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# Temperature-Dependent Ultrasonic and Thermoacoustic Analysis of Ethyl Benzoate and 2-Methyl-2-Propanol Binary System

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**Abstract**
This study presents a comprehensive ultrasonic and thermo-acoustic investigation of binary liquid mixtures of ethylbenzoate and 2-methyl-2-propanol over the entire composition range at temperatures 303.15, 308.15, 313.15, and 318.15 K. Experimental measurements of ultrasonic velocity, density, and viscosity were used to evaluate derived parameters such as adiabatic compressibility, molar volume, acoustic impedance, intermolecular free length, internal pressure, and enthalpy. The variation of these parameters with mole fraction and temperature reveals significant non-ideal behavior, indicating strong molecular interactions between the ester and tertiary alcohol molecules. The decrease in compressibility and free length with increasing ethylbenzoate concentration suggests enhanced molecular association and compact molecular packing, while the increase in acoustic impedance and internal pressure supports stronger cohesive forces. Temperature-dependent trends indicate weakening of interactions at elevated temperatures due to increased thermal agitation. The study demonstrates the effectiveness of ultrasonic techniques in elucidating molecular interactions and structural rearrangements in binary liquid mixtures.

**Keywords:** Ultrasonic velocity, Binary liquid mixtures, Adiabatic compressibility, Intermolecular interactions, Acoustic impedance, Internal pressure

## 1. Introduction
Ultrasonic techniques have proven to be powerful tools for investigating molecular interactions and structural properties in liquids and liquid mixtures. Since the early pioneering studies on ultrasonic propagation in liquids [1, 2], extensive research has demonstrated that ultrasonic velocity, density, and viscosity measurements can provide valuable insight into intermolecular forces and thermodynamic behavior [3, 4]. Derived acoustic parameters such as adiabatic compressibility, free length, and internal pressure are highly sensitive to molecular association and packing effects in liquid systems [5, 6].
Binary liquid mixtures consisting of polar and non-polar or associating components often exhibit non-ideal behavior due to hydrogen bonding, dipole-dipole interactions, and steric effects [7-9]. Ester-alcohol systems are of particular interest because esters act as proton acceptors while alcohols act as proton donors, leading to complex molecular interactions [10, 11]. Ultrasonic investigations of such systems have been widely reported to analyze molecular interactions through excess and deviation properties [12-14].
Earlier theoretical frameworks developed by Eyring and co-workers laid the foundation for interpreting transport and acoustic properties in liquids [2, 3]. Subsequent studies expanded these concepts to binary and ternary liquid mixtures, demonstrating the sensitivity of ultrasonic parameters to temperature and composition [15, 16]. Recent studies continue to emphasize the relevance of ultrasonic techniques for understanding molecular structure in complex fluids [17-20].
Ethylbenzoate is an aromatic ester with moderate polarity, while 2-methyl-2-propanol is a tertiary alcohol characterized by steric hindrance and limited hydrogen-bonding capability. Their mixtures are expected to exhibit interesting interaction effects due to polarity differences and molecular size mismatch. Although several ester-alcohol systems have been studied [9, 11], ultrasonic investigations of ethylbenzoate with tertiary alcohols remain limited. Therefore, the present study aims to examine ultrasonic and thermo-acoustic

properties of ethylbenzoate + 2-methyl-2-propanol mixtures over a wide temperature range, providing deeper insight into molecular interactions and non-ideal mixing behavior.

## 2. Experimental and Theoretical Background

### 2.1 Materials

Ethyl benzoate and 2-methyl-1-propanol of analytical reagent grade were used without further purification. The purity of the liquids was confirmed by comparing measured densities and viscosities of the pure components with literature values.

### 2.2 Preparation of Mixtures

Binary mixtures were prepared by weighing appropriate amounts of the pure components using an electronic balance with an accuracy of ±0.1 mg. The mole fractions were calculated from the measured masses and molar masses of the components. The uncertainty in mole fraction was estimated to be less than ±0.0001.

**2.3 Measurements:** Ultrasonic velocity was measured using a single-crystal ultrasonic interferometer operating at a fixed frequency. Density measurements were carried out using a calibrated pycnometer, while viscosity was determined with an Ostwald viscometer. All measurements were performed at temperatures 303.15, 308.15, 313.15 and 318.15 K, maintained constant within ±0.01 K using a thermostatic water bath. The adiabatic compressibility (β_ad) was calculated using the Newton-Laplace equation [5], while intermolecular free length (L_f) was obtained using Jacobson's relation [6]. Acoustic impedance (Z) was determined as Z = ρU, and internal pressure (π) was evaluated using Eyring's theory of liquids [2, 21]. These relations have been extensively validated in earlier ultrasonic studies of binary mixtures [12, 15, 22].

## 3. Results and Discussion

The experimental values of ultrasonic velocity, density, viscosity and the derived acoustical parameters for the binary mixture ethyl benzoate + 2-methyl-2-propanol at temperatures 303.15, 308.15, 313.15 and 318.15 K are presented in Table 1. The variation of these parameters with mole fraction and temperature provides clear insight into the nature of molecular interactions in the system.

**Table 1:** Ethylbenzoate(X1) + 2-methyl-2-propanol(X2) Ultrasonic velocities, Densities, Viscosities and related Acoustic Parameters

| Mole fraction $X_1$ | Velocity (U) m/s | Density (ρ)X10$^{-3}$ gm/cm$^3$ | Viscosity (η) cP | Mol.Vol. V cm$^3$ mol$^{-1}$ | Ad. Comp. $\beta_{ad}\times10^{-12}$ m$^2$N$^{-1}$ | Int Mol. Free Length $L_{f(Å)}$ | internal pressure π Nm$^{-2}$ | Acoustic impedance (Z) Kg m$^{-2}$ s$^{-1}$ | Enthalpy H Jmol$^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|
| **303.15K** | | | | | | | | | |
| 0.0000 | 1061.0 | 775.30 | 3.3720 | 95.6017 | 14.5198 | 0.7562 | 10.50 | 822.59 | 1003.72 |
| 0.0685 | 1087.8 | 806.20 | 3.2580 | 98.3969 | 14.6776 | 0.7603 | 9.66 | 876.98 | 950.95 |
| 0.1419 | 1115.4 | 837.10 | 3.1360 | 101.4373 | 14.8622 | 0.7651 | 8.87 | 933.70 | 899.62 |
| 0.2209 | 1143.7 | 868.10 | 3.0060 | 104.7339 | 15.0680 | 0.7704 | 8.11 | 992.85 | 849.60 |
| 0.3061 | 1172.6 | 898.70 | 2.8670 | 108.3744 | 15.2998 | 0.7763 | 7.39 | 1053.82 | 800.79 |
| 0.3982 | 1202.0 | 928.40 | 2.7170 | 112.4518 | 15.5623 | 0.7829 | 6.70 | 1115.94 | 752.90 |
| 0.4981 | 1231.7 | 956.90 | 2.5550 | 117.0439 | 15.8542 | 0.7902 | 6.03 | 1178.61 | 705.71 |
| 0.6069 | 1261.4 | 983.30 | 2.3790 | 122.3151 | 16.1815 | 0.7983 | 5.39 | 1240.33 | 658.95 |
| 0.7258 | 1290.8 | 1006.70 | 2.1890 | 128.4527 | 16.5508 | 0.8074 | 4.77 | 1299.45 | 612.53 |
| 0.8562 | 1319.3 | 1025.00 | 1.9810 | 135.7191 | 16.9661 | 0.8175 | 4.17 | 1353.47 | 565.74 |
| 1.0000 | 1346.2 | 1039.20 | 1.7510 | 144.5054 | 17.4389 | 0.8288 | 3.58 | 1398.97 | 517.72 |
| | | | | | **308.15K** | | | | |
| 0.0000 | 1055.7 | 770.10 | 2.5890 | 96.2472 | 14.4722 | 0.7550 | 9.18 | 812.99 | 883.68 |
| 0.0685 | 1081.5 | 801.40 | 2.5150 | 98.9862 | 14.5950 | 0.7582 | 8.48 | 866.71 | 839.61 |
| 0.1419 | 1108.1 | 832.70 | 2.4390 | 101.9733 | 14.7458 | 0.7621 | 7.82 | 922.71 | 797.38 |
| 0.2209 | 1135.3 | 864.00 | 2.3590 | 105.2309 | 14.9179 | 0.7665 | 7.19 | 980.90 | 756.60 |
| 0.3061 | 1163.2 | 894.90 | 2.2730 | 108.8346 | 15.1194 | 0.7717 | 6.59 | 1040.95 | 716.91 |
| 0.3982 | 1191.6 | 924.90 | 2.1810 | 112.8774 | 15.3520 | 0.7776 | 6.01 | 1102.11 | 678.35 |
| 0.4981 | 1220.3 | 953.50 | 2.0810 | 117.4613 | 15.6175 | 0.7843 | 5.45 | 1163.56 | 640.62 |
| 0.6069 | 1249.1 | 979.90 | 1.9740 | 122.7395 | 15.9226 | 0.7919 | 4.92 | 1223.99 | 603.89 |
| 0.7258 | 1277.6 | 1003.20 | 1.8590 | 128.9008 | 16.2706 | 0.8005 | 4.41 | 1281.69 | 568.04 |
| 0.8562 | 1305.5 | 1022.10 | 1.7340 | 136.2236 | 16.6748 | 0.8104 | 3.91 | 1334.35 | 532.75 |
| 1.0000 | 1331.9 | 1034.80 | 1.5960 | 145.1198 | 17.1430 | 0.8217 | 3.43 | 1378.25 | 497.63 |
| | | | | | **313.15K** | | | | |
| 0.0000 | 1047.6 | 764.80 | 2.0460 | 96.9142 | 14.3497 | 0.7518 | 8.29 | 801.20 | 803.24 |
| 0.0685 | 1072.6 | 796.40 | 1.9990 | 99.6077 | 14.4459 | 0.7543 | 7.68 | 854.22 | 765.43 |
| 0.1419 | 1098.3 | 828.10 | 1.9520 | 102.5397 | 14.5666 | 0.7575 | 7.11 | 909.50 | 729.49 |
| 0.2209 | 1124.7 | 859.70 | 1.9020 | 105.7573 | 14.7139 | 0.7613 | 6.57 | 966.90 | 694.80 |
| 0.3061 | 1151.7 | 890.90 | 1.8500 | 109.3232 | 14.8885 | 0.7658 | 6.05 | 1026.05 | 661.53 |
| 0.3982 | 1179.2 | 921.10 | 1.7950 | 113.3430 | 15.0962 | 0.7711 | 5.55 | 1086.16 | 629.53 |
| 0.4981 | 1207.1 | 949.80 | 1.7360 | 117.9189 | 15.3410 | 0.7773 | 5.08 | 1146.50 | 598.62 |
| 0.6069 | 1235.2 | 976.30 | 1.6720 | 123.1921 | 15.6276 | 0.7846 | 4.62 | 1205.93 | 568.67 |
| 0.7258 | 1263.0 | 999.60 | 1.6050 | 129.3651 | 15.9581 | 0.7928 | 4.18 | 1262.49 | 540.11 |
| 0.8562 | 1290.1 | 1018.30 | 1.5340 | 136.7320 | 16.3445 | 0.8023 | 3.75 | 1313.71 | 512.88 |
| 1.0000 | 1316.0 | 1030.60 | 1.4550 | 145.7112 | 16.8043 | 0.8136 | 3.34 | 1356.27 | 486.41 |
| | | | | | **318.15K** | | | | |
| 0.0000 | 1038.1 | 760.00 | 1.6890 | 97.5263 | 14.1796 | 0.7473 | 7.65 | 788.96 | 746.41 |
| 0.0685 | 1062.3 | 792.00 | 1.6570 | 100.1610 | 14.2485 | 0.7491 | 7.12 | 841.34 | 712.75 |
| 0.1419 | 1087.1 | 823.90 | 1.6270 | 103.0624 | 14.3438 | 0.7516 | 6.61 | 895.66 | 681.26 |
| 0.2209 | 1112.7 | 855.80 | 1.5970 | 106.2392 | 14.4672 | 0.7549 | 6.13 | 952.25 | 651.29 |
| 0.3061 | 1138.9 | 887.20 | 1.5660 | 109.7792 | 14.6201 | 0.7588 | 5.67 | 1010.43 | 622.68 |
| 0.3982 | 1165.6 | 917.50 | 1.5330 | 113.7878 | 14.8079 | 0.7637 | 5.23 | 1069.44 | 595.28 |
| 0.4981 | 1192.7 | 946.30 | 1.4990 | 118.3550 | 15.0326 | 0.7695 | 4.81 | 1128.65 | 569.24 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 0.6069 | 1220.0 | 972.80 | 1.4630 | 123.6353 | 15.3002 | 0.7763 | 4.40 | 1186.82 | 544.44 |
| 0.7258 | 1247.1 | 995.90 | 1.4250 | 129.8457 | 15.6166 | 0.7843 | 4.01 | 1241.99 | 520.98 |
| 0.8562 | 1273.6 | 1014.30 | 1.3860 | 137.2712 | 15.9919 | 0.7936 | 3.64 | 1291.81 | 499.15 |
| 1.0000 | 1299.0 | 1026.00 | 1.3430 | 146.3645 | 16.4464 | 0.8048 | 3.27 | 1332.77 | 478.59 |

### 3.1 Ultrasonic Velocity, Density, and Viscosity

The experimental results show that ultrasonic velocity increases monotonically with increasing mole fraction of ethylbenzoate at all temperatures. Similar behavior has been reported for several binary liquid mixtures involving esters and alcohols [9, 13, 18]. The increase in U indicates enhanced rigidity of the medium due to stronger intermolecular attractions.

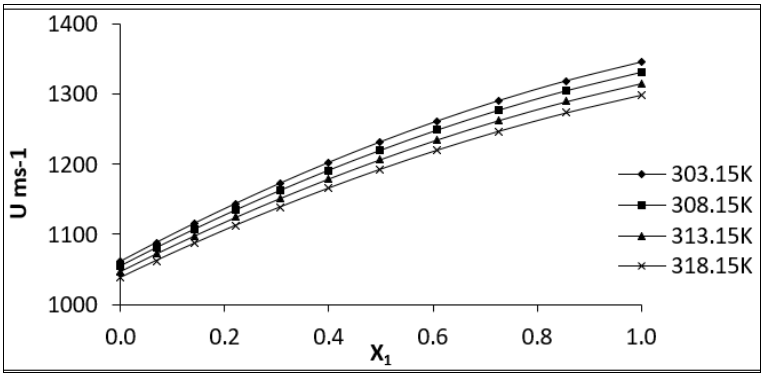


**Fig 1:** Variation of ultrasonic velocity with mole fraction of EB for the system EB + 2-methyl-2-propanol

Density also increases with ethylbenzoate concentration, reflecting increased molecular mass and compact packing [14, 23]. Conversely, viscosity decreases with increasing ethylbenzoate mole fraction and increasing temperature, indicating reduced resistance to flow due to weakening of hydrogen bonding in the tertiary alcohol component [7, 11].

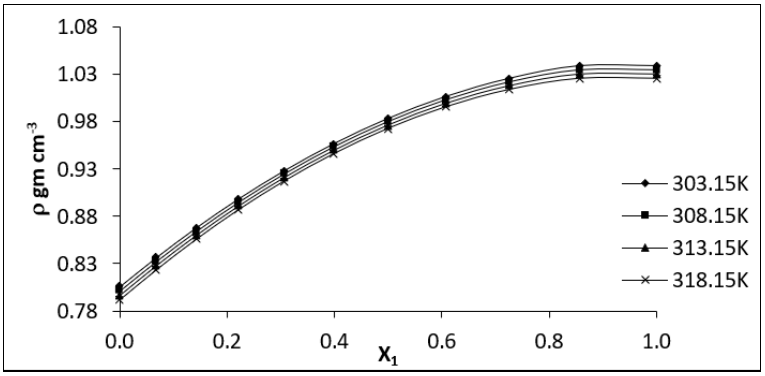


**Fig 2:** Variation of density with mole fraction of EB for the system EB + 2-methyl-2-propanol

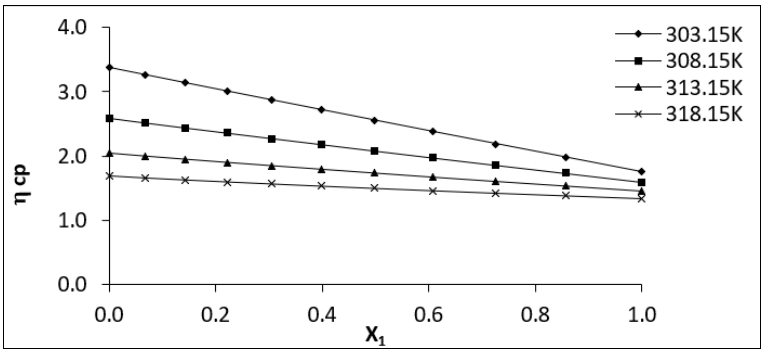


**Fig 3:** Variation of viscosity with mole fraction of EB for the system EB + 2-methyl-2-propanol

### 3.2 Adiabatic Compressibility and Free Length

Adiabatic compressibility decreases with increasing ethylbenzoate concentration, suggesting strong molecular association and reduced compressibility of the medium [6, 12]. The corresponding decrease in intermolecular free length supports the formation of a more closely packed molecular structure [8, 16]. These trends confirm the presence of significant solute-solvent interactions in the system.

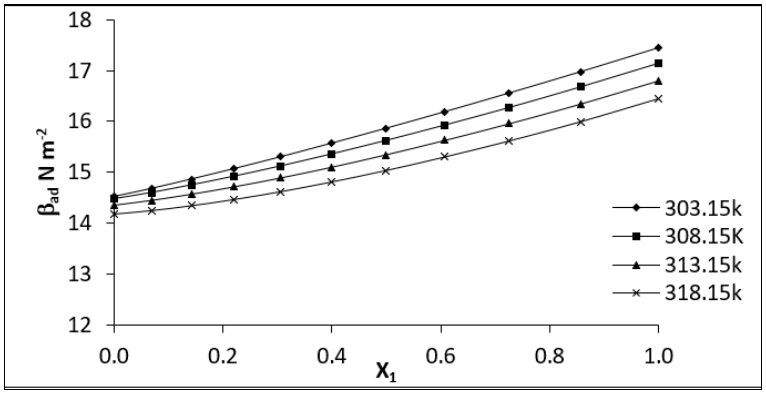


**Fig 4:** Variation of adiabatic compressibility with mole fraction of EB for the system EB + 2-methyl-2-propanol

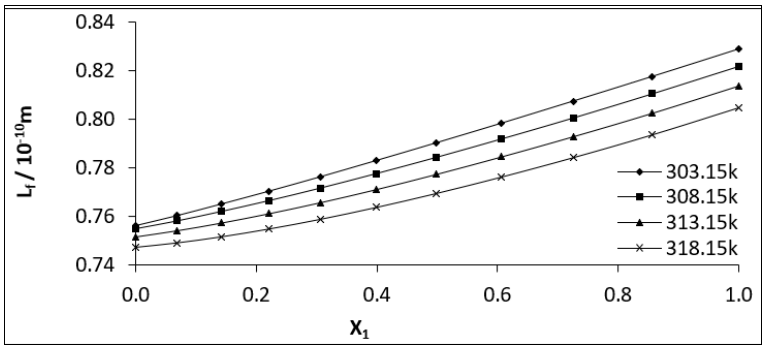


**Fig 5:** Variation of free length with mole fraction of EB for the system EB + 2-methyl-2-propanol

### 3.3 Acoustic Impedance and Internal Pressure

Acoustic impedance increases with mole fraction of ethylbenzoate due to simultaneous increases in density and ultrasonic velocity [19, 24]. Internal pressure values increase with composition but decrease with temperature, indicating that cohesive forces dominate at lower temperatures while thermal agitation weakens interactions at higher temperatures [2, 21, 25].

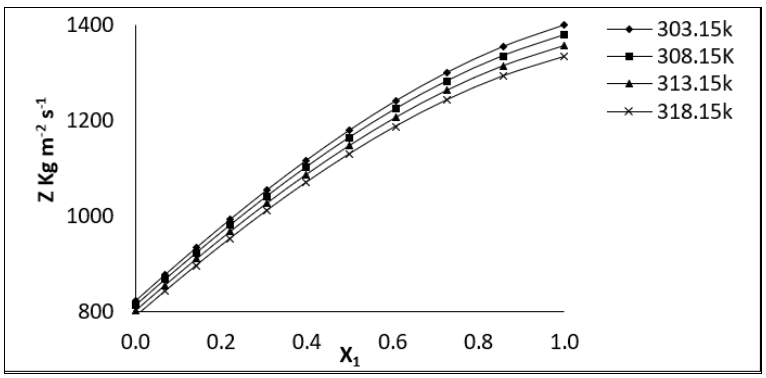


**Fig 6:** Variation of acoustic impedance with mole fraction of EB for the system EB + 2-methyl-2-propanol

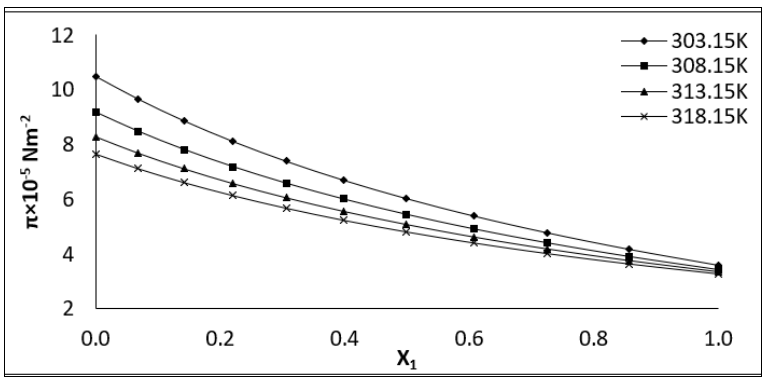


**Fig 7:** Variation of internal pressure with mole fraction of EB for the system EB + 2-methyl-2-propanol

### 3.4 Temperature Effects and Non-Ideal Behavior

Temperature elevation leads to a decrease in viscosity, internal pressure, and acoustic impedance, consistent with earlier reports on binary and ternary mixtures [15, 26]. The

observed nonlinear variation of thermo-acoustic parameters with composition indicates non-ideal mixing behavior, attributed to specific molecular interactions between ester and alcohol molecules [9, 14, 27].

Recent studies further support these interpretations, emphasizing the role of ultrasonic parameters in identifying molecular interactions and excess thermodynamic properties in liquid mixtures [17, 18, 20, 28, 29]. The present results are in excellent agreement with both classical and contemporary literature.

## 4. Conclusion

The ultrasonic and thermo-acoustic investigation of ethylbenzoate + 2-methyl-2-propanol mixtures reveals strong molecular interactions and significant non-ideal behavior across the entire composition and temperature range studied. Decreasing compressibility and free length with increasing ester concentration indicate enhanced molecular association, while temperature-dependent trends confirm the weakening of interactions at elevated temperatures. The study reaffirms ultrasonic techniques as reliable tools for probing molecular interactions in complex liquid mixtures, contributing valuable data to the existing literature.

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