.07	0.87

Table 4. Coefficients *a*, *b* and *c* and temperature derivative of limiting apparent molar expansibility $(\partial^2 V^{\circ}_{\phi}/\partial T^2)_p$ of L-serine in water and aqueous saccharides solutions.

System	$a\times 10^6$ (m^{3}mol^{-1})	$b\times 10^6$ (m^{3}mol^{-1} K^{-1})	$c\times 10^6$ (m^{3}mol^{-1} K^{-2})	$(\partial^2 V^{\circ}_{\phi}/\partial T^2)_p\times 10^8$
L-serine + water	-43.10	0.628	-0.0009	-0.18
L-serine + 0.1 mol dm^{-3} aqueous glucose	-21.15	0.508	-0.0008	-0.16
L-serine + 0.1 mol dm^{-3} aqueous sucrose	16.69	0.275	-0.0004	-0.08
L-serine + 0.1 mol dm^{-3} aqueous lactose	7.39	0.341	-0.0005	-0.10

Table 5. Limiting apparent molar expansibility (ϕ^{o}_{E}) and coefficient of thermal expansion (α) of L-serine in water and aqueous saccharides solutions at different temperatures.

m (mol kg^{-1})	*T* (K)									
	293.15		298.15		303.15		308.15		313.15	
	$\phi^{o}_{E}\times 10^6$ (m^{3}mol^{1}K^{-1})	$\alpha\times 10^3$ (K^{-1})	$\phi^{o}_{E}\times 10^6$ (m^{3}mol^{1}K^{-1})	$\alpha\times 10^3$ (K^{-1})	$\phi^{o}_{E}\times 10^6$ (m^{3}mol^{1}K^{-1})	$\alpha\times 10^3$ (K^{-1})	$\phi^{o}_{E}\times 10^6$ (m^{3}mol^{1}K^{-1})	$\alpha\times 10^3$ (K^{-1})	$\phi^{o}_{E}\times 10^6$ (m^{3}mol^{1}K^{-1})	$\alpha\times 10^3$ (K^{-1})
L-serine + water	0.075	1.252	0.066	1.095	0.056	0.924	0.047	0.773	0.037	0.606
L-serine + 0.1 mol dm^{-3} aqueous glucose	0.056	0.910	0.048	0.776	0.041	0.661	0.033	0.531	0.025	0.401
L-serine + 0.1 mol dm^{-3} aqueous sucrose	0.040	0.636	0.036	0.570	0.032	0.506	0.028	0.442	0.024	0.378

L-serine + 0.1 mol dm^{-3} aqueous lactose	0.039	0.619	0.034	0.538	0.029	0.457	0.024	0.378	0.019	0.299

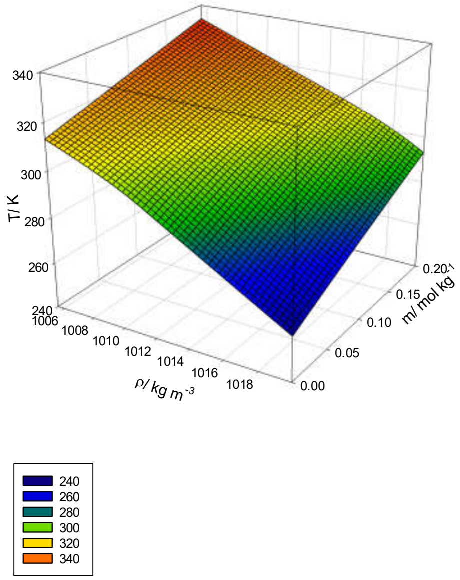

Fig. 1. Plot of density (ρ) against molality (m) for L-serine in aqueous solution of lactose at (293.15, 298.15, 303.15, 308.15 and 313.15) K.

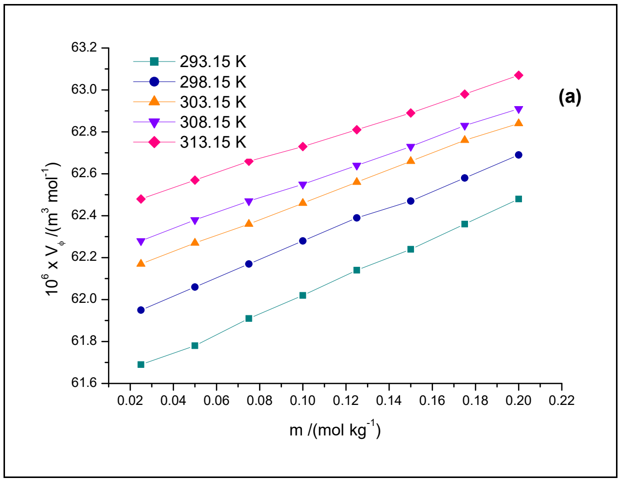

Fig. 2. Plot of apparent molar volume (V_ϕ) against molality (m) for L-serine in aqueous solution of glucose at different temperatures.

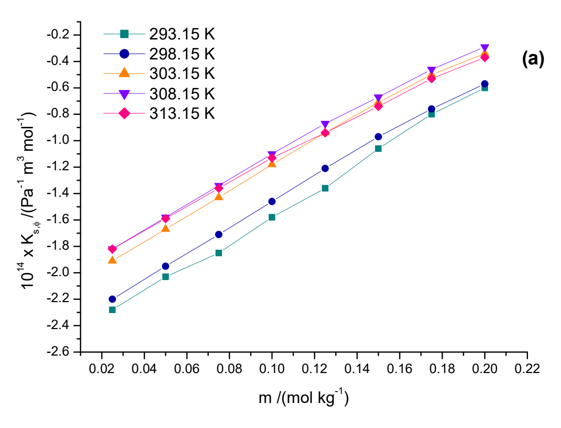

Fig. 3. Plot of apparent molar compressibility ($K_{s,\phi}$) against molality (m) for L-serine in aqueous solution of glucose at different temperatures.