Acoustic characterization and hydration number analysis of nicotinamide (Vitamin B$_3$) in aqueous solutions

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Abstract. The ultrasonic velocity (u) and density (ρ) of aqueous nicotinamide (Vitamin B$_3$) solutions were determined using an Anton Paar DSA 5000 M densimeter–sound velocity analyser at 0.1 MPa. Measurements were carried out over a molal concentration range from 0 to 1.11177 mol.kg^{-1} and at temperatures between 298.15 K and 323.15 K. From these experimental data, hydration number (n_H), acoustic properties like apparent molar isentropic compressibility (K_Φ), limiting apparent molar isentropic compressibility (K_Φ^o) and a semi-empirical interaction factor (S_K) were evaluated. The analysis of these parameters provides insight into solute–solvent interactions, revealing whether nicotinamide acts as a structure-maker or structure-breaker in water. The results also explain the hydration phenomena, acoustic behavior, and structural modifications occurring within these binary mixtures.

1 Introduction

Amides serve as ideal models for studying protein and peptide interactions in biological systems [1]. Nicotinic acid changes into nicotinamide, which is a coenzyme called NAD coenzyme has a main amide ring and a pyridine ring. NAD coenzyme executes a crucial role in kerbs cycle of carbohydrates and amino acids and is important for medicinal purposes [2-3]. Nicotinamide is found naturally in eggs, milk, salmon, yeast, green vegetables and cereal grains. Its anti-inflammatory properties make it useful for identifying inflammatory skin conditions. Nicotinamide, a drug that helps make cancer treatments more effective, also reduces low oxygen levels in tumours, improves blood flow in cancer tissues, and helps lessen anxiety. This vitamin is beneficial for treating pellagra and type 1 diabetes. Additionally, nicotinamide supplementation has been shown to lower oedema and discomfort and enhance joint flexibility in osteoarthritis patients. Nicotinamide was selected as a medication due to its importance in bioenergetics, physiology, dermatology, and

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pharmacology. Nicotinamide is crucial among the eight B vitamins, is water-soluble and moderately soluble in alcohol. Nicotinamide pyridine ring in the meta position plays important for making hydrogen bonds, lead to several chemical connections that are necessary for many biological processes [4-6]. Acoustic testing is a non-destructive and thorough way to look at the unique properties of different materials. This shows how important it is to understand molecular structures in scientific research [7]. Recent furtherance has revealed ultrasonic energy's significance in medicine, agriculture and engineering. Acoustic characteristics reveal important solute-solvent interactions. These results help anticipate biological membrane medication absorption and transport. These results raise questions regarding the substance's characteristics and the way they alter with dosage and temperature, which is critical in clarifying pharmacological activity, hydrogen bonding. These results may enhance medication delivery and bioavailability.

2 Experimental

2.1 Materials and methods

In this investigation, we utilised HPLC-grade nicotinamide (vitamin B_3) with CAS No. 98–92-0 and mass purity ≥ 0.995 procured from Sigma-Aldrich and water with CAS No. 7732–18-5, mass purity ≥ 0.995 and conductivity of less than 1 µS/cm procured from Merck. We employed Wensar (MAB 201) analytical balance with accuracy of 0.0001 g to prepare samples with different molal concentrations. The Anton Paar DSA 5000 M digital vibrating tube density meter, controlled at 3 MHz of frequency was applied in assessing the sample ultrasonic velocity (u) and density (ρ) which has a thermostat regulated the temperature of the measurement cell to within 1 x 10^{-2} K. For accurate findings, distilled water, toluene, and dry air were used to calibrate the device. Distilled water is the largest density calibration point, toluene is the midpoint reference, and dry air is the baseline. Ultrasonic velocity data are used in this calibration process to assure measurement accuracy and consistency between samples. Every measurement was made three times, and the average results are shown in Table 1. The ultrasonic velocity and density exhibit a repeatability of within 0.01 $m.s^{-1}$, 10^{-3} $kg.m^{-3}$ respectively. The uncertainties of ultrasonic velocity and density were 0.5 $m.s^{-1}$ and 0.4 $kg.m^{-3}$ respectively.

2.2 Measurements and parameters

Using density (ρ), ultrasonic velocity (u) and adiabatic compressibility (β) [8] the following parameters were calculated

$$K_{\Phi} = \frac{M\beta_s}{\rho} - \frac{1000\,(\beta_{s0}\rho - \beta_s\rho_0)}{m\rho\rho_0} \qquad (1)$$

$$\boldsymbol{K_{\Phi} = K_{\Phi}^0 + m\,S_K} \qquad (2)$$

$$\boldsymbol{n_H = \frac{n_w}{n_s}\left(1 - \frac{\beta_s}{\beta_{s0}}\right)} \qquad (3)$$

Where $\boldsymbol{M}$ is molecular weight, $\boldsymbol{m}$ is molality, $\boldsymbol{n_w}$ and $\boldsymbol{n_s}$ are number of moles of solvent and solute, $\boldsymbol{\rho_0}$, $\boldsymbol{\rho}$ are densities, $\boldsymbol{\beta_{s0}}, \boldsymbol{\beta_s}$ are adiabatic compressibility of solvent and solution respectively.

3 Results and discussion

The apparent molar isentropic compressibility (K_Φ) quantifies the degree to which a substance tends to shrink under constant temperature and pressure conditions. The intrinsic features of solvent and soulte play a role in the formation of liquid solutions [9-11]. The solute's core contribution results from the contraction of the ion's solvation shell, whereas the solvent's intrinsic contribution indicates how easily the pure solvent can be compressed. Solvent molecules surround the amino acids, highlighting solute-solvent interactions and how certain solute molecules affect solution compressibility. It is a thermodynamic feature relied on in fluid chemistry to acssess the impact of a solute on the compressibility of the solvent. It also elucidates the interactions of solute-solvent and is derived from the isentropic compressibility of the solution. The values of K_Φ at numerous molal concentrations and temperatures are listed in Table 1.

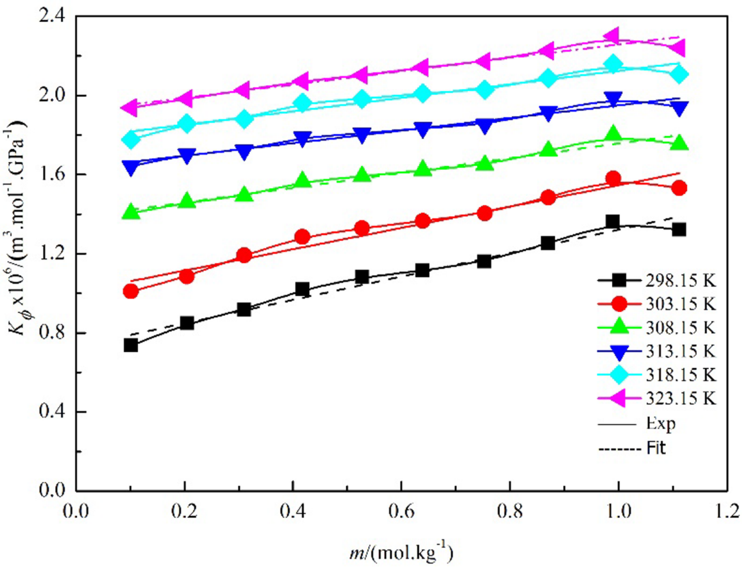

Fig. 1. Variation of apparent molar isentropic compressibility (K_Φ) with molal concentration (m) at different temperatures.

From Figure 1, it has been accentuated that nicotinamide serves solvent structure breaker due to its positive compressibility (K_Φ), which increases with molal concentration from 0.10128 to 1.11177 mol.kg^{-1} in water. It is well-hydrated and forms strong hydrogen bonds with water at concentrations of around 0.10128 to 0.30993 mol.kg^{-1}, resulting in slight compressibility. As the concentration rises from 0.41747 to 0.75348 mol.kg^{-1} indicating that fewer water molecules surround each solute molecule. The escalate in solute-solute interactions and packing alters the solvent structure, leading to a significant increase in K_Φ. When the concentration increases from 0.87048 to 1.11177 mol.kg^{-1} compressibility initially increases and then decreases, likely due to solute particles aggregating, which reduces their impact on disrupting the water structure. The positive values of K_Φ suggests the structure breaking effect. High temperatures weaken hydrogen bonds and decrease the strength of interactions between the solvent and solute, enabling molecules to advance with greater ease and making the fluid easier to compress. Enhanced thermal motion and reduced hydration make the fluid more compressible leading to higher values of [12].

Table 1. Density ρ, ultrasonic velocity u, apparent molar isentropic compressibility K_{Φ}, limiting apparent molar isentropic compressibility K_{Φ}^{o}, emprical slope S_K and hydration number n_H of nicotinamide in water at atmospheric pressure p =0.1MPa.

m /(mol.kg^{-1})	ρx10^{-3} /(kg·m^{-3})	u /(m.s^{-1})	K_{Φ}x10^6 /(m^3.mol^{-1}.GPa^{-1})	K_{Φ}^{o}x10^6 /(m^3.mol^{-1}.GPa^{-1})	S_Kx10^6 (kg.m^3.mol^{-2}.GPa^{-1})	n_H
T = 298.15 K						
0	0.99747	1496.90				
0.10128	0.9974	1501.74	0.73			4.72
0.20458	0.99790	1505.66	0.85			4.47
0.30993	0.99850	1509.36	0.92			4.33
0.41747	0.99910	1512.92	1.02			4.21
0.52716	1.00030	1516.27	1.08	0.73	0.59	4.11
0.63915	1.00090	1519.87	1.11			4.06
0.75348	1.00160	1523.22	1.16			4.00
0.87048	1.01673	1526.21	1.25			3.90
0.99019	1.01882	1528.82	1.36			3.79
1.11177	1.02159	1532.74	1.32			3.82
T = 303.15 K						
0	0.99565	1509.50				
0.10128	0.99812	1513.30	1.01			4.15
0.20458	1.00055	1516.96	1.08			4.07
0.30993	1.00308	1520.09	1.19			3.92
0.41747	1.00541	1523.27	1.29			3.82
0.52716	1.00791	1526.36	1.33	1.00	0.54	3.76
0.63915	1.01035	1529.49	1.37			3.71
0.75348	1.01279	1532.52	1.40			3.67
0.87048	1.01498	1535.22	1.48			3.58
0.99019	1.01704	1537.62	1.58			3.49
1.11177	1.01976	1541.32	1.53			3.53
T = 308.15 K						
0	0.99403	1520.30				
0.10128	0.99646	1523.47	1.40			3.66
0.20458	0.99885	1526.55	1.46			3.60
0.30993	1.00133	1529.47	1.49			3.54
0.41747	1.00363	1532.29	1.56	1.38	0.37	3.47
0.52716	1.00608	1535.05	1.59			3.43
0.63915	1.00848	1537.80	1.62			3.39
0.75348	1.01088	1540.54	1.65			3.36
0.87048	1.01304	1542.93	1.71			3.28
0.99019	1.01507	1545.09	1.80			3.20
1.11177	1.01775	1548.39	1.75			3.24
T = 313.15 K						
0	0.99222	1529.30				
0.10128	0.99461	1532.10	1.64			3.36
0.20458	0.99696	1534.78	1.70			3.29
0.30993	0.99939	1537.37	1.72			3.25
0.41747	1.00165	1539.85	1.79			3.18
0.52716	1.00407	1542.30	1.81	1.63	0.31	3.15
0.63915	1.00643	1544.72	1.83			3.12
0.75348	1.00880	1547.17	1.85			3.09
0.87048	1.01092	1549.28	1.92			3.03
0.99019	1.01291	1551.21	1.99			2.95

1.11177	1.01557	1554.17	1.94			3.00
***T* = 318.15 K**						
0	0.99021	1536.60				
0.10128	0.99256	1539.29	1.73			3.15
0.20458	0.99488	1541.61	1.86			3.09
0.30993	0.99732	1543.87	1.88			3.05
0.41747	0.99950	1546.05	1.96			2.97
0.52716	1.00188	1548.21	1.98	1.78	0.34	2.93
0.63915	1.00420	1550.31	2.01			2.90
0.75348	1.00654	1552.47	2.03			2.87
0.87048	1.00863	1554.33	2.08			2.81
0.99019	1.01060	1556.03	2.16			2.74
1.11177	1.01322	1558.70	2.11			2.79
***T* = 323.15 K**						
0	0.98804	1542.10				
0.10128	0.99035	1545.14	1.93			2.97
0.20458	0.99263	1547.12	1.98			2.92
0.30993	0.99481	1549.07	2.03			2.91
0.41747	0.99717	1550.95	2.07			2.84
0.52716	0.99953	1552.83	2.10	1.92	0.34	2.79
0.63915	1.00180	1554.65	2.14			2.74
0.75348	1.00403	1556.54	2.17			2.70
0.87048	1.00614	1558.16	2.22			2.65
0.99019	1.00813	1559.64	2.30			2.58
1.11177	1.01072	1562.05	2.24			2.62

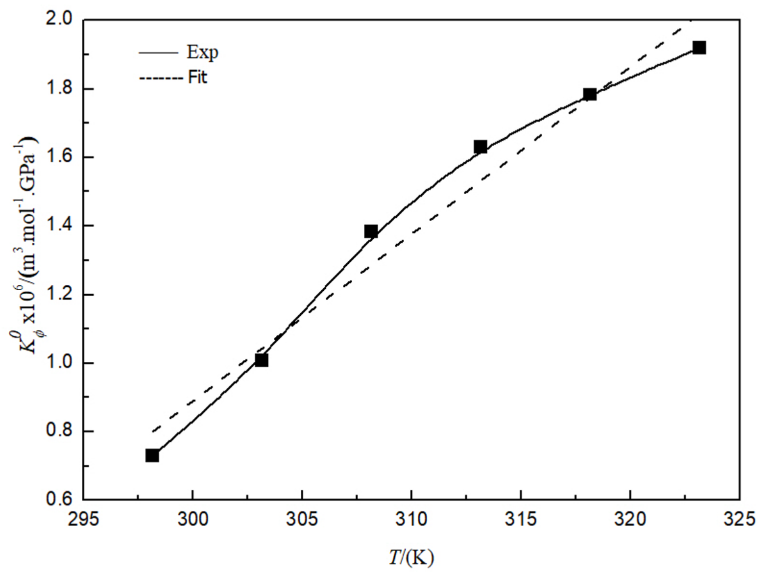

Fig. 2. Variation of limiting apparent molar isentropic compressibility (K_Φ^0) with temperature (T).

The limiting apparent molar isentropic compressibility (K_Φ^0) provides valuable insights over solute-solvent dynamics, especially when solute-solute interactions decrease with infinite dilution. The empirical slopes (S_K) and K_Φ^0 were calculated by using least square fitting method using equation (2) and values are reported in Table 1. Nicotinamide in aqueous solution displays structure-breaking behaviour, as indicated by the positive values of K_Φ^0 that increase with temperature. Figure 2 discloses that escalate in K_Φ^0 suggests that solute-solvent dynamics weaken as the temperature increases, while the positive S_K values indicate enhanced solute-solute interactions as concentration rises. At higher concentrations and temperatures, aggregation and disruption of water structure occur, supplanting hydration-dominated interactions.

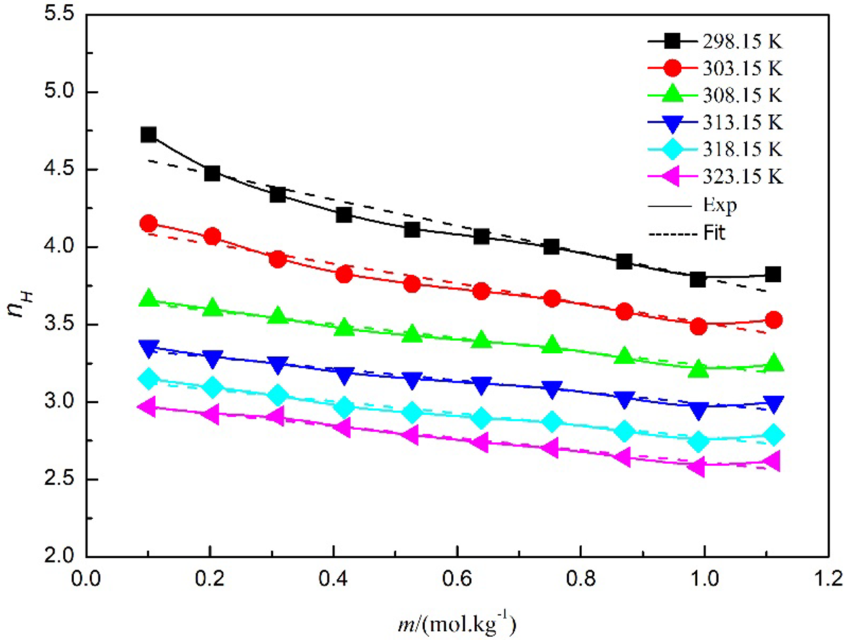

Fig. 3. Variation of hydration number (n_H) with molal concentration (m) at different temperatures.

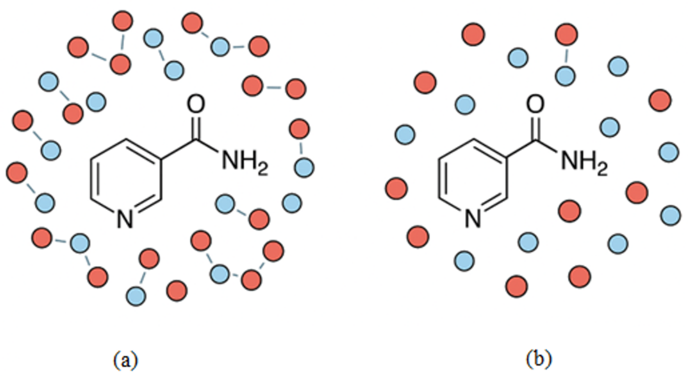

Fig. 4. Variation of hydration shell at (a) 0.10128 and (b) 1.11177 molal concentration (m).

The hydration number (n_H) represents the mean quantity of molecules of water which are firmly or tightly bonded to a solute molecule in a solution. It quantifies the dynamics across solute and solvent, particularly focusing on the hydrogen bonding that occurs between the functional groups of the solute and the water molecules [13]. Hydration number (n_H) is computed using equation (3) and its results are noted in Table 1. From Figure 3 it is observed that as concentration and temperature increase, the hydration number of nicotinamide (n_H) decreases due to shell instability [14]. At low concentrations and temperatures, nicotinamide maintains a stable hydration shell composed of tightly linked water molecules that form hydrogen bonds. However, as concentration rises, overlapping hydration shells and a reduced number of water molecules per solute lead to partial shell breakdown and shown in Figure 4. Additionally, thermal motion disrupts hydrogen bonding at elevated temperatures, causing the hydration shell to become more dispersed. These findings indicate that nicotinamide disrupts the water network, with greater disruption occurring at higher concentrations and temperatures.

4 Conclusions

Positive values apparent molar isentropic compressibility (K_{Φ}) of nicotinamide in aqueous medium shows solvent structure breaking effect which increases with rise in concentration and temperature. Limiting apparent molar compressibility (K_{Φ}^{0}) increases with temperature, suggesting that solute–solvent interactions diminish due to the thermal disruption of the hydration shell. At the same time, the positive empirical slope values (S_K) indicate that solute–solute interactions intensify at higher concentrations. Nicotinamide's hydration number (n_H) decreases with concentration and temperature; in response to congestion and thermal motion, the hydration shell becomes unstable and partially breaks down, disrupting the organised water network.

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