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Solute-solute and Solute-solvent Interactions of Paracetamol in Aqueous Solutions of β-cyclodextrin at Different Temperatures: A Volumetric and Viscometric Approach

Abhijit Sarkar, Habibur Rahaman, Uttam Kumar Singha, Biswajit Sinha*

Department of Chemistry, University of North Bengal, Darjeeling, India.

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ABSTRACT

The densities and viscosities of paracetamol in aqueous β-cyclodextrin solutions with several molal concentrations m = (0.001-0.007) mol kg^{-1} of β-cyclodextrin were determined at T = 298.15-318.15 K under atmospheric pressure. The inclusion has been studied using ultraviolet-visible spectroscopy. Using experimental data apparent molar volume (φV), standard partial molar volume (φ_V^0), the slope (S_V^*), standard isobaric partial molar expansibility (φ_E^0) and its temperature dependence $(\partial\varphi_E^0/\partial T)_P$, the viscosity B-coefficient, and solvation number (Sn) were determined. Free energies of activation of viscous flow per mole of the solvents ($\Delta\mu_1^{0\neq}$) and the solute ($\Delta\mu_2^{0\neq}$) are also calculated. Various results revealed that the solutions are characterized predominantly by solute-solvent interactions and paracetamol behaves as a long-range structure maker.

Key words: *Apparent molar volumes, Viscosity B-coefficients, Paracetamol, Aqueous β-cyclodextrin solutions, Solvation number, Ultraviolet-visible spectroscopy.*

1. INTRODUCTION

Drug action in human body is known as pharmacodynamics. The effectiveness of a drug depends on its bioavailability [1]. The general reason of low oral bioavailability is due to low solubility of drug molecules. To get required pharmacological action, it is important to have a desired concentration of drug in the solution, for which solubility is the important factor. Sometimes, low aqueous soluble drugs require high doses for the desired action. Low water solubility of drugs is a serious problem for generic developments. Drug only in the form of aqueous solution gets absorbed in the absorption sites. Most of the drugs are having poor aqueous solubility. Therefore, the enhancement of drug solubility and its oral bioavailability is a difficult task for drug development process. Sometimes, some carrier molecules are added to the drugs to increase the solubility [2]. It is, therefore, interesting to observe the physicochemical interactions between the drug molecule and the carrier molecule in aqueous media. Different physicochemical properties such as density and viscosity are used as tools to study the interactions. A number of works related to volumetric and viscometric properties of drugs have been carried out by many researchers [3-5].

Paracetamol also known as acetaminophen or N-acetyl-p-amino phenol is a mild analgesic and antipyretic agent and also a nonsteroidal drug [6]. It is often used to treat post-surgical and cancer pains. Paracetamol has less solubility in aqueous media. β-cyclodextrin is a 7-membered sugar ring molecule. It is able to form host-guest complexes with hydrophobic molecules given the unique nature imparted by their structure. β-cyclodextrin has found a large number of applications in a broad range of fields [7]. Cyclodextrins have the ability to solubilize hydrophobic drugs which has pharmaceutical applications and crosslink to form polymers used for drug delivery. Although few works have been done on different properties of paracetamol and β-cyclodextrin [7-14], to the best of our knowledge, the properties of this ternary solution have not been reported. Hence, the purpose of the present work is to study the various interactions interplaying in the aqueous solutions of paracetamol and β-cyclodextrin in terms of apparent molar volumes, standard partial molar volumes and viscosity *B*-coefficients, and solvation number at T = 298.15-318.15 K and at pressure p=101 kPa.

*Corresponding Author:
E-mail: biswachem@gmail.com

2. EXPERIMENTAL

2.1. Materials

Pharmaceutical grade paracetamol (CAS: 103-90-2; Sigma-Aldrich, mass fraction purity >0.990) and A. R grade β-cyclodextrin (CAS: 7585-39-9, Sigma-Aldrich, mass fraction purity >0.980) were used for the present study. The chemicals were used as such but stored *in vacuo* over anhydrous $CaCl_2$ for several hours before use. Doubly distilled deionized water with a specific conductance $<1.10^{-6}$ Scm^{-1} at 298.15 K was used to prepare different aqueous solutions of β-cyclodextrin. Various mixed solvents were prepared by mass, and necessary adjustments were done to achieve exact molal concentrations (m = 0.001, 0.003, 0.005, and 0.007) of β-cyclodextrin in the mixed solvents at 298.15 K. The physical properties of these mixed solvents are given in Supplementary Table S1. Stock solutions of paracetamol in different solvent mixtures were prepared by mass, and all the working solutions were prepared afresh before the use by mass dilution. The mass measurements were made on a digital electronic analytical balance (Mettler, AG 285, Switzerland) with an uncertainty of $\pm1.10^{-4}$ g. The conversion of molalities into molarities was accomplished using experimental density data whenever needed [15]. Estimated standard relative uncertainty in molality of paracetamol solutions, i.e., u_r (m) was evaluated to 0.01. The molecular structures of paracetamol, i.e., N-(4-hydroxyphenyl) acetamide and β-cyclodextrin are shown in Figure 1.

2.2. Apparatus and Procedure

The densities were measured with a vibrating tube density meter (Anton Paar, DMA 4500M). The densitimeter was calibrated at the experimental temperatures with doubly distilled, degassed water and dry air at atmospheric pressure. The temperature was automatically kept constant with an accuracy of $\pm1.10^{-2}$ K using the built-in Peltier technique. The stated repeatability and accuracy of the densities were $\pm1.10^{-5}$ g cm^{-3} and $\pm5.10^{-5}$ g cm^{-3}, respectively. However, standard uncertainty of the density measurements for most of the solutions was found to be within ±0.1 kg m^{-3}.

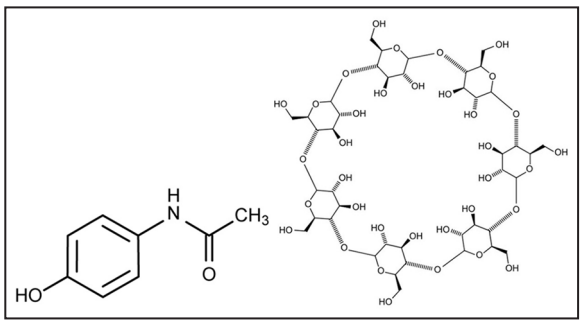

Figure 1: Molecular structure of paracetamol. Molecular structure of β-cyclodextrin.

The viscosity was measured by means of a suspended Canon-type Ubbelohde viscometer thoroughly cleaned, dried, and calibrated at the experimental temperatures with triply distilled, degassed water and purified methanol [16,17]. It was filled with an experimental liquid and placed vertically in a glass-sided thermostatic bath (Julabo, Germany) maintained constant to ±0.01 K. After attainment of thermal equilibrium, the efflux times of flow of the liquid samples were recorded with a digital stopwatch correct to ±0.01s. Adequate precautions were adopted to minimize evaporation loses during the viscosity measurements, and an average of triplicate measurements was taken into account. The uncertainty in viscosity measurements was within 0.001 mPa.s.

The absorption spectra of paracetamol in aqueous solutions of β-cyclodextrin were recorded on Jasco V-530 double beam ultraviolet (UV)-visible spectrophotometer. It was coupled with the thermostatic arrangement and maintained at 298.15 K. A quartz cell of 1 cm path length was used, and spectroscopic grade water was used as the reference solvent for all the absorption measurements.

Refractive indices were measured with an Abbe-refractometer at 298.15 K. Water was circulated through the refractometer from the thermostatic bath (mentioned above) maintained to ±0.01 K of 298.15 K. The refractometer was calibrated with doubly distilled, degassed water before each series of measurements. The estimated uncertainty in refractive indices was found to be ±0.0002.

3. RESULTS AND DISCUSSION

The experimental molalities (m), densities (ρ), viscosities (η), and apparent molar volumes (φ_V) of paracetamol solutions in various aqueous β-cyclodextrin solutions (used as solvents) at the experimental temperatures are reported in Table S2.

3.1. Standard Partial Molar Volumes

The apparent molar volume φ_V of a solute is defined as the difference between the volume of the solution and the volume of the pure solvent per mole of solute [18-20]. The apparent molar volumes φ_V were obtained from the following relation:

$$\varphi_V = \frac{M}{\rho} - \frac{1000(\rho - \rho_1)}{m\rho\rho_1} \quad (1)$$

Where M is the molar mass of paracetamol, m is the molality of the solution, ρ_1 and ρ are the densities of the solvent and solution, respectively. Uncertainties in φ_V values were within $\pm0.11\text{-}0.62\times10^{-6}$ m^3 mol^{-1}. Supplementary Table S2 shows that apparent molar volumes φ_V increase with increasing temperature and β-cyclodextrin content in the solutions under the study.

Such trends indicate that the interactions between solute and solvent as well as those between solute-solute or solute-cosolute change with temperature and solvent compositions. However, more clear information regarding solute-solute or solute-solvent interactions can be had from limiting apparent molar φ_V^0 volumes at an infinitesimal concentration or standard partial molar volumes φ_V^0 of the solute. As the plots of φ_V against the square root of molar concentration $\sqrt{m}$ were linear in the studied concentration range of paracetamol at all experimental temperatures, standard partial molar volume φ_V^0 was obtained from the Masson equation [21]:

$$\varphi_V = \varphi_V^0 + S_V^* \sqrt{m} \quad (2)$$

Actually, the φ_V^0 values were determined by fitting the dilute data ($m < 0.1$) to Equation (2) using a weighted least squares linear regression, and the correlation coefficient (R^2) values were within the range 0.993-0.999. The weighting factors were set inverse to the variance of the φ_V values for each data point. The intercept φ_V^0, i.e., the standard partial molar volume provides a measure of ion-solvent interactions, and the slope S_V^* provides information regarding ion-ion interactions. The values of φ_V^0 and S_V^* along with standard deviations (σ) for paracetamol in different aqueous β-cyclodextrin solutions at the experimental temperatures are reported in Table 1. Our results (Table 1) show that values are positive and increase when both the experimental temperatures and β-cyclodextrin content in the solvents increase. This trend in φ_V^0 values indicates the presence of strong solute-solvent interactions and such interactions further strengthen at elevated temperatures and with higher concentrations of β-cyclodextrin in the ternary solutions and such a trend in φ_V^0 values is at par the trends in φ_V values (as listed in Supplementary Table S2) for the studied solutions. These facts may be attributed to increase in solvation of the ions at higher cosolute concentrations. Dependence of φ_V^0 values on the solvent composition is depicted in Figure 2.

The parameter S_V^* is a volumetric coefficient that characterizes pair-wise interaction between the solvated species or ion-ion interaction in solution phase [22-24]. Its sign is determined by the interactions between the solute species. In the present study, S_V^* values were found to negative for all the studied solutions. For a weak ionic species such as paracetamol and a non-ionic species such as β-cyclodextrin, negative S_V^* values suggest that the presence of weak pair-wise interaction between the solute-solute or the solute-co-solute and such interactions probably diminishes with increasing molality of β-cyclodextrin due to solvent-induced cosphere overlap or solute-solute hydrophobic interactions [25].

Table 1: Standard partial molar volumes (φ_V^0), the slopes (S_V^*), and corresponding standard deviations (σ) for paracetamol in aqueous solutions of β-cyclodextrin at T=298.15-318.15 K and at pressure P=101 kPa.

T/K	$\varphi_V^0 \times 10^6$ / $m^3\ mol^{-1}$	$S_V^* \times 10^6$ / $m^3\ kg^{1/.2}\ mol^{-3/2}$	$\sigma \times 10^6$ / $m^3\ mol^{-1}$
		0.001[a]	
298.15	127.68±0.42	−17.97±0.19	0.14
308.15	128.11±0.85	−16.52±0.21	0.16
318.15	128.66±0.77	−14.74±0.17	0.11
		0.003[a]	
298.15	127.91±0.62	−18.43±0.29	0.12
308.15	128.73±0.67	−18.72±0.32	0.11
318.15	129.42±0.60	−17.85±0.24	0.11
		0.005[a]	
298.15	128.63±1.11	−18.87±0.43	0.06
308.15	129.41±1.12	−21.09±0.42	0.08
318.15	130.22±0.94	−20.91±0.23	0.16
		0.007[a]	
298.15	129.64±1.07	−22.08±0.18	0.04
308.15	129.94±1.11	−22.49±0.26	0.07
318.15	130.85±1.12	−18.48±0.08	0.06

[a]Molality of β-cyclodextrin in aqueous solutions in $mol.kg^{-1}$. Standard errors are given the parenthesis. Standard uncertainties are: u(T)=±0.01 K, u(p) =±1 kPa, $u_r(m) = 0.01$

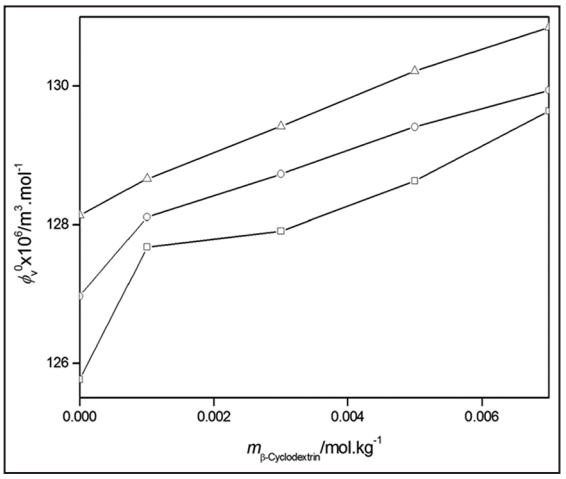

Figure 2: Dependence of standard partial molar volumes (φ_V^0) for paracetamol on the molality of β-cyclodextrin in aqueous solutions at T = 298.15-318.15 K. Symbols: ϒ, T = 298.15 K; ⊄, T = 308.15 K; Δ, T = 318.15 K.

3.2. Standard Transfer Volumes

Limiting thermodynamic transfer properties provide information about the solute-cosolute interaction,

because at infinite dilution, the interactions between individual solute molecules are negligible. Hence, $\Delta_t\varphi_V^0$ is free from solute-solute interactions and provides valuable information about solute-cosolute interactions. The standard partial molar volume of transfer ($\Delta_t\varphi_V^0$) was obtained from the following relation [26]:

$$\Delta_t \varphi_V^0 = \varphi_V^0 [\beta \text{ cyclodextrin} + \text{water}] - \varphi_V^0 [\text{water}] \quad (3)$$

The $\Delta_t\varphi_V^0$ values are depicted in Figure 3 as a function of molality of β-cyclodextrin in the aqueous solutions. $\Delta_t\varphi_V^0$ values are positive at all the experimental temperatures and increase monotonically with the increase in β-cyclodextrin content in ternary solutions. φ_V^0 values are taken from our previously published paper [27]. According to the cosphere overlap model, as developed by Friedman and Krishnan [28], the overlap of hydration cospheres of two ionic species results in an increase in volume but that of hydration cospheres of hydrophobic-hydrophobic and ion-hydrophobic groups results in a decrease in volume. The positive $\Delta_t\varphi_V^0$ values indicate that ion-hydrophilic and hydrophilic-hydrophilic group interactions predominate over ion-hydrophobic, hydrophobic-hydrophobic, and hydrophilic-hydrophobic interactions, and the overall effect of the overlap of the hydration cospheres of paracetamol and β-cyclodextrin reduces the electrostriction of water by paracetamol. Such reduced electrostriction results in a concomitant increase in volume, and this effect further increases with increasing molality of β-cyclodextrin in the ternary solutions increase.

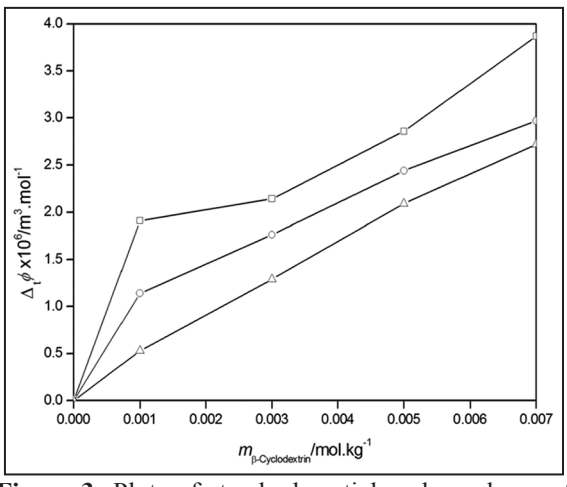

Figure 3: Plots of standard partial molar volume of transfer ($\Delta_t\varphi_V^0$) for paracetamol on the molality of β-cyclodextrin in aqueous solutions at T = 298.15-318.15 K. symbols: ϒ, T = 298.15 K; ⊄, T = 308.15 K; Δ, T = 318.15 K.

The partial molar volume of a solute can also be explained by a simple model [29,30] as given by the following relation:

$$\varphi_V^0 = \varphi_{VW} + \varphi_{Void} - \varphi_S$$

Where φ_{VW} is the van der Waals volume, φ_{Void} is the volume associated with voids or empty space, and φ_S is the shrinkage volume due to electrostriction. Assuming the φ_{VW} and φ_{Void} to have same magnitudes in water and in aqueous β-cyclodextrin solutions for the same solute, the increase in φ_V^0 values and the concomitant positive $\Delta_t\varphi_V^0$ values can be attributed to the decrease in the shrinkage volume (φ_S) of water by paracetamol in the presence of β-cyclodextrin. This fact suggests that β-cyclodextrin has a dehydration effect on the hydrated paracetamol. Thus, the interactions between paracetamol and β-cyclodextrin can roughly be summarized as follows:

1. Interaction of H^+ ions from paracetamol and water with the -OH groups β-cyclodextrin.
2. Interaction of the O: and N: from paracetamol with –OH groups of β-cyclodextrin.
3. Interaction of ionic part of paracetamol with the hydrophobic part of β-cyclodextrin.

While interactions of 1-2 types impart positive contributions, interaction of 3 types imparts negative contribution to φ_V^0 values. Therefore, the overall positive φ_V^0 values indicate that ionic group interactions predominate over ionic-hydrophobic interactions. Anyway, standard partial molar volumes of a solute reflect a overall result of several solute-solute and solute-solvent interactions prevailing in solutions such as: Electrostatic interactions between the local charge on the solute or ions and the dipole moment of H_2O, interlocking packing interactions of the solute or ions with H_2O leading to interstitial packing or caging as well as solvation, and other polar-ionic group (H-bonding) interactions between different polar and non-polar groups of β-cyclodextrin and paracetamol; all these interactions can characterize the overall state of the solutions studied.

3.3. Apparent Molar Expansibilities

Apparent molar volumes (φ_V) and densities (ρ) at the experimental temperatures were used to calculate the apparent molar expansibilities (φ_E) of paracetamol solutions using the following relation [19].

$$\varphi_E = \alpha\varphi_V + \frac{1000(\alpha - \alpha_1)}{m\rho_1} \quad (5)$$

Where α and α_1 are the coefficients of isobaric thermal expansion of the solvent and solution, respectively, and other symbols have their usual significance. α and

α_1 are defined as: $\alpha = -\rho^{-1} (\partial\rho_1/\partial T)_P$ and $\alpha_1 = -\rho_1^{-1}(\partial\rho/\partial T)_P$. The uncertainty in the coefficients of isobaric thermal expansion was $\pm 2.10^{-5}$ K^{-1}, and the uncertainty in φ_E values was within ±0.001-0.002×10^{-6} m^{-3} mol^{-1} K^{-1}, respectively. The standard partial molar expansibilities (φ_E^0) were then determined from the following relation [31]:

$$\varphi_E = \varphi_E^0 + S_E \sqrt{m}$$

$(\partial\varphi_E^0/\partial T)_P$ values were obtained from the slope of a linear fit of φ_E^0 values (a least squares linear regression used) against experimental temperature (T) with the correlation coefficient (R^2) values within the range of 0.886-0.974. The φ_E^0 values are an important indicator of solute-solvent interactions and help in the interpretation of the long-range structure making or breaking properties of solutes [32-34]. The φ_E^0 values along with corresponding errors for different experimental solutions at different temperatures are given in Table 2. It reveals that φ_E^0 values are positive and further increase when experiment temperature increases. Such a trend in values can be ascribed to the structural perturbation influenced by the gradual appearance of "caging effect" or "packing effect" [35,36] for paracetamol in the studied solutions, and it has hydrophobic character. According to Hepler [37,38], if the term $\left(\partial\varphi_E^0/\partial T\right)_P$ is positive, the solute is a structure maker, and otherwise, it is a structure breaker. The $\left(\partial\varphi_E^0/\partial T\right)_P$ values for different ternary solutions are given in Table 2. It shows that the $\left(\partial\varphi_E^0/\partial T\right)_P$ values are positive for all the studied solutions. Thus, paracetamol seems to act a net structure maker in aqueous β-cyclodextrin solutions, and the studied systems are characterized by the predominance of hydrophobic hydration over the electrostriction of water by the solute and cosolute molecules, i.e., some of the electrostricted water molecules in the hydration spheres of the solute, cosolute, or their constituents ions get released in favor of the normal bulk structure of water on overlap of the cospheres, resulting in volume increase in coexistence of the solute and cosolute.

3.4. UV Spectroscopy

The UV-visible absorption spectra used to confirm the formation of the inclusion complex between paracetamol and β-cyclodextrin. In the following study, we measured the absorption spectra of paracetamol in water and several concentrations of aqueous β-cyclodextrin solutions at 298.15 K. The absorption spectrum of β-cyclodextrin (1.10^{-4} $mol.L^{-1}$) solution did not have any considerable absorption band in the wavelength range 220-300 nm, and the absorption spectra of paracetamol (1.10^{-4} $mol.L^{-1}$) solution shows a peak at 243 nm (Figure 4) [27,39]. To determine the apparent formation constant for the inclusion complex of paracetamol and β-cyclodextrin, the concentration of

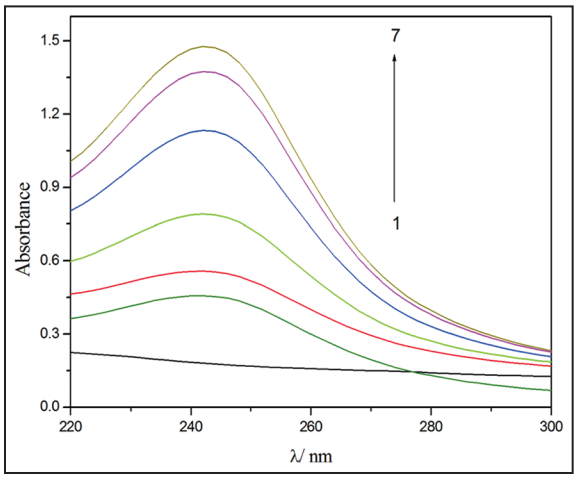

Figure 4: (1) Absorption spectra of aqueous β-cyclodextrin (1.10^{-4} $mol.L^{-1}$) solution and paracetamol with various in aqueous β-cyclodextrin concentrations (2) 0 $mol.L^{-1}$, (3) 3.10^{-4} $mol.L^{-1}$, (4) 5.10^{-4} $mol.L^{-1}$, (5) 9.10^{-4} $mol.L^{-1}$, (6) 12.10^{-4} $mol.L^{-1}$, (7) 14.10^{-4} $mol.L^{-1}$.

Table 2: Standard partial molar expansibilities (φ_E^0) for paracetamol in aqueous solutions β-cyclodextrin at T=298.15-318.15 K and at pressure P=101 kPa.

Solvent	$\varphi_E^0 \cdot 10^{-5}$ / $m^3 \cdot mol^{-1} \cdot K^{-1}$			$S_E \cdot 10^{-5}$ / $m^3 \cdot kg^{1/2} \cdot mol^{-1} \cdot K^{-1}$			$\left(\frac{\delta\varphi_E^0}{\delta T}\right)_p \cdot 10^{-8}$ / $m^3 \cdot mol^{-1} \cdot K^{-2}$
	298.15 K	308.15 K	318.15 K	298.15 K	308.15 K	318.15 K	
0.001[a]	4.20±0.09	4.24±0.09	4.29±0.10	−1.63±0.05	−1.64±0.05	−1.65±0.05	1.87
0.003[a]	3.37±0.03	3.40±0.03	3.43±0.03	−1.33±0.03	−1.33±0.03	−1.33±0.03	0.43
0.005[a]	3.05±0.04	3.08±0.04	3.12±0.04	−0.96±0.02	−0.97±0.02	−0.98±0.02	0.32
0.007[a]	1.44±0.01	1.45±0.01	1.47±0.011	−0.15±0.01	−0.18±0.01	−0.21±0.01	0.07

[a]Molality of β-cyclodextrin in aqueous solutions. Standard errors are given the parenthesis. Standard uncertainties are: u(T) =±0.01 K, u(p) =±1 kPa, $u_r(m)$ = 0.01

paracetamol was held constant at 1.10^{-4} mol.L^{-1}, and at the same time, concentrations of β-cyclodextrin have been manipulated as 3.10^{-5} mol.L^{-1}, 5.10^{-5} mol.L^{-1}, 9.10^{-5} mol.L^{-1}, 12.10^{-5} mol.L^{-1}, and 14.10^{-5} mol.L^{-1}. The absorbances of the solutions were measured at 243 nm. The absorption spectra of inclusion complex at different concentrations of β-cyclodextrin are shown in Figure 4. It is found that the absorbance value increased with the increment of β-cyclodextrin concentrations when paracetamol concentration remains fixed. It is an indicative of the increased solubility of the guest molecules during the formation of the inclusion complex [40]. Since the phenyl part of the paracetamol is more likely to go to the hydrophobic cavity of β-cyclodextrin, the theoretical stoichiometric ratio for the inclusion complex should be 1:1. This theory can be verified if we get a linear relationship from the reciprocal plot of 1/Abs versus 1/(β-cyclodextrin) based on Hildebrand-Benesi equation [41].

$$\frac{1}{A} = \frac{1}{\varepsilon[G]_0 K[\beta - CD]} + \frac{1}{\varepsilon[G]_0} \quad (7)$$

Where A is the absorbance for the paracetamol solution at each β-cyclodextrin concentrations, and $[G]_0$, K, and [β−CD] ε are the initial concentration of paracetamol, apparent formation constant of paracetamol, concentrations of β-cyclodextrin and molar absorptivity, respectively. Figure 5 shows the reciprocal plots of absorbance and concentration which determines the stoichiometric ratio for the inclusion complex formed. A good linear relationship was obtained from the graph. This graph clears that the ratio for the inclusion complex between paracetamol and β-cyclodextrin is 1:1. The same thing was observed by a number of researchers [42,43]. The apparent formation constant based on the figure was 0.975×10^4.

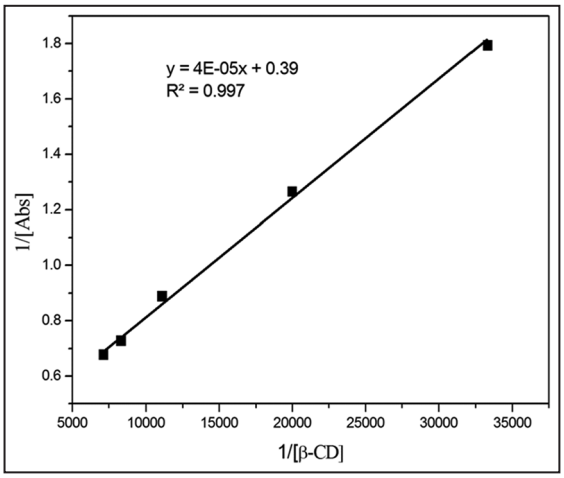

Figure 5: Reciprocal plot for 1/A vs. 1/(β-cyclodextrin) of paracetamol β-cyclodextrin inclusion complex.

3.5. Viscometric Results

As paracetamol behaves as a weak electrolyte [27], solution viscosities were analyzed with the modified Jones-Dole equation [24,44].

$$\eta_r = 1+Bc \quad (8)$$

Where $\eta_r = \eta/\eta_1$; η_1, η, and c are the viscosities of solvent, the viscosities of solution, and molarity of the solute in the solutions, respectively. The viscosity B-coefficients [38,45,46] were estimated by least squares linear regression analysis. Viscosity B-coefficient depends on solute-solvent interactions. Table 3 shows that the viscosity B-coefficients are positive and increase with the rise in the temperature. These results thus reflect strong solute-solvent interactions in the ternary solutions and suggest net structural enhancement at higher temperatures. Such interactions are also well reflected by the increase in solution viscosities induced by increasing the β-cyclodextrin concentration in the ternary solutions.

3.6. Solvation Number

We have also calculated solvation or hydration numbers (S_n) for paracetamol using the relation [47]: $S_n = B/\varphi_V^0$. S_n is indicative of the formation of a primary solvation sphere around a solute. The range $S_n \approx 0$-2.5 indicates unsolvated solutes [47], and higher S_n values indicate solvated solutes with primary solvation sphere. Hence, an inspection of S_n values given in Table 3 indicated that paracetamol remains solvated with primary solvation spheres in the aqueous solutions investigated here, as already discussed on the basis of φ_V^0 values.

3.7. Thermodynamics of Viscous Flow

According to Feakings' transition state theory of relative viscosity [48,49], the free energy of activation of viscous flow per mole of the solute ($\Delta\mu_2^{0\neq}$) is related to the viscosity B-coefficients by the following relation:

$$\Delta\mu_2^{0\neq} = \Delta\mu_1^{0\neq} + RT(1000B + \varphi_{V,2}^0 - \varphi_{V,1}^0)/\varphi_{V,1}^0 \quad (9)$$

Where $\varphi_{V,1}^0$ and $\varphi_{V,2}^0$ are the partial molar volumes of the solvent and solute, respectively. The free energy of activation of viscous flow for the solvent/solvent mixture per mole ($\Delta\mu_1^{0\neq}$) is given by the following relation [49]:

$$\Delta\mu_1^{0\neq} = \Delta G_1^{0\neq} = RT\ln(\eta_1 \varphi_{V,1}^0 / hN_A) \quad (10)$$

Where N_A is the Avogadro's number, and the other symbols have their usual significance. The entropy of activation for ternary solutions ($\Delta S_2^{0\neq}$) were obtained from the negative slope of the plots of $\Delta\mu_2^{0\neq}$ against T [50],

Table 3: Viscosity B-coefficients of paracetamol with the correlation coefficients R^2, standard deviations σ for linear regression of Equation (8) along with the solvation number S_n in aqueous solutions of β-cyclodextrin at T=298.15-318.15 K and at pressure P=101 kPa.

Parameters	298.15 K	308.15 K	318.15 K
		0.001[a]	
$\frac{B\times10^3}{m^3\ mol^{-1}}$	0.328±0.026	0.423±0.008	0.503±0.036
R^2	0.99974	0.99997	0.99982
σ	0.004	0.001	0.005
Sn	2.57±0.02	3.29±0.03	3.89±0.01
		0.003[a]	
$\frac{B\times10^3}{m^3\ mol^{-1}}$	0.336±0.030	0.440±0.008	0.528±0.040
R^2	0.99999	0.99993	0.99993
σ	0.004	0.001	0.005
S_n	2.61±0.03	3.42(±0.02	4.08±0.02
		0.005[a]	
$\frac{B\times10^3}{m^3\ mol^{-1}}$	341±0.013	0.448±0.013	0.539±0.036
R^2	0.99998	0.99993	0.99996
σ	0.005	0.003	0.003
S_n	2.65±0.03	3.46±0.01	4.14±0.02
		0.007[a]	
$\frac{B\times10^3}{m^3\ mol^{-1}}$	0.349±0.033	0.454±0.012	0.541±0.045
R^2	0.99998	0.99999	0.99996
σ	0.004	0.002	0.005
S_n	2.69±0.01	3.50±0.01	4.15±0.0.1

[a]Molality of β-cyclodextrin in aqueous solutions. Standard errors are given the parenthesis. Standard uncertainties are: u(T) =±0.01 K, u(p) =±1 kPa, u_r(m) =0.01

$$\Delta S_2^{0\#} = -d(\Delta\mu_2^{0\#})/dT \quad (11)$$

Moreover, the activation enthalpy ($\Delta H_2^{0\neq}$) has been calculated using the following relation:

$$\Delta H_2^{0\neq} = \Delta\mu_2^{0\neq} + T\Delta S_2^{0\neq} \quad (12)$$

The parameters $(\varphi_{V,2}^0 - \varphi_{V,1}^0)$, $\Delta\mu_1^{0\neq}$, $\Delta\mu_2^{0\neq}$, $\Delta H_2^{0\neq}$, and $T\Delta S_2^{0\neq}$ are reported in Table 4. It shows that $\Delta\mu_1^{0\neq}$ is almost invariant of the solvent compositions and temperatures, implying that $\Delta\mu_2^{0\neq}$ is dependent mainly on the viscosity B-coefficients and $(\varphi_{V,2}^0 - \varphi_{V,1}^0)$ terms. The values $\Delta\mu_2^{0\neq}$ contain the change in the free energy of activation of solvent molecules in the presence of solute as well as the contribution from the movement of solute molecules or ions. $\Delta\mu_2^{0\neq}$ values were positive and greater than $\Delta\mu_1^{0\neq}$ values at all the experimental temperatures for all the aqueous solvent media, suggesting that solute-solvent interactions are stronger in the ground state than in the transition state, and in the transition state, the solvation of the solute (ions) is less favored energetically. According to Feakins *et al.* [51], the fact that $\Delta\mu_2^{0\neq} > \Delta\mu_1^{0\neq} >$ for solutes with positive viscosity B-coefficients indicates stronger solute-solvent interactions, thereby suggesting the formation of transition state to be accompanied by the rupture and distortion of the intermolecular forces in solvent structure. The greater the value of $\Delta\mu_2^{0\neq}$, the greater is the structure-promoting tendency of a solute, and the positive $\Delta\mu_2^{0\neq}$ values for paracetamol in the studied solutions suggest it to be a net structure promoter/maker. However, negative $\Delta S_2^{0\neq}$ and $\Delta H_2^{0\neq}$ values suggest that the transition state is associated with bond formation between solute-solvent components, and the procedure is exothermic in nature.

3.8. Refractometric Results

The dimensionless optical property refractive index, n_D, is very sensitive to changes in molecular organization of pure liquids, solutions, and mixtures. The apparent molar refractivity, R_D, of a solute can be expressed as follows [52]:

$$R_D = \frac{1000}{c}\left[\frac{n_D^2-1}{n_D^2+2} - \frac{1}{\rho_1}\left(\rho - \frac{cM}{1000}\right)\frac{n_{D,1}^2-1}{n_{D,1}^2+2}\right] \quad (13)$$

Where n_D and $n_{D,1}$ are the refractive indices of the solution and solvent, respectively, at 298.15 K and other symbols have their usual meanings. R_D values, given in Table 5, increases linearly as the concentration of paracetamol in all the solvent/solvent mixtures and also increases as the concentration of β-cyclodextrin increases in the studied solutions. This indicated that refractive indices are directly related to ion-solvent interactions in the solutions. As R_D is directly proportional to the molecular polarizability, the increasing trend in R_D values indicates an overall increase in the molecular polarizabilities ($\alpha_P = 3R_M/4\pi N_A$) [51]. The molar refractivities (R_M) were estimated using Lorentz-Lorenz equation.

4. CONCLUSION

In summary, different derived parameters such as φ_V^0 and viscosity B-coefficients for the solutions of

Table 4: Values of $\varphi_{V.2}^{0}-\varphi_{V.1}^{0}$, $\Delta\mu_1^{0\neq}$, $\Delta\mu_2^{0\neq}$, $\Delta H_2^{0\neq}$, and $T\Delta S_2^{0\neq}$ for paracetamol in aqueous solutions of β-cyclodextrin at T=298.15-318.15 K and at pressure P=101 kPa.

Parameters	T=298.15 K	T=308.15 K	T=318.15 K
		0.001[a]	
$\frac{(\varphi_{V,2}^{0}-\varphi_{V,1}^{0})\times10^{6}}{m^{3}\ mol^{-1}}$	109.53	109.91	110.29
$\frac{\Delta\mu_1^{0'}}{kJ\,mol^{-1}}$	10.11±0.01	10.03±0.01	9.89±0.01
$\frac{\Delta\mu_2^{0\neq}}{kJ\,mol^{-1}}$	69.82±0.01	85.09±0.01	98.17±0.01
$\frac{T\Delta S_2^{0\neq}}{kJ\,mol^{-1}}$	−422.51±0.01	−436.68±0.01	−450.85±0.01
$\frac{\Delta H_2^{0\neq}}{kJ\,mol^{-1}}$	−352.69±0.01	−351.59±0.01	−352.69±0.01
		0.003[a]	
$\frac{(\varphi_{V,2}^{0}-\varphi_{V,1}^{0})\times10^{6}}{m^{3}\ mol^{-1}}$	109.68	110.44	110.96
$\frac{\Delta\mu_1^{0\neq}}{kJ\,mol^{-1}}$	10.15	10.07	9.90
$\frac{\Delta\mu_2^{0\neq}}{kJ\,mol^{-1}}$	70.77	87.22	101.42
$\frac{T\Delta S_2^{0\neq}}{kJ\,mol^{-1}}$	−456.96	−472.29	−487.61
$\frac{\Delta H_2^{0\neq}}{kJ\,mol^{-1}}$	−386.19	−385.07	−386.19
		0.005[a]	
$\frac{(\varphi_{V,2}^{0}-\varphi_{V,1}^{0})\times10^{6}}{m^{3}\ mol^{-1}}$	110.51	111.13	111.73
$\frac{\Delta\mu_1^{0\neq}}{kJ\,mol^{-1}}$	10.15	10.09	9.93
$\frac{\Delta\mu_2^{0\neq}}{kJ\,mol^{-1}}$	71.85	88.44	101.89
$\frac{T\Delta S_2^{0\neq}}{kJ\,mol^{-1}}$	−465.61	−481.22	−486.84

(Contd...)

Table 4: *(Continued)*

Parameters	T=298.15 K	T=308.15 K	T=318.15 K
$\frac{\Delta H_2^{0\neq}}{kJ\,mol^{-1}}$	−393.75	−392.79	−393.75
		0.007[a]	
$\frac{(\varphi_{V,2}^0-\varphi_{V,1}^0)\times10^6}{m^3\ mol^{-1}}$	111.53	111.68	112.41
$\frac{\Delta\mu_1^{0\neq}}{kJ\,mol^{-1}}$	10.17	10.11	9.95
$\frac{\Delta\mu_2^{0\neq}}{kJ\,mol^{-1}}$	73.22	89.51	103.70
$\frac{T\Delta S_2^{0\neq}}{kJ\,mol^{-1}}$	−474.39	−489.88	−504.70
$\frac{\Delta H_2^{0\neq}}{kJ\,mol^{-1}}$	−401.18	−400.12	−401.18

[a]Molality of β-cyclodextrin in aqueous solutions in mol.kg^{-1}. Standard uncertainties are: u(T) =±0.01 K, u(p) =±1 kPa, u_r(m) =0.01

Table 5: Refractive indices (n_D), molar refractivities (R_M), apparent molar refractivities (R_D), and molar polarizabilities (α_P) as a function of molarities (m) of paracetamol in β-cyclodextrin solutions.

c/mol.dm^{-3}	n_D	$R_M.10^6$/m^3.mol^{-1}	$R_D.10^6$/m^3.mol^{-1}	$\alpha_P.\ 10^{-30}$/m^3.mol^{-1}
		0.000[a]		
0.006	1.3338	3.73±0.01	120.13±0.90	1.48±0.01
0.0134	1.3342	3.74±0.01	84.64±0.78	1.48±0.01
0.0267	1.3347	3.75±0.01	65.56±0.42	1.48±0.01
0.0401	1.3352	3.76±0.01	59.10±0.52	1.49±0.01
0.0536	1.3357	3.77±0.01	55.78±0.33	1.49±0.01
0.0671	1.3362	3.78±0.01	53.74±0.35	1.50±0.01
		0.001[a]		
0.006	1.3341	3.73±0.01	121.43±0.73	1.48±0.01
0.0134	1.3345	3.74±0.01	85.38±0.65	1.48±0.01
0.0267	1.3350	3.75±0.01	66.54±0.31	1.49±0.01
0.0401	1.3355	3.76±0.01	60.01±0.44	1.49±0.01
0.0536	1.3360	3.77±0.01	55.85±0.51	1.50±0.01
0.0671	1.3365	3.78±0.01	53.78±0.31	1.50±0.01
		0.003[a]		
0.006	1.3345	3.74±0.01	128.75±0.55	1.48±0.01
0.0134	1.3349	3.75±0.01	89.10±0.70	1.49±0.01
0.0267	1.3354	3.76±0.01	67.87±0.49	1.49±0.01
0.0401	1.3359	3.77±0.01	60.54±0.45	1.50±0.01
0.0536	1.3364	3.78±0.01	56.92±0.48	1.50±0.01

(Contd...)

Table 5: *(Continued)*

$c/mol.dm^{-3}$	n_D	$R_M.10^6/m^3.mol^{-1}$	$R_D.10^6/m^3.mol^{-1}$	$\alpha_P.\ 10^{-30}/m^3.mol^{-1}$
0.0671	1.3369	3.79±0.01	54.61±0.24	1.50±0.01
		0.005[a]		
0.006	1.3349	3.75±0.01	138.41±0.86	1.49±0.01
0.0134	1.3353	3.76±0.01	93.45±0.56	1.49±0.01
0.0267	1.3358	3.77±0.01	69.96±0.54	1.50±0.01
0.0401	1.3363	3.78±0.01	62.57±0.46	1.50±0.01
0.0536	1.3368	3.79±0.01	58.11±0.41	1.50±0.01
0.0671	1.3372	3.80±0.01	54.79±0.38	1.51±0.01
		0.007[a]		
0.006	1.3353	3.76±0.01	139.39±0.96	1.49±0.01
0.0134	1.3357	3.77±0.01	94.60±0.43	1.50±0.01
0.0267	1.3362	3.78±0.01	70.58±0.57	1.50±0.01
0.0401	1.3367	3.79±0.01	62.97±0.47	1.50±0.01
0.0536	1.3372	3.80±0.01	59.05±0.34	1.51±0.01
0.0671	1.3376	3.81±0.01	55.32±0.12	1.51±0.01

[a]Molality of β-cyclodextrin in aqueous solutions in $mol.kg^{-1}$. Standard errors are given the parenthesis. Standard uncertainties are: u(T) =±0.01 K, u(p) =±1 kPa

paracetamol in the aqueous solvent systems indicated strong host-guest interaction between paracetamol and β-cyclodextrin, and also, the studied solutions are predominantly characterized by ion-solvent interactions rather than by ion-ion interactions, and the paracetamol acts as a net structure promoter both in water and aqueous solution of cosolutes. S_n values indicated that the paracetamol remains solvated with primary solvation spheres in the aqueous solvent systems investigated.

5. ACKNOWLEDGMENT

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6. REFERENCES

1. V. R. Vemula, V. Lagishetty, S. Lingala, (2010) Solubility enhancement techniques, ***International Journal of Pharmaceutical Sciences Review and Research,*** **5(1):** 41-51.
2. H. A. Joshi, D. K. Dyade, R. N. Patil, (2012) Effect of solubility enhancers on the solubility of paracetamol, ***Indo American Journal of Pharmaceutical Research,*** **2(11):** 1387-1392.
3. H. Kumar, K. Kaur, (2012) Investigation on molecular interaction of amino acids in antibacterial drug ampicillin solutions with reference to volumetric and compressibility measurements, ***Journal of Molecular Liquids,*** **173**: 130-136.
4. S. S. Dhondge, S. P. Zoadape, D. V. Parwate, (2012) Volumetric and viscometric studies of some drugs in aqueous solutions at different temperatures, ***Journal of Chemical Thermodynamics,*** **48:** 207-212.
5. S. Ryshetti, A. Gupta, S. J. Tangeda, R. L. Gardas, (2014) Acoustic and volumetric properties of betaine hydrochloride drug in aqueous d (+)-glucose and sucrose solutions, ***Journal of Chemical Thermodynamics,*** **77:** 123-130.
6. R. A. Granberg, A. C. Rasmuson, (1999) Solubility of paracetamol in pure solvents, ***Journal of Chemical Engineering and Data,*** **44**: 1391-1395.
7. A. Ali, P. Bidhuri, S. Uzair, (2013) Thermodynamic and spectroscopic studies of alanine and phenylalanine in aqueous β-cyclodextrin solutions, ***Journal of Saudi Chemical Society***. DOI: org/10.1016/j.jscs.2013.11.003.
8. C. F. Ribeiro, A. J. M. Valente, C. I. A. V. Santos, P. M. R. A. Prazeres, V. M. M. Lobo, H. D. Burrows, M. A. Esteso, A. M. T. Cabral, F. J. B. Veiga, (2007) Binary mutual diffusion coefficients of aqueous solutions of α-cyclodextrin, 2-hydroxypropyl-α-cyclodextrin, and 2-hydroxypropyl-β-cyclodextrin at temperatures from (298.15 to 312.15) K, ***Journal of Chemical Engineering and Data,*** **52(2):** 586-590.
9. T. Ray, D. Ekka, M. C. Roy, M. N. Roy, (2015) Exploration of host guest inclusion complex of β-cyclodextrin with an ionic liquid ([C4mpy]Cl) in aqueous media by physicochemical approach, ***Chemical Science Review and Letters,*** **4(14):** 619-629.
10. M. N. Roy, D. Ekka, M. C. Roy, S. Saha, (2014) Host-guest inclusion complexes of α

and β-cyclodextrins with α-amino acids, ***RSC Advances,*** **4:** 42383-42390.
11. M. J. Iqbal, Q. M. Malik, (2005) Partial molar volume of paracetamol in water, 0.1 M HCl and 0.154 M NaCl at T=(298.15, 303.15, 308.15 and 310.65) K and at 101.325 kPa, ***Journal of Chemical Thermodynamics,*** **37:** 1347-1350.
12. H. Shekaari, M. T. Z. Moattar, F. Ghaffari, (2015) Solvation properties of acetaminophen in aqueous ionic liquid, 1-hexyl-3-methylimidazolium bromide, solutions at different temperatures, ***Journal of Molecular Liquids,*** **202:** 86-94.
13. C. F. Ribeiro, M. C. F. Barros, L. M. P. Verissimo, C. I. A. V. Santos, A. M. T. Cabral, G. D. Gaspar, M. A. Esteso, (2012) Diffusion coefficients of paracetamol in aqueous solutions, ***Journal of Chemical Thermodynamics,*** **54:** 97-99.
14. A. Tromans, E. Konigsberger, P. M. May, G. Hefter, (2005) Heat capacities and volumes of aqueous dicarboxylate salt solutions of relevance to the bayer process, ***Journal of Chemical and Engineering Data,*** **50:** 2019-2025.
15. D. P. Shoemaker, C. W. Garland, (1967) ***Experiments in Physical Chemistry,*** New York: McGraw-Hill, p131-138.
16. K. N. Marsh, (1987) ***Recommended Reference Materials for the Realization of Physicochemical Properties***, Oxford, U. K: Blackwell Scientific Publications.
17. J. A. Dean, (1973) ***Lange's Handbook of Chemistry***. 11th ed. New York: McGraw-Hill.
18. J. Krakowiak, (2011) Apparent molar volumes and compressibility's of tetrabutyl-ammonium bromide in organic solvents, ***Journal of Chemical Thermodynamics,*** **43:** 882-894.
19. D. Brahman, B. Sinha, (2011) Partial molar volumes and viscosity B-coefficients of N,N'-ethylene-bis(salicylideneiminato)cobalt(II) in binary mixtures of 1,4-dioxane+methanol at ***T***=(298.15, 303.15, 308.15, and 313.15) K, ***Journal of Chemical and Engineering Data,*** **56:** 3073-3082.
20. D. Brahman, B. Sinha, (2014) Partial molar volumes and viscosity B-coefficients for N,N'-ethylene-bis(salicylideneiminato)-diaquochromium(III) chloride in methanolic solutions of 1-butyl-2,3-dimethylimidazolium tetrafluoroborate at T=(298.15, 308.15, and 318.15) K, ***Journal of Chemical Thermodynamics,*** **68:** 260-269.
21. D. O. Masson, (1929) Solute molecular volumes in relation to solvation and ionization, ***Philosophical Magazine,*** **8:** 218-235.
22. I. Banik, M. N. Roy, (2015) Structural effects of three carbohydrates in nicotinic acid/water mixed solvents, ***Journal of Molecular Liquids,*** **203:** 66-79.
23. A. Sarkar, B. Sinha, (2013) Solution thermodynamics of aqueous nicotinic acid solutions in the presence of tetrabutylammonium hydrogen sulphate, ***Journal of Serbian Chemical Society,*** **78:** 1225-1240.
24. D. Brahman, B. Sinha, (2014) Non-covalent interactions between {N,N'-bis[(2-pyridinyl) methylene]-1, 2-benzenediamine]-bis(nitrato)} Cu(II) with pyridoxine hydrochloride in methanol at T=(298.15, 308.15 and 318.15) K, ***Journal of Chemical Thermodynamics,*** **75:** 136-144.
25. D. Brahman, B. Sinha, (2013) Effect of tetrabutylammonium bromide on solution behavior of salicylaldehyde anil zinc (II) in methanol at T=(298.15, 308.15 and 318.15) K, ***Journal of Chemical Thermodynamics,*** **67:** 13-20.
26. B. Sinha, A. Sarkar, P. K. Roy, D. Brahman, (2011) Physicochemical properties of L-alanine in aqueous silver sulphate solutions at (298.15, 308.15, and 318.15) K, ***International Journal of Thermophysics,*** **32:** 2062-2078.
27. A. Sarkar, B. Pandit, B. Sinha, (2016) Effect of paracetamol in aqueous sodium malonate solutions with reference to volumetric and viscometric measurements, ***Journal of Chemical Thermodynamics,*** **96:** 161-168.
28. H. L. Friedman, C. V. Krishnan, F. Franks, (Ed.), (1973) ***Water: A Comprehensive Treatise***. Vol. 3. Ch. 1. New York: Plenum Press.
29. R. Bhatt, J. C. Ahlluwalia, (1985) Partial molar heat capacities and volumes of transfer of some amino acids and peptides from water to aqueous sodium chloride solutions at 298.15 K, ***Journal of Physical Chemistry,*** **89:** 1099-1105.
30. R. K. Wadi, P. Ramasami, (1997) Partial molal volumes and adiabatic compressibilities of transfer of glycine and DL-alanine from water to aqueous sodium sulfate at 288.15, 298.15 and 308.15 K, ***Journal of Chemical Society, Faraday Transaction,*** **93:** 243-247.
31. H. S. Harned, B. B. Owen, (1964) ***The Physical Chemistry of Electrolytic Solutions***. 3rd ed. New York: Reinhold Publishing Corporation.
32. B. Sinha, P. K. Roy, B. K. Sarkar, D. Brahman, M. N. Roy, (2010) Apparent molar volumes and viscosity B-coefficients of caffeine in aqueous thorium nitrate solutions at T=(298.15, 308.15, and 318.15) K, ***Journal of Chemical Thermodynamics,*** **42:** 380-386.
33. M. N. Roy, B. Sinha, P. K. Roy, (2010) Apparent molar volumes and viscosity B-coefficients of glycine in aqueous silver sulphate solutions at T=(298.15, 308.15, 318.15) K, ***Acta Chimica Slovenica,*** **57:** 651-659.
34. A. Sarkar, B. K. Pandit, K. Acharjee, B. Sinha, (2015) Volumetric and viscometric behavior of ferrous sulfate in aqueous lactose solutions at different temperatures, ***Indian Journal of Advances in Chemical Sciences,*** **3:** 219-229.
35. M. L. Parmar, D. S. Banyal, (2005) Effect of temperature on the partial molar volumes of some

bivalent transition metal nitrates and magnesium nitrate in DMF + water mixtures, ***Indian Journal of Chemistry,*** **44A:** 1582-1588.
36. F. J. Millero, (1972) ***Structure and Transport Process in Water and Aqueous Solutions,*** New York: R. A. Horne.
37. L. G. Hepler, (1969) Thermal expansion and structure in water and aqueous solutions, ***Canadian Journal of Chemistry,*** **47:** 4617-4622.
38. D. Brahman, B. Sinha, (2014) Solution behaviour of (N,N'-ethylenebis(salicylideneiminato))-iron(III) chloride in aqueous methanol at 298.15, 303.15 and 313.15 K, ***Journal of the Serbian Chemical Society,*** **79:** 225-239.
39. N. Li, Y. H. Zang, Y. N. Yu, X. L. Xiong, (2005) Inclusion complex of trimethoprim with β-cyclodextrin, ***Journal of Pharmaceutical and Biomedical Analysis,*** **39:** 824-829.
40. H. Jiang, D. Li, Y. Shanshan, (2007) Determination of phenol at ng l-1 level by flow-injection chemiluminescence combined with on-line solid-phase extraction, ***Spectrochimica Acta A,*** **66:** 878-883.
41. E. D. Davies, J. A. Ripmester, (1996) ***Physical Methods in Supramolecular Chemistry,*** Oxford, UK: Pergamon Press, p426.
42. H. Y. Wang, J. Han, X. J. Feng, (2007) Spectroscopic study of orange G-β-cyclodextrin complex and its analytical application, ***Spectrochimica Acta A,*** **66:** 578-585.
43. P. Sambasevam, S. Mohamad, N. M. Sarih, N. A. Ismail, (2013) Synthesis and characterization of the inclusion complex of β-cyclodextrin and azomethine, ***International Journal of Molecular Sciences,*** **14:** 3671-3682.
44. W. Devine, B. M. Lowe, (1971) Viscosity B-coefficients at 15 and 25 °C for glycine, β-alanine, 4-amino-n-butyric acid, and 6-amino-n-hexanoic acid in aqueous solution, ***Journal of Chemical Society A,*** **44**: 2113-2116.
45. G. Jones, M. Dole, (1929) The viscosity of aqueous solutions of strong electrolytes with special reference to barium chloride, ***Journal of the American Chemical Society,*** **51:** 2950-2964.
46. T. S. Banipal, D. Kaur, P. K. Banipal, (2004) Apparent molar volumes and viscosities of some amino acids in aqueous sodium acetate solutions at 298.15 K, ***Journal of Chemical and Engineering Data,*** **49:** 1236-1246.
47. H. J. V. Tyrrell, M. Kennerley, (1968) Viscosity B-coefficients between 5° and 20° for glycolamide, glycine, and N-methylated glycines in aqueous solution, ***Journal of the Chemical Society A,*** **44:** 2724-2728.
48. A. K. Nain, M. Lather, R. K. Sharma, (2011) Volumetric, ultrasonic and viscometric behavior of l-methionine in aqueous-glucose solutions at different temperatures, ***Journal of Molecular Liquids,*** **159:** 180-188.
49. H. Kumar, K. Kaur, (2012) Effect of potassium citrate salts on the transport behavior of l-alanine in aqueous solutions at T=(293.15 to 308.15) K, ***Journal of Chemical Engineering and Data,*** **57:** 3416-3421.
50. N. Roy, R. Chanda, R. K. Das, D. Ekka, (2012) Densities and viscosities of citric acid in aqueous cetrimonium bromide solutions with reference to the manifestation of solvation, ***Journal of Chemical Engineering and Data,*** **56:** 3285-3290.
51. S. Glasstone, K. Laidler, H. Eyring, (1941) ***The Theory of Rate Processes,*** New York: McGraw-Hill.
52. H.A Lorentz, (1906) Theory of Electronics, Leipzig: Teubner

****Bibliographical Sketch***

Dr. B. Sinha is an Assistant Professor in the Department of Chemistry, University of North Bengal, West Bengal, India. His research areas include Solution Thermodynamics, Coordination Chemistry & Analytical Chemistry. He has published 4 books and more than 60 research articles in different peer reviewed national & international journals.

Abhijit Sarkar is a research scholar in the Department of Chemistry, University of North Bengal, West Bengal, India and also an engineer in Indian Oil Corporation Ltd. He has published 3 books and 14 research articles in different peer reviewed national & international journals.

SUPPLEMENTARYTABLES

Table S1: Densities (ρ) and viscosities (η) of different aqueous solutions of β-cyclodextrin at T=298.15-318.15 K and at pressure P=101 kPa.

m[a]	T/K	$\frac{\rho \times 10^{-3}}{(\mathrm{kg\,m^{-3}})}$		$\frac{\eta}{(\mathrm{mPa\,s})}$	
		Expt.	Lit.	Expt.	Lit.
0.001	298.15	0.99752	0.99747[a]	1.3034	1.304[a]
	308.15	0.99439	0.99440[b]	1.1031	1.10[b]
	318.15	0.99058		0.9026	
0.003	298.15	0.99818	0.99815[a]	1.3132	1.313[a]
	308.15	0.99510	0.99510[b]	1.1128	1.11[b]
	318.15	0.99126		0.9122	
0.005	298.15	0.99892	0.99890[a]	1.3230	1.323[a]
	308.15	0.99573	0.99575[b]	1.1224	1.12[b]
	318.15	0.99193			
				0.9218	
0.007	298.15	0.99962		1.3328	
	308.15	0.99643		1.1310	
	318.15	0.99259		0.9314	

Standard uncertainties are: u(T) =±0.01 K, u(p) =±1 kPa, u(m) =±1.10^{-2} mol.kg^{-1}, u(ρ) = ±0.1 kg.m^{-3}, u(η) =0.001 mPa.s, [a][28], [b][29]

Table S2: Molalities (m), densities (ρ), viscosities (η), and apparent molar volumes (φ_V) of paracetamol in different aqueous β-cyclodextrin solutions at T=298.15-318.15 K and at pressure P=101 kPa.

m (mol.kg^{-1})	ρ 10^{-3} (kg.m^{-3})	η (mPa. s)	$\varphi_V.10^6$ (m^3.mol^{-1})
0.001[a]			
T=298.15 K			
0.0060	0.99767	1.307	126.392
0.0134	0.997867	1.3094	125.468
0.0267	0.99823	1.3144	124.723
0.0401	0.99861	1.3204	124.083
0.0536	0.999	1.3265	123.603
0.0671	0.99941	1.3326	122.996
T=308.15 K			
0.0060	0.99454	1.1066	126.711
0.0134	0.99473	1.1112	126.309
0.0267	0.99509	1.1139	125.411
0.0401	0.99546	1.1221	124.893
0.0536	0.99585	1.1281	124.283
0.0671	0.99625	1.1352	123.748
T=318.15 K			
0.0060	0.990727	0.9061	127.61
0.0134	0.99092	0.9097	126.696
0.0267	0.99126	0.9156	126.556
0.0401	0.99164	0.9215	125.524
0.0536	0.99201	0.9275	125.228

(Contd...)

Table S2: *(Continued)*

m (mol.kg^{-1})	ρ 10^{-3} (kg.m^{-3})	η (mPa. s)	$\varphi_V.10^6$ (m^3.mol^{-1})
0.0671	0.99239	0.9335	124.879
0.003[a]			
T=298.15 K			
0.0060	0.998329	1.3145	126.493
0.0133	0.99852	1.3181	125.736
0.0266	0.99888	1.3219	124.936
0.0401	0.99926	1.329	124.27
0.0536	0.99965	1.3351	123.677
0.0671	1.00006	1.3412	123.084
T=308.15 K			
0.0060	0.995247	1.1152	127.144
0.0133	0.995431	1.1198	126.729
0.0266	0.99579	1.1247	125.621
0.0401	0.99616	1.1318	125.076
0.0536	0.99655	1.1389	124.353
0.0671	0.99695	1.1449	123.831
T=318.15 K			
0.0060	0.991403	0.9146	128.2188
0.0133	0.991589	0.9181	127.2756
0.0266	0.99194	0.9229	126.3894
0.0401	0.99231	0.9311	125.7113
0.0536	0.99268	0.9371	125.3011
0.0671	0.99306	0.9431	124.9651
0.005[a]			
T=298.15 K			
0.0060	0.999064	1.3254	127.253
0.0133	0.99925	1.3279	126.416
0.0266	0.999606	1.3328	125.392
0.0401	0.99997	1.34	124.885
0.0535	1.00035	1.346	124.359
0.0670	1.00075	1.3521	123.724
T=308.15 K			
0.0060	0.995872	1.1248	127.92
0.0133	0.996059	1.1294	126.817
0.0266	0.99641	1.1343	125.939
0.0401	0.99678	1.1425	125.201
0.0535	0.99717	1.1496	124.481
0.0670	0.99756	1.1546	124.032
T=318.15 K			
0.0060	0.992069	0.9242	128.827
0.0133	0.992252	0.9288	127.742
0.0266	0.992604	0.9325	126.552
0.0401	0.99297	0.9419	125.833
0.0535	0.99334	0.9478	125.426

(Contd...)

Table S2: *(Continued)*

m (mol.kg^{-1})	ρ 10^{-3} (kg.m^{-3})	η (mPa. s)	$\varphi_V.10^6$ (m^3.mol^{-1})
0.0670	0.99372	0.9538	125.011
0.007[a]			
T=298.15 K			
0.0060	0.99976	1.3353	127.8485
0.0133	0.99994	1.3377	127.0983
0.0266	1.00028	1.3404	126.3032
0.0401	1.00066	1.3509	125.0676
0.0535	1.00104	1.357	124.4784
0.0670	1.00143	1.3619	123.9575
T=308.15 K			
0.0060	0.99657	1.1334	128.183
0.0133	0.99675	1.138	127.428
0.0266	0.9971	1.1429	126.248
0.0401	0.99747	1.1511	125.384
0.0535	0.99786	1.1582	124.602
0.0670	0.99824	1.1643	124.267
T=318.15 K			
0.0060	0.992726	0.9338	129.264
0.0133	0.992896	0.9373	128.896
0.0266	0.99323	0.941	127.785
0.0401	0.99357	0.9503	127.296
0.0535	0.99394	0.9574	126.505
0.0670	0.99431	0.9633	126.014

[a]Molality of β-cyclodextrin in aqueous solutions in mol.kg$^{-1.}$ Standard uncertainties are: u(T) =±0.01 K, u(p) =±1 kPa, u_r(m) = 0.01, u(ρ) =±0.1 kg.m^{-3}, and u(η) =0.001 mPa.s