

# Investigation of Thermo-Acoustic Properties of Ethanol-Cyclohexane Binary Mixture at Different Temperatures

Wakulkar A. P.<sup>1,\*</sup>, Lanjewar M. R.<sup>2</sup>, Shah S. A.<sup>3</sup>, Bhukya P. P.<sup>1</sup>

## Abstract

The density, viscosity, and speed of sound for ethanol-cyclohexane binary mixtures were determined across mole fractions ranging from 0.1 to 0.9 using an Anton Paar DSA 5000 M within the temperature span of 288.15–318.15 K. From these experimental measurements, several thermodynamic and acoustic properties, such as isentropic compressibility, relative association, free volume, relaxation time, Gibbs free energy of activation, internal pressure, and solubility parameter, were derived. These parameters serve as useful indicators of the strength and type of molecular interactions present in the system. The trends observed in both measured and calculated values were interpreted to highlight the influence of non-covalent interactions, including hydrogen bonding, dispersion forces, and dipole-dipole associations, on the structural arrangement and dynamic behavior of the liquid mixtures. The study of ethanol-cyclohexane mixtures reveals that intermolecular interactions arise from a balance of Van der Waals forces, hydrogen bonding, molecular size, and cohesive effects. Density and viscosity decrease with cyclohexane concentration, while ultrasonic velocity increases, indicating structural rearrangements and association between components. Derived parameters confirm that solute–solvent and solute–solute interactions vary with composition and weaken at higher temperatures due to thermal agitation. Furthermore, the results emphasize the non-ideal behavior of the system, suggesting deviations from ideal mixing due to specific interaction effects. Overall, the system demonstrates that molecular interactions in liquid mixtures are governed by both physical forces and molecular geometry, which are crucial for understanding mixture behavior in industrial and pharmaceutical applications.

**Keywords:** Compressibility, relaxation time, solubility parameter, intermolecular interactions

## INTRODUCTION

Measurement of ultrasonic velocity allows the precise determination of important acoustic and thermodynamic parameters, which are highly sensitive to molecular interactions in liquid mixtures. The nature and relative strength

of molecular interactions between the components of liquid mixtures have been effectively investigated using ultrasonic methods [1–3]. These interactions provide deeper insight into the nature of the solvent and solute, particularly whether the solute modifies or distorts the structure of the solvent. The structure, intrinsic nature, and prevailing conditions of both solutes and solvents play a crucial role in determining the resulting properties and interactions within the solution [4].

The velocity of ultrasound in liquids is primarily influenced by the intermolecular binding forces, and it serves as an effective tool for probing molecular interactions in both binary and ternary mixtures [5–9]. Systematic studies on binary and multicomponent liquid mixtures, which hold great practical importance in

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various industrial processes, provide a wide range of solutions with tailored compositions and properties. The observed nonlinearity in such systems can be attributed to molecular dimensions and the forces acting between molecules. Measurements of ultrasonic velocity, when combined with density and viscosity data, yield valuable insights into molecular interactions involving ions, dipoles, hydrogen bonding, multipolar, and dispersive forces [10–13].

To study and understand the behavior of alcohol + alkane systems under varying operating conditions, knowledge of their thermophysical properties is essential. In recent years, mixtures of alkanol + alkane have attracted considerable attention due to their practical applications, particularly as petrol additives and in rectification processes involving binary azeotropes. The binary mixtures of alcohols and alkanes have, therefore, been investigated extensively and systematically [14–16].

Davila et al. [17] studied the compressed liquid densities of methyl benzoate, cyclohexane, and hexanol. They reported that the structure of methyl benzoate is disrupted by the globular-shaped cyclohexane, which acts as an order destroyer [18].

In our recent investigations [19–21], we reported experimental data on the thermodynamic properties of binary mixtures comprising alkanols and alkanes to gain deeper insights into their behavior. As a continuation of this work, we now present density ( $\rho$ ), viscosity ( $\eta$ ), and speed of sound ( $u$ ) data and the computation of related parameters for ethanol–cyclohexane binary mixtures studied within the temperature range of 288.15–318.15 K.

## MATERIAL AND METHODS

The present study aims to determine the density ( $\rho$ ), viscosity ( $\eta$ ), and ultrasonic velocity ( $U$ ) of ethanol–cyclohexane binary mixtures over the temperature range 288.15–318.15 K and mole fraction range of 0.1–0.9. Ethanol (CAS 64-17-5) and Cyclohexane (CAS 110-82-7) used in the present work were procured from Merck KGaA, Darmstadt, Germany, with assay of 99.8% and 99.5%, respectively. Glassware was cleaned using standard procedures and dried to absolute dryness, confirmed with anhydrous  $\text{CuSO}_4$ . Density, viscosity, and ultrasonic velocity measurements were carried out using an Anton Paar DSA 5000 M instrument.

The instrument provides high-precision measurements, with density accurate to  $\pm 0.000007 \text{ g cm}^{-3}$ , ultrasonic velocity with an accuracy of  $\pm 0.01 \text{ m s}^{-1}$ , and viscosity with an accuracy of  $\pm 0.1\%$  [22].

The literature and experimental density, speed of sound, and viscosity value of ethanol and cyclohexane with standard deviation at  $T = 288.15\text{--}318.15 \text{ K}$ , are given in Tables 1–12, which show accuracy and calibration of instruments.

**Table 1.** Density ( $\rho$ ), ultrasonic velocity ( $u$ ), and viscosity ( $\eta$ ) of ethanol and cyclohexane at different temperatures.

T (K)	Ethanol $\rho$ ( $\text{g/cm}^3$ ) Lit [23, 24]	Ethanol $\rho$ ( $\text{g/cm}^3$ ) This Work	Ethanol $u$ (m/s) Lit [25, 26]	Ethanol $u$ (m/s) This Work	Ethanol $\eta$ ( $\text{mPa}\cdot\text{s}$ ) Lit [27]	Ethanol $\eta$ ( $\text{mPa}\cdot\text{s}$ ) This Work
288.15	0.78950	0.79444	1161.78	1178.63	1.1870	1.30911
293.15	0.78520	0.79017	1144.00	1161.82	1.0820	1.18635
298.15	0.78070	0.78588	1127.58	1144.03	0.9870	1.08135
303.15	0.77690	0.78158	1094.07	1127.62	0.9015	0.98628
308.15	0.77210	0.77723	–	1110.89	0.8306	0.90056
313.15	0.76840	0.77285	–	1094.09	0.7642	0.83051
318.15	–	0.76842	–	1077.81	–	0.76332

**Table 2.** Density ( $\rho$ ), ultrasonic velocity ( $u$ ), and viscosity ( $\eta$ ) of cyclohexane at different temperatures (comparison of literature and experimental data).

T (K)	Cyclohexane $\rho$ (g/cm <sup>3</sup> ) Lit [28, 29]	Cyclohexane $\rho$ (g/cm <sup>3</sup> ) This Work	Cyclohexane $u$ (m/s) Lit [30–32]	Cyclohexane $u$ (m/s) This Work	Cyclohexane $\eta$ (mPa·s) Lit [28, 31–32]	Cyclohexane $\eta$ (mPa·s) This Work
288.15	0.7784	0.77728	1280.0	1301.04	0.890	1.0722
293.15	0.7737	0.77369	1254.0	1278.12	–	0.9696
298.15	0.76914	0.77080	1229.1	1253.98	0.821	0.8931
303.15	0.76446	0.76761	1208.0	1229.88	0.757	0.8203
308.15	–	0.76421	–	1206.58	–	0.7496
313.15	–	0.76262	–	1184.22	–	0.6903
318.15	–	0.75633	–	1161.16	–	0.6353

## THEORY AND CALCULATIONS

Various acoustic parameters were derived from experimental measurements by applying the following relations,

$$\beta_a = (U^2 \rho)^{-1} [33] \quad (1)$$

$$R_A = \rho / \rho_o (U_o/U)^{1/3} [34] \quad (2)$$

$$V_f = (M_{\text{eff}} U / \eta K)^{3/2} [35] \quad (3)$$

$$\tau = 4/3 \eta \beta_a [36] \quad (4)$$

$$\Delta G = K_b.T.\text{Log}_{eh}(\tau.K_b.T) [37] \quad (5)$$

$$\pi_i = bRT(K\eta/U)^{1/2}(\rho^{2/3}/M_{\text{eff}})^{7/6} [38] \quad (6)$$

$$\delta_s = \sqrt{p^*/V} [39], \quad (7)$$

where,  $K$  is the temperature-independent Jacobson's constant.

The comparison of experimentally measured values of ultrasonic velocity, viscosity, and density with their theoretically predicted counterparts in binary mixtures provides valuable insight into the nature of molecular interactions between the constituent components. Such theoretical evaluations play an important role in developing reliable models for understanding and predicting the behavior of liquid mixtures across diverse conditions [40].

## RESULT AND DISCUSSION

**Table 3.** Density vs concentration.

	288.15 K	293.15 K	298.15 K	303.15 K	308.15 K	313.15 K	318.15 K
0.1	792.352	788.159	783.867	779.725	775.583	771.203	766.204
0.2	789.361	784.668	780.476	776.234	772.093	767.812	762.813
0.3	787.067	782.374	778.082	773.740	769.400	765.019	760.220

0.4	785.371	780.579	776.087	771.697	767.006	762.626	757.826
0.5	784.175	779.683	774.991	770.500	765.809	761.369	756.729
0.6	783.878	779.485	774.692	770.311	765.410	761.160	756.529
0.7	783.379	778.986	774.194	770.012	765.310	761.060	756.430
0.8	782.980	778.687	773.894	769.613	764.811	760.561	756.031
0.9	782.981	778.388	773.695	769.314	764.413	760.162	755.632

**Table 4.** Viscosity vs concentration.

	288.15 K	293.15 K	298.15 K	303.15 K	308.15 K	313.15 K	318.15 K
0.1	0.0011815	0.0010729	0.0009759	0.0008866	0.0008147	0.0007545	0.0007034
0.2	0.0011267	0.0010228	0.0009295	0.0008446	0.0007767	0.0007180	0.0006661
0.3	0.0010909	0.0009894	0.0009003	0.0008183	0.0007536	0.0006955	0.0006438
0.4	0.0010651	0.0009689	0.0008813	0.0007976	0.0007350	0.0006777	0.0006261
0.5	0.0010480	0.0009523	0.0008663	0.0007844	0.0007212	0.0006653	0.0006165
0.6	0.0010375	0.0009405	0.0008569	0.0007756	0.0007142	0.0006572	0.0006096
0.7	0.0010307	0.0009354	0.0008511	0.0007724	0.0007109	0.0006532	0.0006048
0.8	0.0010289	0.0009382	0.0008528	0.0007766	0.0007149	0.0006577	0.0006106
0.9	0.0010368	0.0009493	0.0008660	0.0007910	0.0007273	0.0006693	0.0006209

**Table 5.** Ultrasonic velocity vs concentration.

	288.15 K	293.15 K	298.15 K	303.15 K	308.15 K	313.15 K	318.15 K
0.1	1177.99	1160.39	1141.99	1126.39	1109.99	1093.39	1075.39
0.2	1183.58	1163.78	1144.38	1128.58	1111.88	1094.58	1077.38
0.3	1191.17	1170.97	1151.77	1134.87	1116.97	1098.57	1079.57
0.4	1199.36	1179.36	1158.96	1141.16	1122.56	1103.96	1083.36
0.5	1212.15	1190.95	1170.75	1152.75	1134.45	1113.15	1091.75
0.6	1226.34	1205.34	1184.34	1164.54	1144.94	1124.74	1103.04
0.7	1242.13	1219.13	1196.93	1176.33	1156.53	1136.53	1114.93
0.8	1258.92	1236.32	1213.32	1191.92	1171.12	1149.72	1128.52
0.9	1279.31	1257.11	1234.51	1210.81	1188.81	1166.51	1143.81

**Table 6.** Isentropic compressibility vs concentration.

	288.15 K	293.15 K	298.15 K	303.15 K	308.15 K	313.15 K	318.15 K
0.1	9.0949E-10	9.4228E-10	9.7821E-10	1.0108E-09	1.0465E-09	1.0846E-09	1.1286E-09
0.2	9.0433E-10	9.4096E-10	9.7836E-10	1.0114E-09	1.0476E-09	1.0871E-09	1.1294E-09
0.3	8.9545E-10	9.3217E-10	9.6882E-10	1.0035E-09	1.0418E-09	1.0831E-09	1.1286E-09
0.4	8.8517E-10	9.2107E-10	9.5930E-10	9.9508E-10	1.0346E-09	1.0759E-09	1.1243E-09
0.5	8.6791E-10	9.0426E-10	9.4104E-10	9.7630E-10	1.0146E-09	1.0600E-09	1.1083E-09
0.6	8.4826E-10	8.8303E-10	9.2028E-10	9.5725E-10	9.9664E-10	1.0385E-09	1.0864E-09
0.7	8.2736E-10	8.6371E-10	9.0160E-10	9.3852E-10	9.7690E-10	1.0172E-09	1.0635E-09
0.8	8.0585E-10	8.4019E-10	8.7774E-10	9.1460E-10	9.5333E-10	9.9468E-10	1.0386E-09
0.9	7.8036E-10	8.1294E-10	8.4809E-10	8.8663E-10	9.2565E-10	9.6676E-10	1.0115E-09

**Table 7.** Relative association vs concentration.

	288.15 K	293.15 K	298.15 K	303.15 K	308.15 K	313.15 K	318.15 K
0.1	0.998734	0.998683	0.998999	0.998769	0.998819	0.998679	0.998669
0.2	0.993395	0.993293	0.993984	0.993654	0.993761	0.993927	0.993637

0.3	0.988400	0.988358	0.988812	0.988628	0.988788	0.989111	0.989589
0.4	0.984020	0.983746	0.984233	0.984203	0.984072	0.984410	0.985321
0.5	0.979054	0.979419	0.979532	0.979372	0.979092	0.980075	0.981368
0.6	0.974893	0.975258	0.975395	0.975816	0.975584	0.976429	0.977750
0.7	0.970127	0.970945	0.971338	0.972167	0.972187	0.972913	0.974134
0.8	0.965303	0.966053	0.966570	0.967409	0.967502	0.968543	0.969696
0.9	0.960148	0.960329	0.960760	0.961977	0.962178	0.963368	0.964847

**Table 8.** Free volume vs concentration.

	288.15 K	293.15 K	298.15 K	303.15 K	308.15 K	313.15 K	318.15 K
0.1	3.9604E-08	4.4746E-08	5.0360E-08	5.6969E-08	6.3272E-08	6.9408E-08	7.5199E-08
0.2	4.7835E-08	5.3925E-08	6.0694E-08	6.8628E-08	7.6095E-08	8.3618E-08	9.1395E-08
0.3	5.6178E-08	6.3399E-08	7.1243E-08	8.0420E-08	8.8855E-08	9.7747E-08	1.0693E-07
0.4	6.4781E-08	7.2807E-08	8.1761E-08	9.2778E-08	1.0233E-07	1.1272E-07	1.2340E-07
0.5	7.3817E-08	8.2997E-08	9.3225E-08	1.0573E-07	1.1708E-07	1.2842E-07	1.3983E-07
0.6	8.3046E-08	9.3761E-08	1.0501E-07	1.1889E-07	1.3118E-07	1.4470E-07	1.5731E-07
0.7	9.2681E-08	1.0423E-07	1.1683E-07	1.3167E-07	1.4538E-07	1.6079E-07	1.7536E-07
0.8	1.0236E-07	1.1440E-07	1.2835E-07	1.4380E-07	1.5857E-07	1.7480E-07	1.9004E-07
0.9	1.1150E-07	1.2396E-07	1.3845E-07	1.5407E-07	1.6999E-07	1.8718E-07	2.0341E-07

**Table 9.** Relaxation time vs concentration.

	288.15 K	293.15 K	298.15 K	303.15 K	308.15 K	313.15 K	318.15 K
0.1	1.4328E-12	1.3480E-12	1.2729E-12	1.1950E-12	1.1367E-12	1.0911E-12	1.0585E-12
0.2	1.3585E-12	1.2832E-12	1.2125E-12	1.1390E-12	1.0849E-12	1.0407E-12	1.0030E-12
0.3	1.3025E-12	1.2297E-12	1.1630E-12	1.0949E-12	1.0467E-12	1.0044E-12	9.6876E-13
0.4	1.2570E-12	1.1898E-12	1.1272E-12	1.0582E-12	1.0139E-12	9.7216E-13	9.3854E-13
0.5	1.2127E-12	1.1481E-12	1.0870E-12	1.0210E-12	9.7561E-13	9.4032E-13	9.1106E-13
0.6	1.1735E-12	1.1073E-12	1.0514E-12	9.8996E-13	9.4906E-13	9.0997E-13	8.8296E-13
0.7	1.1370E-12	1.0773E-12	1.0232E-12	9.6653E-13	9.2591E-13	8.8591E-13	8.5754E-13
0.8	1.1055E-12	1.0510E-12	9.9802E-13	9.4706E-13	9.0874E-13	8.7226E-13	8.4553E-13
0.9	1.0788E-12	1.0290E-12	9.7925E-13	9.3505E-13	8.9766E-13	8.6271E-13	8.3736E-13

**Table 10.** Gibbs' free energy vs concentration.

	288.15 K	293.15 K	298.15 K	303.15 K	308.15 K	313.15 K	318.15 K
0.1	8.5493E-21	8.5206E-21	8.4997E-21	8.4479E-21	8.4444E-21	8.4741E-21	8.5459E-21
0.2	8.3377E-21	8.3213E-21	8.2999E-21	8.2472E-21	8.2463E-21	8.2700E-21	8.3096E-21
0.3	8.1703E-21	8.1492E-21	8.1286E-21	8.0820E-21	8.0938E-21	8.1165E-21	8.1572E-21
0.4	8.0291E-21	8.0160E-21	7.9999E-21	7.9397E-21	7.9584E-21	7.9756E-21	8.0182E-21
0.5	7.8866E-21	7.8717E-21	7.8506E-21	7.7902E-21	7.7948E-21	7.8318E-21	7.8877E-21
0.6	7.7557E-21	7.7253E-21	7.7137E-21	7.6609E-21	7.6775E-21	7.6901E-21	7.7503E-21
0.7	7.6303E-21	7.6142E-21	7.6018E-21	7.5607E-21	7.5726E-21	7.5743E-21	7.6220E-21
0.8	7.5188E-21	7.5144E-21	7.4994E-21	7.4756E-21	7.4930E-21	7.5072E-21	7.5602E-21
0.9	7.4213E-21	7.4286E-21	7.4213E-21	7.4223E-21	7.4409E-21	7.4597E-21	7.5175E-21

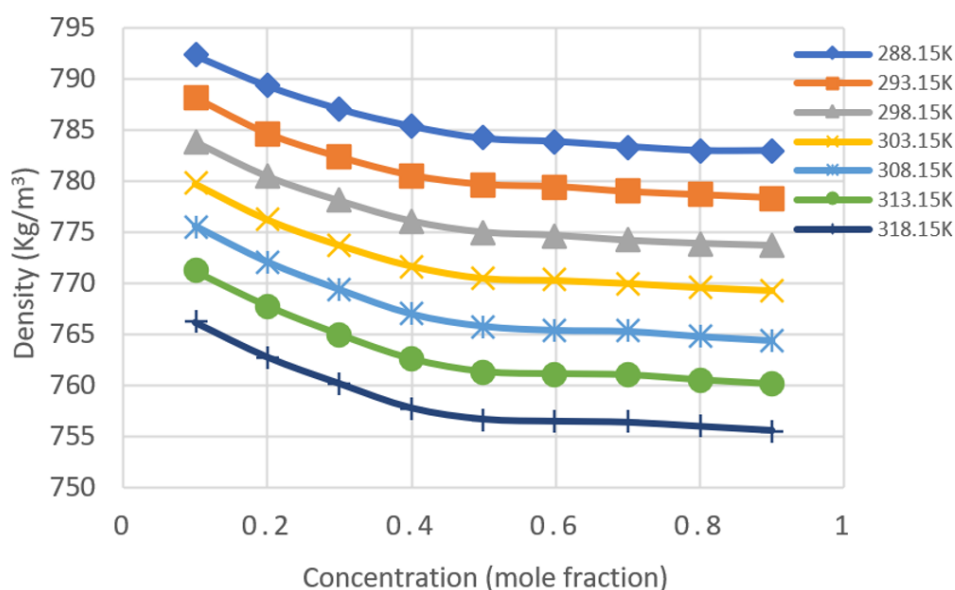
**Table 11.** Internal pressure vs concentration.

	288.15 K	293.15 K	298.15 K	303.15 K	308.15 K	313.15 K	318.15 K
0.1	887814185.2	864150909.5	841876547.5	818636029.1	800691659.3	785995060.0	774137415.5
0.2	791743466.2	770878228.1	751041911.8	730343919.4	714720566.8	701249071.1	688635958.6
0.3	715519035.4	696403398.9	678781143.9	660382259.9	646896953.5	634407708.2	622918925.0
0.4	652824960.2	636197998.4	620124752.4	602231343.0	590093725.0	578438752.2	567818496.2

0.5	599789005.5	584577283.2	569665797.5	553284875.5	541398281.7	531428954.1	522684422.4
0.6	555105145.7	540324154.2	527000601.4	512185171.5	501709945.7	491618203.5	483776939.5
0.7	516088860.4	503005997.9	490474386.0	477484477.0	467686022.6	457876794.3	450097754.8
0.8	482416603.6	471190172.3	459305149.4	447994038.6	438952091.0	430215247.5	423392695.9
0.9	453918548.1	444026239.7	433510565.0	423752217.3	415086031.9	406976442.4	400572269.7

**Table 12.** Solubility parameter vs concentration.

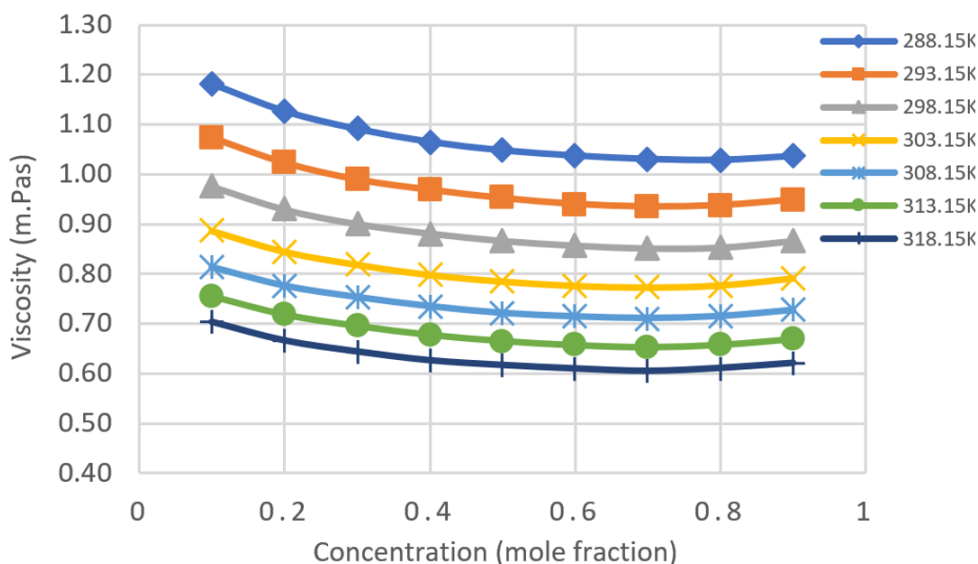
	288.15 K	293.15 K	298.15 K	303.15 K	308.15 K	313.15 K	318.15 K
0.1	29796.21	29396.44	29015.11	28611.82	28296.50	28035.60	27823.33
0.2	28137.94	27764.69	27405.14	27024.88	26734.26	26481.11	26241.87
0.3	26749.19	26389.46	26053.43	25697.90	25434.17	25187.45	24958.34
0.4	25550.44	25222.97	24902.30	24540.40	24291.84	24050.75	23828.94
0.5	24490.59	24178.03	23867.67	23522.01	23267.97	23052.74	22862.29
0.6	23560.67	23244.87	22956.49	22631.51	22398.88	22172.46	21994.93
0.7	22717.59	22427.80	22146.66	21851.42	21626.05	21398.06	21215.51
0.8	21963.98	21706.92	21431.41	21165.87	20951.18	20741.63	20576.51
0.9	21305.36	21071.93	20820.92	20585.24	20373.66	20173.66	20014.30

**Figure 1.** Variation of density vs concentration of cyclohexane at different temperature, ethanol-cyclohexane system.

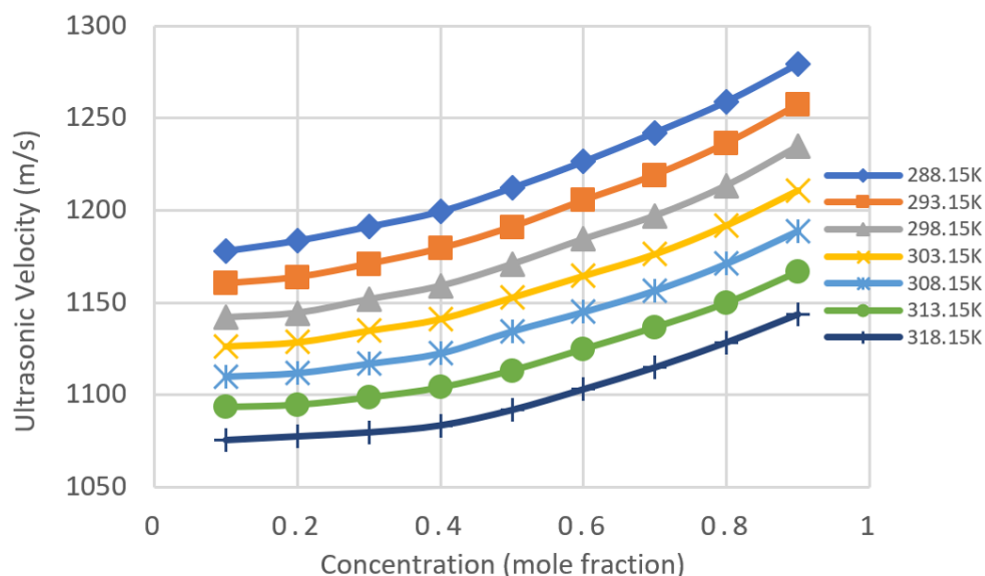
From Figure 1, the density of ethanol–cyclohexane mixtures shows a gradual decrease with increasing cyclohexane concentration. The incorporation of solute molecules modifies the molecular packing of the medium, which depends on the extent of solute–solvent interactions. In the present system, the relatively weak association between ethanol and cyclohexane molecules accounts for the observed decrease in density as the cyclohexane content increases. Density decreases with rising temperature. This behavior can be attributed to the weakening of non-covalent interactions, such as van der Waals and cohesive forces caused by enhanced thermal agitation, which leads to a more loosely packed molecular arrangement in the liquid phase [41].

From Figure 2, it is observed that the viscosity of ethanol–cyclohexane mixtures decrease with increasing cyclohexane concentration. This trend can be attributed to differences in molecular structure, surface area, and relative velocity of the constituent molecules. Since cyclohexane is a non-polar solute, its addition to ethanol

does not promote additional structural ordering in the medium due to the absence of significant electrostatic interactions. Moreover, the overall viscosity decreases as cyclohexane, which possesses a lower viscosity than ethanol, becomes the dominant component in the mixture. A similar effect is noted with increasing temperature, where enhanced thermal motion reduces cohesive and frictional forces between molecules, thereby facilitating greater relative motion and resulting in a further decrease in viscosity [42–45].



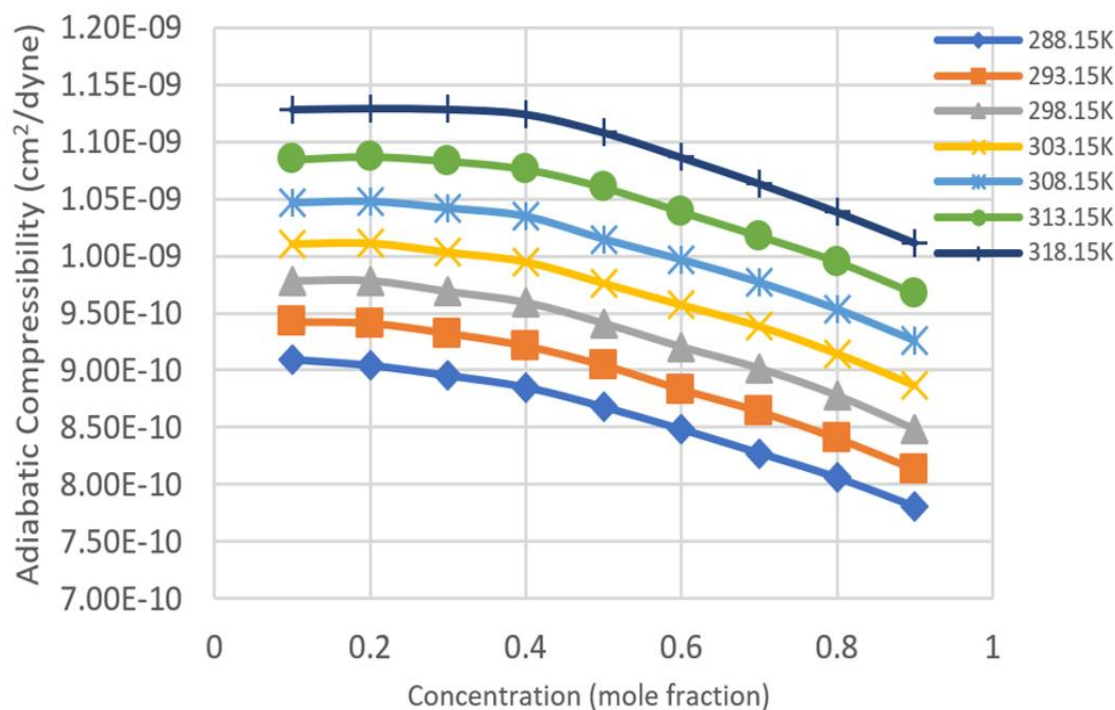
**Figure 2.** Variation of viscosity vs concentration of cyclohexane at different temperature, ethanol-cyclohexane system.



**Figure 3.** Variation of ultrasonic viscosity vs concentration of cyclohexane at different temperature, ethanol-cyclohexane system.

From Figure 3, in ethanol–cyclohexane mixtures, ultrasonic velocity rises consistently with increasing cyclohexane content. Such an increase typically indicates stronger molecular association in the solution, primarily due to van der Waals forces and cohesive interactions. In this system, the gradual increase in velocity with rising cyclohexane concentration suggests a progressive enhancement of intermolecular interactions between the components. Conversely, ultrasonic velocity decreases with increasing temperature. With rising temperature, the increased molecular kinetic energy causes greater separation

between molecules, thereby lowering packing efficiency. This thermal agitation weakens the relatively weak electrostatic and cohesive interactions, thereby lowering the ultrasonic velocity [46–48].



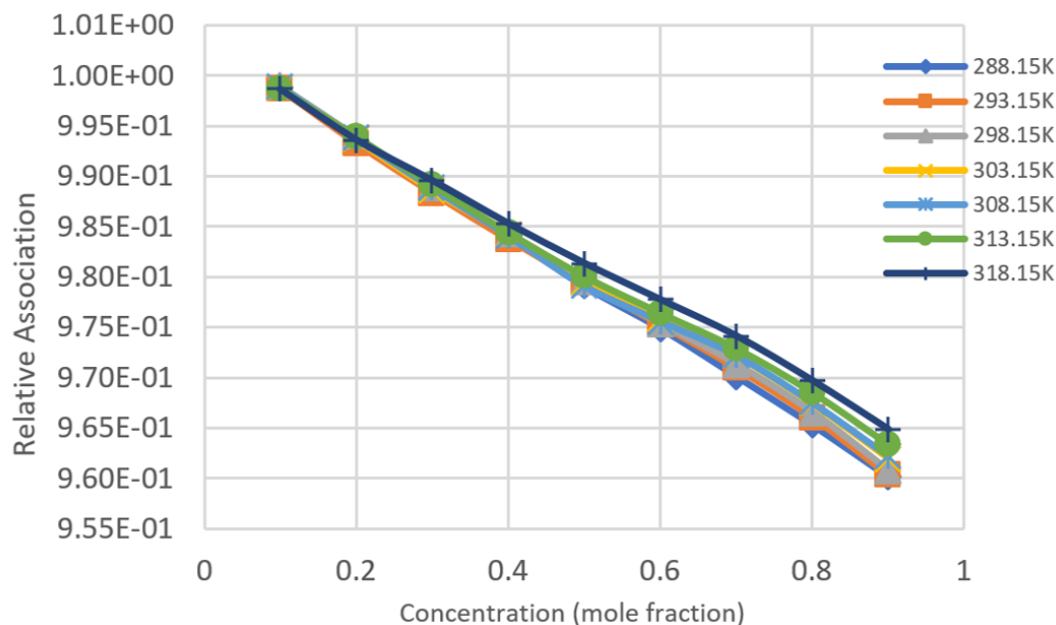
**Figure 4.** Variation of isentropic compressibility vs concentration of cyclohexane at different temperature, ethanol-cyclohexane system.

From Figure 4, it is evident that the isentropic compressibility of ethanol-cyclohexane mixtures decreases with increasing cyclohexane concentration. A reduction in compressibility indicates enhanced molecular association within the system, as the formation of new solute–solvent structures results in a more compact and less compressible medium compared to pure ethanol. The extent of compressibility is influenced by electrostriction and provides valuable insight into lyophobic–lyophilic interactions. Positive values suggest lyophilic interactions and a reduction in structural compressibility, attributed to the greater prevalence of hydrogen-bonded ethanol molecules. Thus, the observed decreasing trend in compressibility with higher cyclohexane concentration supports the occurrence of strengthened solute–solvent interactions through intermolecular association.

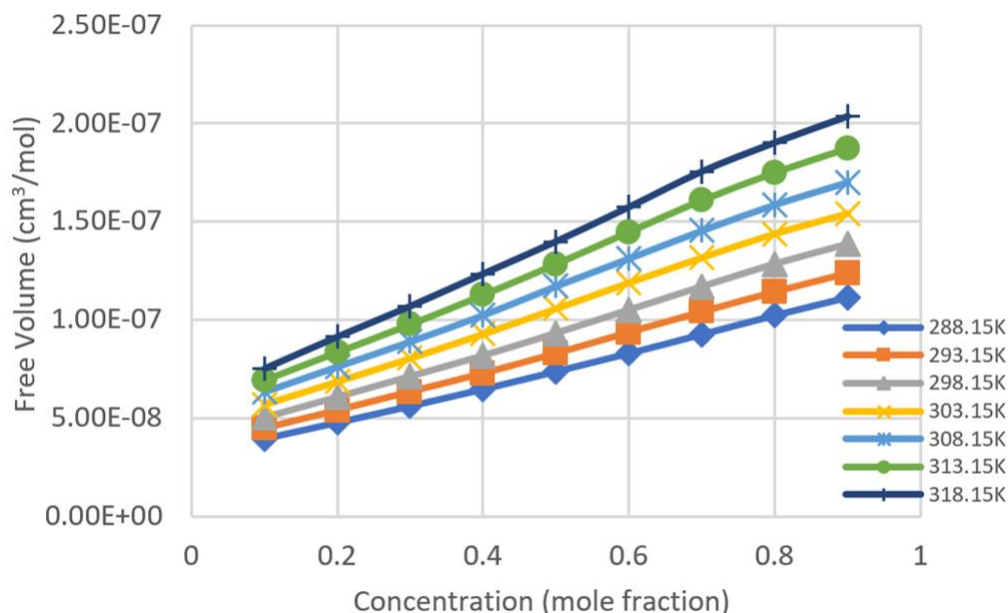
In contrast, with increasing temperature, the isentropic compressibility of the ethanol-cyclohexane system increases. This behavior arises from enhanced thermal motion, which disrupts molecular order, increases intermolecular spacing, and leads to volumetric expansion of the solution. Consequently, the medium becomes more compressible at elevated temperatures [49–53].

Relative association quantifies the extent of molecular association among the components of a mixture and is primarily dependent on the density of the system. An increasing trend in relative association generally indicates enhanced solute–solvent or solute–solute interactions. A slight increase is typically attributed to solute–solvent interactions, whereas a pronounced increase reflects stronger solute–solute interactions. Thus, this parameter provides valuable insight into the strength and type of molecular interactions within a liquid medium. From Figure 5, it is observed that the relative association of ethanol-cyclohexane mixtures decreases with increasing cyclohexane concentration, suggesting a weakening of molecular association between solute and solvent molecules. This reduction may arise from diminished intermolecular forces, such as Van der Waals and cohesive interactions, between ethanol and cyclohexane [54]. However, since other derived parameters point toward enhanced

interactions, the observed decrease in relative association could also be attributed to the predominance of cyclohexane in the mixture, whose density is lower than that of ethanol. Because relative association is directly dependent on density, this effect becomes more apparent at higher solute concentrations.



**Figure 5.** Variation of relative association vs concentration of cyclohexane at different temperature, ethanol-cyclohexane system.



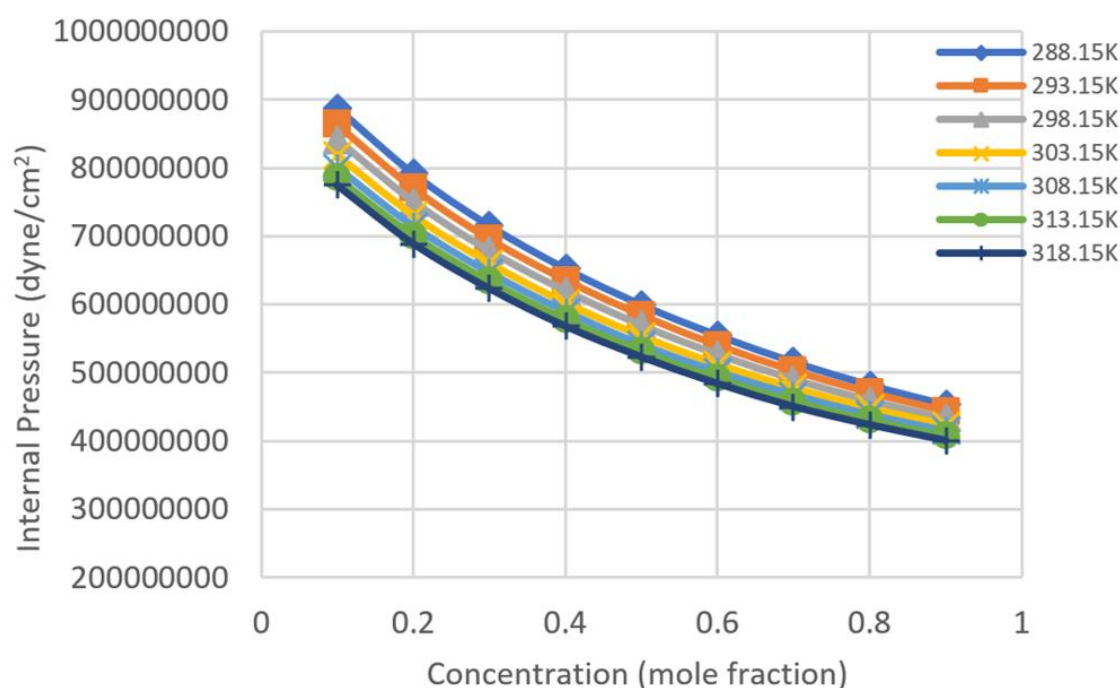
**Figure 6.** Variation of free volume vs concentration of cyclohexane at different temperature, ethanol-cyclohexane system.

The influence of temperature further highlights the dynamic nature of the association. At elevated temperatures, hydrogen bonding between solute and solvent molecules typically weakens, leading to a decrease in relative association. In this case, however, an unusual increase is observed. This can be explained by the disruption of weaker ethanol-cyclohexane cohesive and dispersive forces, which frees

ethanol molecules to establish stronger hydrogen bonding among themselves, thereby increasing the relative association with rising temperature.

Free volume represents the average space available for a central molecule to move within a hypothetical cell, constrained by the repulsive interactions of neighboring molecules. It may also be considered as the monomeric voids present in the system due to imperfect packing of solvent molecules. From Figure 6, it is evident that the free volume of ethanol-cyclohexane mixtures increases with rising cyclohexane concentration, indicating enhanced molecular association between the constituent molecules.

Furthermore, the observed increase in free volume with temperature suggests a weakening of intermolecular interactions at elevated temperatures. This can be attributed to thermal agitation, which disrupts ordered packing and reduces the extent of molecular association within the solution.



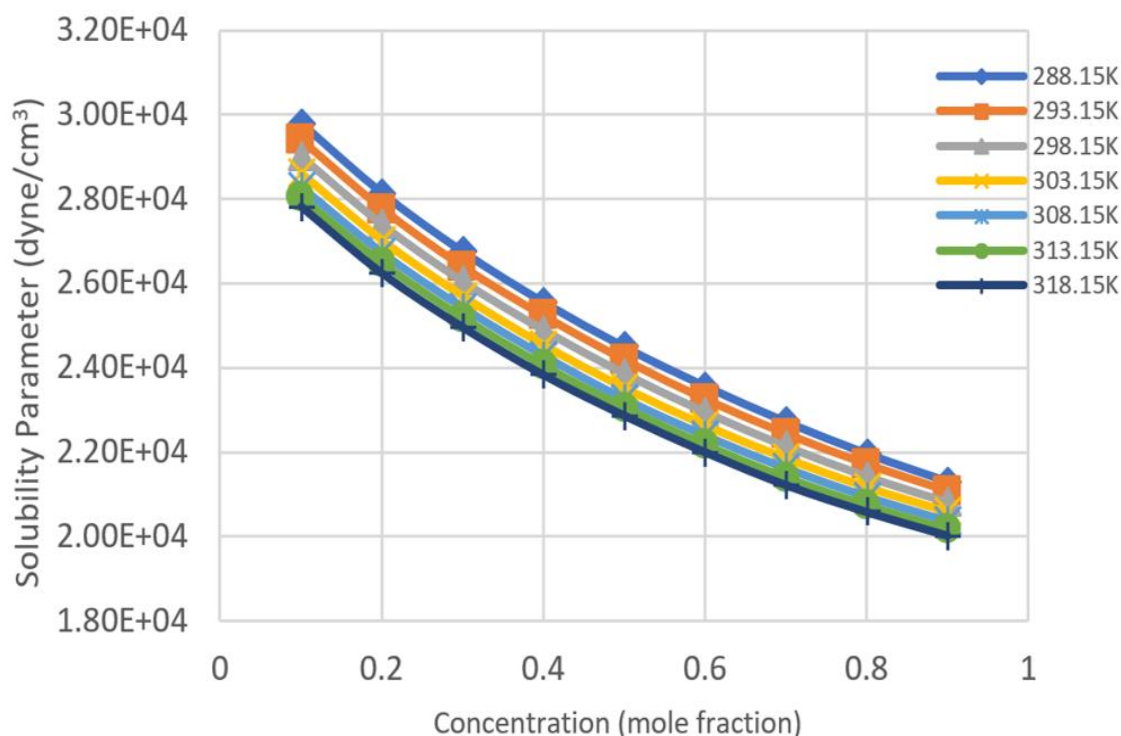
**Figure 7.** Variation of internal pressure vs concentration of cyclohexane at different temperature, ethanol-cyclohexane system.

From Figure 7, it is evident that the internal pressure of ethanol-cyclohexane mixtures decreases with increasing cyclohexane concentration. Internal pressure originates from the equilibrium between the attractive and repulsive forces operating among the molecules in a solution. While parameters, such as ultrasonic velocity, density, isentropic compressibility, and free length, indicate strengthening of solute-solvent interactions, the observed decrease in internal pressure with higher cyclohexane concentration suggests the growing dominance of solute-solute interactions within the mixture.

With increasing temperature, the internal pressure of ethanol-cyclohexane solutions further decreases. This behavior reflects the weakening of intermolecular forces due to enhanced thermal motion, leading to reduced cohesive interactions at elevated temperatures.

From Figure 8, it is observed that the solubility parameter of the ethanol-cyclohexane system decreases with increasing cyclohexane concentration. This trend indicates a reduction in the heat of vaporization, largely attributable to the dominance of cyclohexane, which possesses weaker cohesive forces compared to ethanol. The decrease in solubility parameter reflects the weakening of cohesive

and van der Waals interactions between solute and solvent molecules, thereby suggesting a decline in the overall intermolecular association in the mixture.



**Figure 8.** Variation of solubility parameter vs concentration of cyclohexane at different temperature, ethanol-cyclohexane system.

Typically, the solubility parameter is expected to increase (become less negative) with rising temperature, as thermal motion reduces the strength of intermolecular forces and lowers the enthalpy of vaporization – an effect generally observed in systems involving solid solutes and liquid solvents. In contrast to the expected trend, the ethanol-cyclohexane system exhibits different behavior. The anomaly can be explained by the lower boiling point of cyclohexane relative to ethanol, which makes cyclohexane more volatile. With increasing temperature, cyclohexane vaporizes more easily, raising the solution's vapor pressure and reducing its effective solubility in ethanol. As a result, the solubility parameter decreases with temperature in this binary mixture.

## CONCLUSIONS

The present investigation highlights the complex interplay of molecular forces in ethanol–cyclohexane binary mixtures over a wide range of concentrations and temperatures. It is evident from density, viscosity, and ultrasonic velocity measurements, along with their derived thermodynamic parameters, that the nature of molecular interactions cannot be attributed to a single type of force. Instead, van der Waals interactions, hydrogen bonding, molecular size, shape, and cohesive forces collectively govern the structural organization of the mixtures. The gradual decrease in density and viscosity with increasing cyclohexane concentration, accompanied by an increase in ultrasonic velocity, suggests that molecular packing and association vary systematically with composition. While weak solute–solvent interactions dominate at lower concentrations, the introduction of non-polar cyclohexane disrupts the hydrogen-bonded network of ethanol, leading to reduced viscosity and density. However, the rise in ultrasonic velocity indicates localized strengthening of cohesive forces and the formation of compact molecular arrangements. Temperature, on the other hand, weakens these associations due to enhanced thermal agitation, resulting in decreased density, viscosity, and velocity. Derived parameters provide further insights into the microscopic behavior of the mixtures. The decreasing trend in compressibility and internal pressure with composition reflects enhanced molecular association, whereas the observed variations in relative association suggest competition between solute–solvent and solute–solute interactions.

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