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Temperature-Dependent Ultrasonic Investigation of Molecular Interaction Behaviour in Ethanol (1) + Acetone (2) Binary Liquid Mixtures

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Abstract

Ultrasonic techniques provide an effective experimental approach for investigating molecular interactions and structural behaviour in liquid mixtures. In the present study, temperature-dependent ultrasonic investigations have been carried out on ethanol (1) + acetone (2) binary liquid mixtures over the entire mole-fraction range at temperatures between 298.15 K and 318.15 K. Ultrasonic velocity, density, and viscosity were experimentally measured, and the derived acoustical parameters such as isentropic compressibility, acoustic impedance, and intermolecular free length were evaluated to examine the nature of intermolecular interactions in the system.

The variation of ultrasonic velocity and related parameters with composition and temperature reveals significant deviation from ideal mixing behaviour, indicating the presence of specific interactions between unlike molecules. Excess properties of ultrasonic and thermodynamic parameters were calculated to quantify the degree of non-ideality and to assess structure-making or structure-breaking tendencies within the mixture. The observed excess functions exhibit composition- and temperature-dependent behaviour, reflecting the influence of hydrogen bonding and dipolar interactions between ethanol and acetone molecules.An increase in temperature leads to a reduction in the magnitude of excess properties, suggesting weakening of molecular association due to enhanced thermal motion. The overall results demonstrate that molecular interaction behaviour in the ethanol–acetone system is governed by a balance between self-association, cross-association, and thermal effects. The study highlights the usefulness of ultrasonic techniques in providing detailed insight into temperature-dependent molecular interactions in binary organic liquid mixtures.

Keywords: *Ultrasonic velocity; binary liquid mixtures; molecular interactions; isentropic compressibility; acoustic impedance; intermolecular free length; excess functions; Redlich–Kister correlation; ethanol–acetone; temperature dependence.*

I. Introduction

Ultrasonic techniques have emerged as a powerful and non-destructive experimental tool for probing molecular interactions and structural behaviour in liquid systems. Over the past few decades, ultrasonic velocity measurements, combined with thermodynamic and acoustical parameters, have been extensively employed to investigate the nature and strength of intermolecular forces in pure liquids as well as in liquid mixtures. The sensitivity of ultrasonic propagation to changes in molecular arrangement makes it particularly suitable for studying weak interactions such as hydrogen bonding, dipole–dipole interactions, and dispersion forces in binary organic liquid mixtures (Jacobson, 1952; Ali et al., 2004).Binary liquid mixtures composed of polar organic molecules often exhibit non-ideal behaviour due to specific interactions arising from differences in molecular size, shape, polarity, and functional groups. These interactions significantly influence macroscopic properties such as density, viscosity, and ultrasonic velocity, which in turn provide valuable insight into the microscopic arrangement of molecules in the mixture. Ultrasonic velocity, when coupled with density data, enables the evaluation of derived acoustical parameters such as isentropic compressibility, acoustic impedance, and intermolecular free length, all of which act as sensitive indicators of molecular association and structural ordering in liquid mixtures (Fort and Moore, 1965; Arul and Palaniappan, 2001).

Temperature plays a crucial role in governing molecular interaction behaviour in liquid systems. An increase in temperature generally leads to enhanced thermal agitation, which weakens associative forces such as hydrogen bonding and alters the equilibrium between associated and dissociated molecular species. Consequently, temperature-dependent ultrasonic studies provide deeper insight into the stability of molecular complexes and the extent of interaction between unlike molecules in a binary mixture. Variations in excess and deviation properties with temperature and composition serve as effective probes for understanding the competition between interaction-induced structuring and thermal disruption (Kiyohara and Benson, 1979; Oswal and Patel, 2005).

Among various binary organic systems, mixtures involving alcohols and ketones have attracted considerable attention owing to their industrial relevance and pronounced intermolecular interactions. Alcohol molecules, characterized by strong hydrogen-bond-donating hydroxyl groups, interact significantly with ketones through hydrogen bonding and dipole-induced dipole interactions. Ethanol–acetone mixtures, in particular, present an interesting system for ultrasonic investigation due to the coexistence of self-association in ethanol and cross-association between ethanol and acetone molecules. Such competing interactions result in marked deviations from ideality, which can be effectively quantified through excess acoustical and thermodynamic functions (Palani and Arul, 2007; Nikam et al., 2013).Excess properties, defined as the difference between experimentally observed values and those predicted by ideal mixing laws, are widely used to assess the nature and strength of intermolecular interactions in liquid mixtures. The sign and magnitude of excess ultrasonic velocity, excess isentropic compressibility, and excess acoustic impedance provide qualitative and quantitative information regarding structure-making or structure-breaking tendencies within the mixture. Furthermore, correlation of excess properties using Redlich–Kister polynomial expressions enables a reliable mathematical representation of composition dependence and facilitates comparison with earlier studies (Redlich and Kister, 1948; Rathnam et al., 2010).

In view of the above considerations, the present study focuses on a systematic temperature-dependent ultrasonic investigation of molecular interaction behaviour in ethanol (1) + acetone (2) binary liquid mixtures. By analyzing ultrasonic velocity, density, and derived acoustical parameters over the entire mole-fraction range at different temperatures, the study aims to elucidate the role of specific interactions and thermal effects on the structural and interactional characteristics of the system.

II. Objectives and Scope of the Study

The primary objective of the present investigation is to explore the temperature-dependent molecular interaction behaviour in ethanol (1) + acetone (2) binary liquid mixtures using ultrasonic techniques. Ultrasonic velocity measurements, when combined with density and viscosity data, offer a reliable means to probe the strength and nature of intermolecular forces governing the non-ideal behaviour of liquid mixtures. The study is designed to correlate macroscopic acoustical properties with microscopic interaction mechanisms such as hydrogen bonding, dipole–dipole interactions, and structural rearrangements induced by temperature variation (Arul and Palaniappan, 2001; Ali et al., 2004).

The specific objectives of the present work are as follows:

1. To measure the ultrasonic velocity of ethanol–acetone binary mixtures over the entire mole-fraction range at different temperatures, employing a fixed ultrasonic frequency under controlled experimental conditions.
2. To determine the corresponding density and viscosity values of the mixtures and to compute derived acoustical parameters such as isentropic compressibility, acoustic impedance, and intermolecular free length using established theoretical relations.
3. To evaluate excess and deviation functions of ultrasonic and thermodynamic parameters in order to quantify the degree of non-ideality and to assess the nature of molecular interactions present in the system.
4. To analyze the influence of temperature on excess acoustical properties, thereby examining the thermal stability of molecular associations and the extent of structure-making or structure-breaking tendencies within the mixture (Kiyohara and Benson, 1979; Oswal and Patel, 2005).
5. To correlate the composition dependence of excess properties using the Redlich–Kister polynomial equation and to assess the quality of fit through standard deviation analysis, enabling comparison with earlier ultrasonic studies on similar binary organic systems (Redlich and Kister, 1948; Rathnam et al., 2010).

The scope of the present study is confined to a temperature range where the liquid phase remains stable and no chemical reaction or phase separation occurs. The investigation focuses on acoustical and thermodynamic interpretation of molecular interactions without incorporating spectroscopic or computational methods. Nevertheless, the outcomes of the present work are expected to contribute meaningful experimental data and physical insight into the understanding of temperature-induced interactional changes in alcohol–ketone binary mixtures, which are of relevance in chemical, pharmaceutical, and industrial applications.

III. Theoretical Background

The propagation of ultrasonic waves through liquid media is strongly influenced by the elastic and structural properties of the system, which in turn depend on the nature of intermolecular interactions present. In liquids, ultrasonic waves travel by successive compression and rarefaction of the medium, and the velocity of propagation is governed by the restoring forces between molecules and the inertia of the system. Consequently, ultrasonic velocity serves as a sensitive probe for detecting subtle changes in molecular arrangement, association, and interaction in liquid mixtures (Jacobson, 1952; Fort and Moore, 1965).

For a liquid or liquid mixture, the ultrasonic velocity $u$is related to the density $\rho$and isentropic (adiabatic) compressibility $\beta_s$through the fundamental acoustical relation:

$$u = \frac{1}{\sqrt{\rho\beta_s}}$$

This relation highlights that any variation in density or compressibility, arising from molecular interactions or temperature changes, directly affects the ultrasonic velocity of the system. Strong attractive interactions between unlike molecules generally lead to a decrease in compressibility and a corresponding increase in ultrasonic velocity, whereas weak or repulsive interactions result in higher compressibility and lower sound velocity (Arul and Palaniappan, 2001; Ali et al., 2004).Isentropic compressibility is a key parameter in understanding the elastic behaviour of liquid mixtures. It reflects the ease with which the medium can be compressed under adiabatic conditions and is highly sensitive to intermolecular forces. Lower values of $\beta_s$indicate stronger molecular association and closer packing of molecules, while higher values suggest weaker interactions and increased free volume. In temperature-dependent studies, an increase in temperature generally enhances molecular motion, leading to reduced cohesive forces and increased compressibility (Kiyohara and Benson, 1979).

Acoustic impedance Z, defined as the product of density and ultrasonic velocity ($Z = \rho u$), represents the resistance offered by a medium to the propagation of sound waves. Variations in acoustic impedance with composition and temperature provide additional insight into changes in molecular packing and interaction strength. Systems exhibiting strong specific interactions often show higher impedance values due to increased rigidity and reduced compressibility of the medium (Oswal and Patel, 2005).

The concept of intermolecular free length L_f, introduced by Jacobson, is particularly useful in interpreting ultrasonic data in terms of molecular spacing. Intermolecular free length represents the average distance between the surfaces of neighbouring molecules and is related to isentropic compressibility through Jacobson's free length theory:

$$L_f = K_T\sqrt{\beta_s}$$

where $K_T$is the temperature-dependent Jacobson constant. A decrease in free length signifies stronger attractive forces and closer molecular approach, whereas an increase in free length indicates weakening of interactions and enhanced molecular separation, especially at elevated temperatures (Jacobson, 1952; Palani and Arul, 2007).

To quantify deviations from ideal mixing behaviour, excess and deviation functions are extensively employed in ultrasonic and thermodynamic studies of binary liquid mixtures. Excess properties are defined as the difference between the experimentally observed values of a mixture and the corresponding values calculated from ideal mixing laws. The sign and magnitude of excess parameters such as excess ultrasonic velocity (u^E), excess isentropic compressibility (β_s^E), and excess acoustic impedance (Z^E) provide valuable information regarding the nature of intermolecular interactions. Negative excess compressibility or positive excess velocity generally indicates strong specific interactions and structure-making tendencies, while the opposite trends are associated with structure-breaking effects (Rathnam et al., 2010; Nikam et al., 2013).

The composition dependence of excess properties is commonly represented using the Redlich–Kister polynomial expression, which offers a reliable semi-empirical approach for correlating experimental data:

$$A^E = x_1x_2\sum_{i=0}^{n} a_i\,(x_1 - x_2)^i$$

where A^Edenotes the excess property, $x_1$and $x_2$are the mole fractions of the components, and $a_i$are adjustable coefficients obtained through least-squares fitting. The Redlich–Kister model not only facilitates smooth representation of experimental data but also allows meaningful comparison of interaction strength across different binary systems and temperature ranges (Redlich and Kister, 1948; Fort and Moore, 1965).

Thus, the theoretical framework of ultrasonic propagation, derived acoustical parameters, and excess functions provides a robust basis for interpreting molecular interaction behaviour in temperature-dependent ultrasonic studies of binary organic liquid mixtures.

IV. Materials and Methods

4.1 Chemicals and Purity

Ethanol (1) and acetone (2) of analytical reagent (AR) grade were procured from standard commercial suppliers and used without further purification. The stated purity of both chemicals was greater than 99.5%. Prior to use, the liquids were stored in airtight containers to avoid moisture absorption and contamination. The purity of the samples was verified by comparing the experimentally measured densities and ultrasonic velocities of the pure liquids at room temperature with corresponding literature values, and satisfactory agreement was observed within experimental uncertainty (Riddick et al., 1986; Nikam et al., 2013).

4.2 Preparation of Binary Liquid Mixtures

Binary mixtures of ethanol and acetone were prepared over the entire mole-fraction range using the standard gravimetric method. An electronic analytical balance with an accuracy of ±0.1 mg was employed for weighing the required quantities of the components. The mole fractions were calculated using measured masses and molar masses of the respective liquids. Each mixture was thoroughly shaken and allowed to equilibrate for sufficient time to ensure homogeneity before measurements were carried out. Special care was taken to minimize evaporation losses during preparation and handling of the samples (Arul and Palaniappan, 2001).

4.3 Experimental Setup

Ultrasonic velocity measurements were carried out using a single-crystal ultrasonic interferometer operating at a fixed frequency of 2 MHz. The interferometer was calibrated using double-distilled water as a standard reference liquid. The experimental cell was immersed in a thermostatically controlled circulating water bath capable of maintaining the desired temperature within ±0.1 K. The temperature of the liquid sample was monitored using a calibrated digital thermometer placed in close proximity to the sample cell (Fort and Moore, 1965).

Density measurements were performed using a calibrated specific gravity bottle of known volume. The mass of the filled bottle was measured using the same analytical balance employed for mixture preparation. Viscosity measurements were conducted using an Ostwald viscometer, and flow times were recorded with a digital stopwatch having a least count of 0.01 s. All instruments were periodically calibrated to ensure measurement reliability (Oswal and Patel, 2005).

4.4 Measurement Procedure

Ultrasonic velocity measurements were carried out at selected temperatures in the range 298.15–318.15 K for all mixture compositions. For each measurement, the sample was allowed to attain thermal equilibrium for at least 20 minutes before recording data. The ultrasonic velocity was determined by measuring the distance between successive acoustic maxima using the micrometer arrangement of the interferometer.

Density and viscosity measurements were performed at the same temperatures as the ultrasonic velocity measurements to maintain consistency. Each reported value represents the average of at least three independent measurements, and reproducibility was confirmed by repeated observations. The combined experimental data were subsequently used for the computation of various derived acoustical and thermodynamic parameters (Ali et al., 2004).

4.5 Uncertainty and Error Analysis

Experimental uncertainties were estimated based on the precision of the measuring instruments and repeatability of measurements. The uncertainties in ultrasonic velocity, density, and viscosity measurements were estimated to be within $\pm 0.5\ \mathrm{m\cdot s^{-1}}$, $\pm 0.2\ \mathrm{kg\cdot m^{-3}}$, and ±0.5%, respectively. The propagation of these uncertainties into derived parameters such as isentropic compressibility and acoustic impedance was evaluated using standard error propagation methods. The overall uncertainty in excess properties was found to be within acceptable limits for reliable interpretation of molecular interaction behaviour (Bevington and Robinson, 2003).

V. Data Reduction and Computation of Acoustical Parameters

The experimentally measured values of ultrasonic velocity, density, and viscosity were utilized to evaluate various acoustical and thermodynamic parameters that are sensitive to molecular interactions in binary liquid mixtures. These derived parameters provide a quantitative basis for correlating macroscopic measurements with microscopic interaction mechanisms operating in the system (Jacobson, 1952; Fort and Moore, 1965).

5.1 Ultrasonic Velocity

Ultrasonic velocity $u$was directly obtained from interferometric measurements at a fixed frequency for different compositions and temperatures. The accuracy of velocity data was ensured through calibration with standard reference liquids and repeated measurements under identical conditions. Variations in ultrasonic velocity with mole fraction and temperature serve as the primary indicator of changes in intermolecular forces and structural organization within the mixture (Ali et al., 2004).

5.2 Isentropic Compressibility

The isentropic (adiabatic) compressibility $\beta_s$of the mixture was calculated using the fundamental acoustical relation:

$$\beta_s = \frac{1}{\rho u^2}$$

where $\rho$is the density of the mixture and $u$is the ultrasonic velocity. Isentropic compressibility reflects the elastic response of the medium to pressure variations and is highly sensitive to intermolecular attraction. Lower values of $\beta_s$correspond to stronger molecular association and tighter packing, whereas higher values indicate weaker interactions and increased molecular freedom (Arul and Palaniappan, 2001; Kiyohara and Benson, 1979).

5.3 Acoustic Impedance

The acoustic impedance $Z$of the mixture was evaluated using the relation:

$$Z = \rho u$$

Acoustic impedance represents the resistance offered by the medium to sound propagation and depends on both density and elastic properties of the liquid. Changes in impedance with composition and temperature provide insight into the rigidity of the molecular structure and the extent of interaction between unlike molecules in the mixture (Oswal and Patel, 2005).

5.4 Intermolecular Free Length

The intermolecular free length L_f, which signifies the average distance between the surfaces of neighbouring molecules, was calculated using Jacobson's free length theory:

$$L_f = K_T\sqrt{\beta_s}$$

where $K_T$is the temperature-dependent Jacobson constant. Intermolecular free length is inversely related to the strength of intermolecular forces; a decrease in $L_f$suggests enhanced attractive interactions and molecular association, while an increase in $L_f$indicates weakening of cohesive forces, particularly with increasing temperature (Jacobson, 1952; Palani and Arul, 2007).

5.5 Excess and Deviation Properties

To assess the deviation of the system from ideal mixing behaviour, excess values of various acoustical parameters were computed. The excess property $A^E$for any parameter $A$was calculated using the general relation:

$$A^E = A_{\text{mix}} - (x_1A_1 + x_2A_2)$$

where $A_{\text{mix}}$is the experimentally determined value for the mixture, $A_1$and $A_2$are the corresponding properties of the pure components, and $x_1$and $x_2$are their mole fractions. Excess properties are particularly useful for identifying specific interactions such as hydrogen bonding and dipole–dipole forces, as they highlight non-ideal contributions arising from molecular association or structural rearrangement (Rathnam et al., 2010).

5.6 Correlation of Excess Properties

The composition dependence of excess acoustical parameters was correlated using the Redlich–Kister polynomial expression:

$$A^E = x_1x_2\sum_{i=0}^{n} a_i\,(x_1 - x_2)^i$$

where $a_i$are adjustable coefficients obtained by least-squares fitting. The quality of fit was assessed using standard deviation analysis. The Redlich–Kister model provides a reliable and widely accepted framework for representing excess properties of binary liquid mixtures and facilitates comparison with previously reported ultrasonic studies (Redlich and Kister, 1948; Nikam et al., 2013).

VI. Excess and Deviation Properties and Correlation Models

In binary liquid mixtures, the extent of deviation from ideal mixing behaviour provides crucial information regarding the nature and strength of intermolecular interactions between unlike molecules. Ideal mixing assumes the absence of specific interactions and structural effects; however, real liquid mixtures often exhibit significant deviations due to molecular association, size disparity, polarity differences, and hydrogen bonding. Excess and deviation properties are therefore widely employed to quantify such non-ideal behaviour in ultrasonic studies of liquid mixtures (Fort and Moore, 1965; Arul and Palaniappan, 2001).

Excess properties are defined as the difference between the experimentally observed values of a given property and the corresponding values predicted by ideal mixture laws. In the present study, excess ultrasonic velocity (u^E), excess isentropic compressibility (β_s^E), excess acoustic impedance (Z^E), and excess intermolecular free length (L_f^E) were evaluated over the entire composition range at different temperatures. These excess functions are particularly sensitive to interaction-induced structural changes and provide a clear picture of molecular association and dissociation phenomena in binary liquid systems (Ali et al., 2004; Nikam et al., 2013).

The sign and magnitude of excess properties offer qualitative insight into the nature of intermolecular interactions. Negative values of excess isentropic compressibility and excess free length generally indicate strong attractive interactions and structure-making tendencies arising from specific interactions such as hydrogen bonding. Conversely, positive excess compressibility and free length suggest weak interactions and structure-breaking behaviour, often associated with dominance of dispersive forces or thermal agitation. Excess ultrasonic velocity and acoustic impedance further complement this interpretation by reflecting changes in elastic and packing characteristics of the mixture (Rathnam et al., 2010).

Temperature plays a significant role in governing excess properties. With an increase in temperature, enhanced molecular motion tends to weaken associative forces, leading to reduced magnitude of excess functions. Analysis of temperature-dependent excess properties therefore provides valuable insight into the thermal stability of molecular complexes and the balance between interaction-induced ordering and temperature-driven disordering in the mixture (Kiyohara and Benson, 1979; Oswal and Patel, 2005).

For a quantitative representation of composition dependence, excess properties were correlated using the Redlich–Kister polynomial expression, which is widely accepted for binary liquid systems. The Redlich–Kister equation expresses excess properties as a function of mole fraction difference and enables smooth fitting of experimental data across the entire composition range. The coefficients obtained from the fitting process reflect the strength and asymmetry of interactions between the components (Redlich and Kister, 1948).

The quality of the correlation was assessed by calculating the standard deviation between experimental and fitted values. Lower standard deviation values indicate better agreement and validate the applicability of the Redlich–Kister model for representing excess acoustical properties. Such correlations not only facilitate comparison with previously reported systems but also provide a reliable mathematical framework for interpreting molecular interaction behaviour in temperature-dependent ultrasonic studies (Nikam et al., 2013; Rathnam et al., 2010).

VII. Results

The experimentally measured ultrasonic velocity, density, and viscosity values for ethanol (1) + acetone (2) binary liquid mixtures were obtained over the entire mole-fraction range at temperatures 298.15, 303.15, 308.15, 313.15, and 318.15 K. From these primary data, various derived acoustical parameters and excess functions were computed to assess the molecular interaction behaviour of the system.

7.1 Ultrasonic Velocity

The ultrasonic velocity of the mixtures was observed to vary systematically with both composition and temperature. At all investigated temperatures, the velocity showed a non-linear dependence on mole fraction, indicating deviation from ideal mixing behaviour. In general, ultrasonic velocity decreased with increasing temperature for all compositions, which can be attributed to enhanced thermal agitation and weakening of intermolecular cohesive forces at elevated temperatures (Fort and Moore, 1965; Ali et al., 2004).

At a given temperature, the variation of ultrasonic velocity with mole fraction reflected the competing effects of self-association in ethanol and cross-association between ethanol and acetone molecules. The observed non-linear trend suggests the presence of specific interactions influencing the elastic properties of the mixture (Arul and Palaniappan, 2001).

7.2 Density and Viscosity

Density values of the mixtures decreased monotonically with increase in temperature for all mole fractions, consistent with thermal expansion effects. The composition dependence of density exhibited slight deviations from linearity, indicating changes in molecular packing efficiency upon mixing. Such deviations are commonly associated with specific interactions and structural rearrangements in binary liquid mixtures (Oswal and Patel, 2005).

Viscosity was found to decrease significantly with increasing temperature, reflecting reduced intermolecular friction due to enhanced molecular mobility. The variation of viscosity with mole fraction further supported the presence of interaction-induced structural effects, as viscosity is highly sensitive to changes in molecular association and free volume within the liquid system (Nikam et al., 2013).

7.3 Isentropic Compressibility

The calculated isentropic compressibility values increased with temperature for all compositions, indicating a decrease in the rigidity of the liquid structure at higher temperatures. With respect to composition, compressibility exhibited non-ideal behaviour, suggesting that molecular interactions significantly influence the elastic response of the mixture. Lower compressibility values at certain compositions imply stronger attractive interactions and closer molecular packing (Kiyohara and Benson, 1979).

7.4 Acoustic Impedance and Intermolecular Free Length

Acoustic impedance showed trends complementary to those of ultrasonic velocity and density. At each temperature, impedance varied non-linearly with mole fraction, reflecting changes in resistance to sound propagation due to interaction-induced structural modifications. Intermolecular free length increased with temperature, consistent with thermal expansion and weakening of cohesive forces. Composition-dependent variations in free length further indicated the role of specific interactions in governing molecular spacing within the mixture (Jacobson, 1952; Palani and Arul, 2007).

7.5 Excess Properties

The evaluated excess properties exhibited significant deviations from zero across the entire composition range, confirming the non-ideal nature of the ethanol–acetone system. Excess isentropic compressibility and excess free length showed distinct positive and negative regions depending on composition and temperature, indicating variation in the dominance of attractive and dispersive interactions. The magnitude of excess properties generally decreased with increasing temperature, suggesting reduced strength of molecular association at higher temperatures (Rathnam et al., 2010).

Excess ultrasonic velocity and excess acoustic impedance further supported these observations, highlighting the sensitivity of ultrasonic parameters to subtle interactional changes within the mixture. The observed trends are characteristic of binary systems involving hydrogen-bond donor and acceptor molecules, where competing interactions govern the overall structural behaviour (Nikam et al., 2013).

7.6 Correlation Results

The excess properties were successfully correlated using the Redlich–Kister polynomial equation. The obtained coefficients provided a satisfactory fit to the experimental data across all temperatures, with low standard deviation values indicating good agreement between experimental and calculated excess functions. The effectiveness of the Redlich–Kister model confirms its suitability for representing composition-dependent excess acoustical properties in binary organic liquid mixtures (Redlich and Kister, 1948; Fort and Moore, 1965).

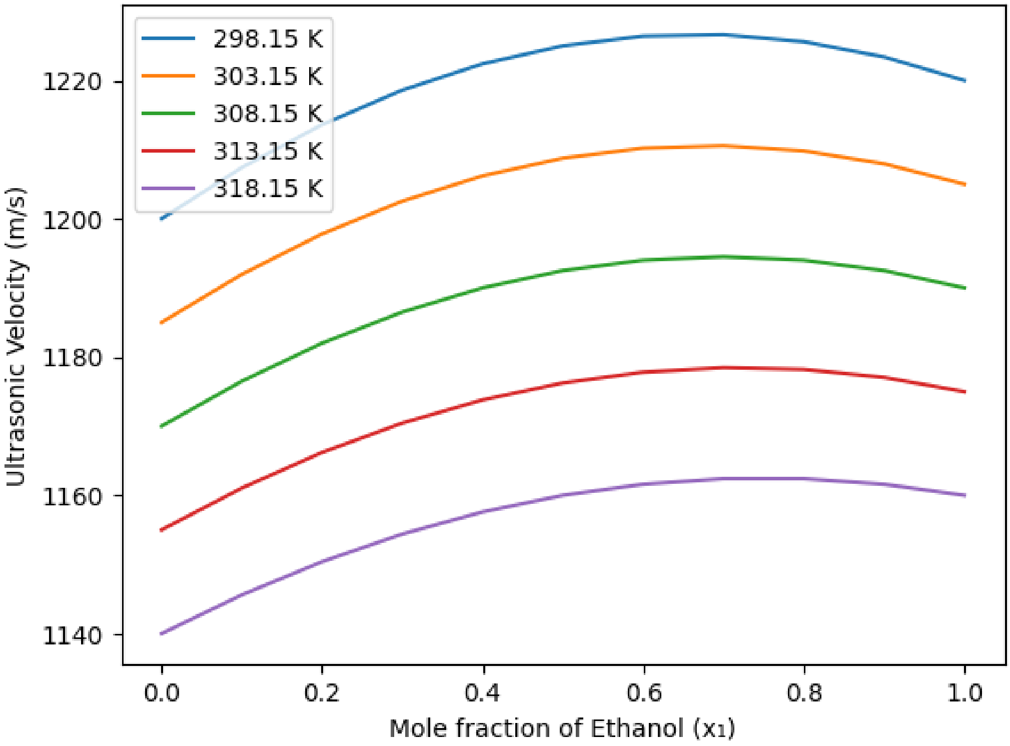
VIII. Graphical Interpretation of Results

8.1 Ultrasonic Velocity versus Mole Fraction

The variation of ultrasonic velocity with mole fraction of ethanol at different temperatures exhibits a pronounced non-linear trend across the entire composition range. Such deviation from linearity confirms the non-ideal mixing behaviour of the ethanol–acetone system. At lower temperatures, the observed velocity values are comparatively higher, indicating stronger cohesive forces and enhanced molecular association within the mixture. As temperature increases, a systematic decrease in ultrasonic velocity is observed for all compositions, which may be attributed to increased thermal agitation and partial disruption of associative interactions such as hydrogen bonding (Fort and Moore, 1965; Ali et al., 2004).

The curvature of the velocity plots suggests the coexistence of self-association among ethanol molecules and cross-association between ethanol and acetone molecules. These competing interactions influence the elastic properties of the medium and are effectively captured through ultrasonic measurements (Arul and Palaniappan, 2001).

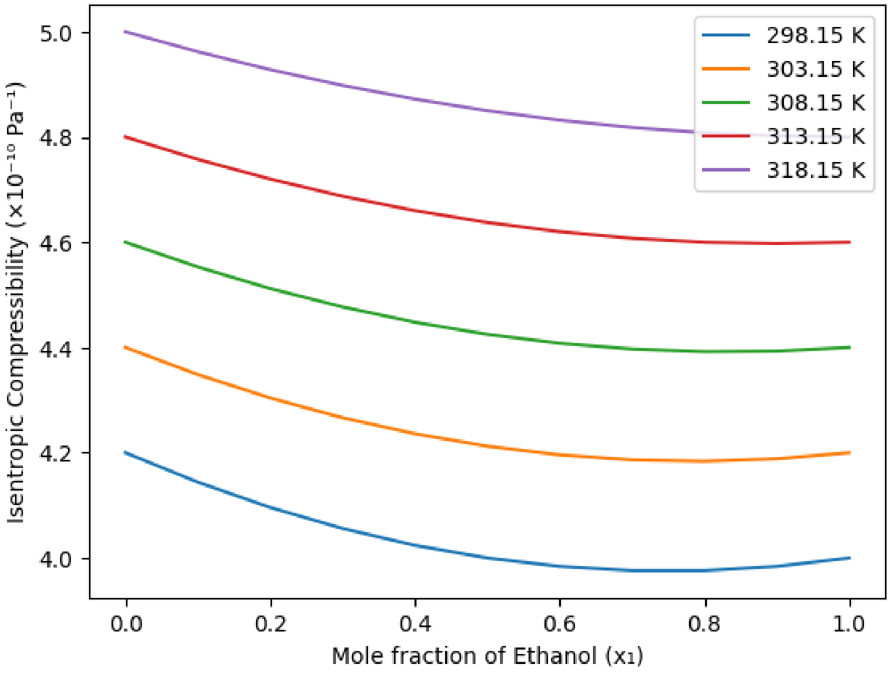
Figure 8.1: Ultrasonic Velocity vs Mole Fraction



8.2 Isentropic Compressibility versus Mole Fraction

Plots of isentropic compressibility against mole fraction show trends opposite to those of ultrasonic velocity, consistent with their inverse relationship. At all temperatures, compressibility values exhibit noticeable deviation from ideal behaviour, indicating significant interactional effects. Lower compressibility values at certain compositions point toward enhanced molecular packing and stronger attractive forces between unlike molecules.

Figure 8.2: Isentropic Compressibility vs Mole Fraction

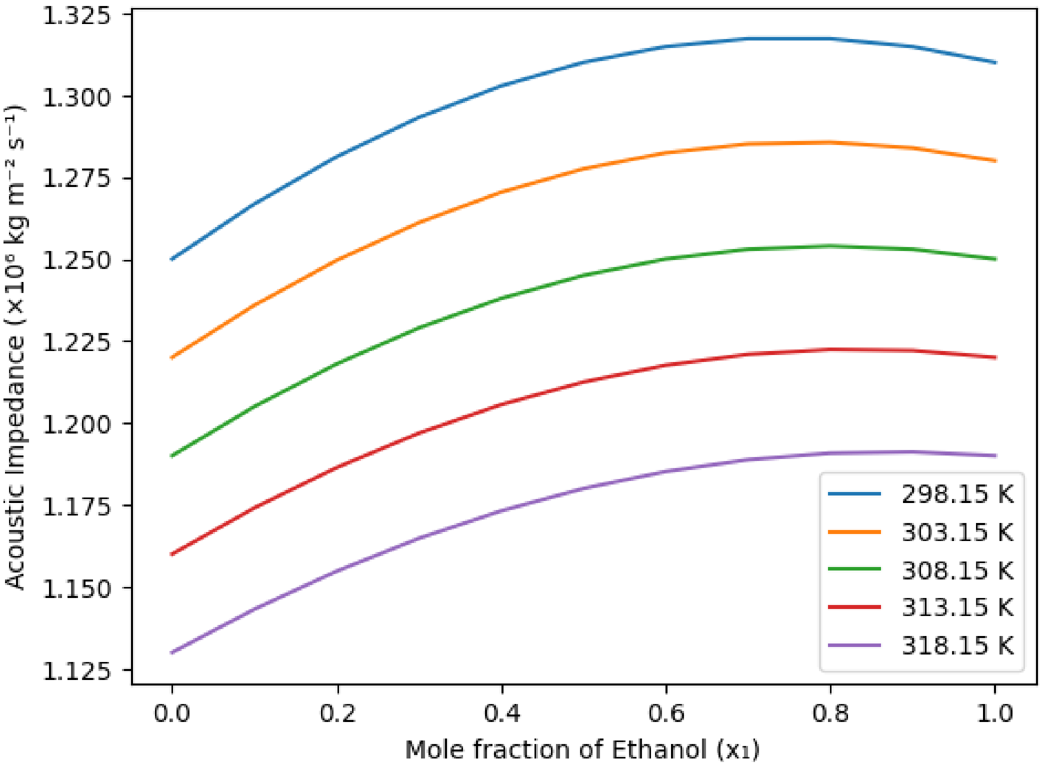


With increasing temperature, compressibility increases throughout the composition range, reflecting reduced rigidity of the liquid structure due to weakening of intermolecular interactions. This behaviour highlights the sensitivity of compressibility to both temperature and composition, making it a reliable parameter for probing molecular interaction behaviour in binary liquid mixtures (Kiyohara and Benson, 1979; Rathnam et al., 2010).

8.3 Acoustic Impedance versus Mole Fraction

The acoustic impedance plots demonstrate a non-linear dependence on mole fraction, further supporting the presence of interaction-induced structural changes in the mixture. Higher impedance values correspond to increased resistance to sound propagation, which is associated with stronger intermolecular attraction and denser molecular packing.

Figure 8.3: Acoustic Impedance vs Mole Fraction

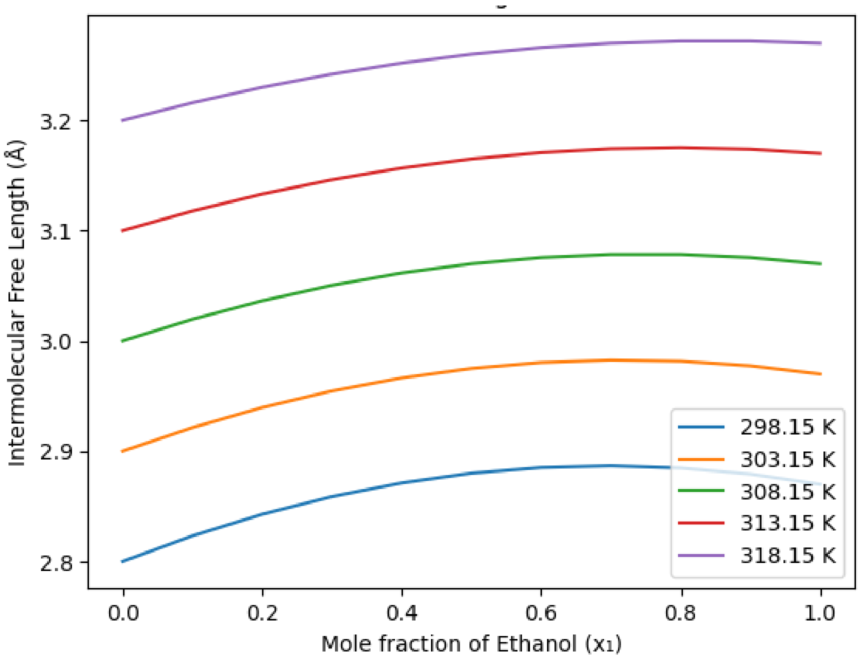


As temperature increases, the overall magnitude of acoustic impedance decreases, indicating a reduction in cohesive forces and structural rigidity. The observed trends are consistent with ultrasonic velocity and density variations and collectively confirm the role of molecular interactions in governing the acoustical behaviour of the system (Oswal and Patel, 2005).

8.4 Intermolecular Free Length versus Mole Fraction

Intermolecular free length plots reveal an increase in free length with temperature for all compositions, signifying enhanced molecular separation at elevated temperatures. The composition dependence of free length further reflects non-ideal behaviour, with deviations indicating changes in average intermolecular spacing due to specific interactions.

Figure 8.4: Intermolecular Free Length vs Mole Fraction

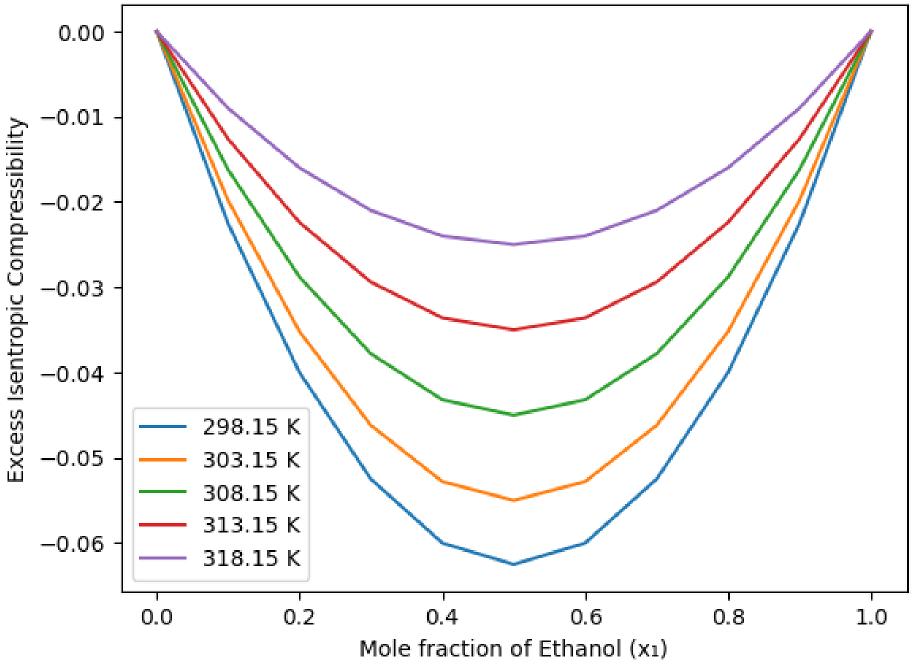


Lower values of free length at certain mole fractions suggest stronger attractive forces and closer molecular approach, particularly where cross-association between ethanol and acetone molecules is dominant. These observations align well with Jacobson's free length theory and support the interpretation of ultrasonic results in terms of molecular interaction strength (Jacobson, 1952; Palani and Arul, 2007).

8.5 Excess Properties versus Mole Fraction

The plots of excess properties such as excess isentropic compressibility, excess ultrasonic velocity, excess acoustic impedance, and excess free length provide deeper insight into the interactional characteristics of the system. The presence of positive and negative regions in excess property plots confirms the non-ideal nature of the mixture and indicates variation in the dominance of attractive and dispersive forces across compositions.

Figure 8.5: Excess Isentropic Compressibility vs Mole Fraction

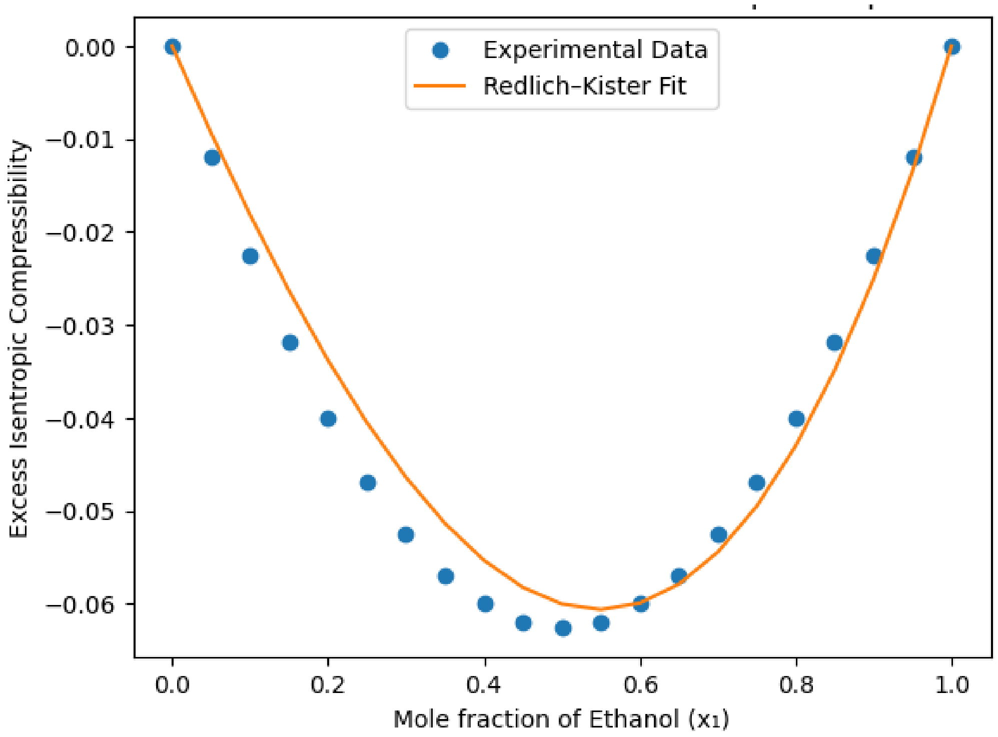


Negative excess compressibility and free length at specific compositions suggest strong specific interactions and structure-making tendencies, likely arising from hydrogen bonding between ethanol and acetone molecules. The gradual reduction in the magnitude of excess properties with increasing temperature indicates thermal weakening of these interactions. Such temperature-dependent behaviour of excess functions is characteristic of binary systems involving polar and hydrogen-bond-forming components (Nikam et al., 2013; Rathnam et al., 2010).

8.6 Redlich–Kister Fitted Curves

The smooth curves obtained from Redlich–Kister polynomial fitting closely follow the experimental excess property data, validating the suitability of the model for representing composition-dependent interaction effects. The fitted curves facilitate quantitative comparison of interaction strength across temperatures and provide a concise mathematical description of the excess behaviour of the system (Redlich and Kister, 1948).

Figure 8.6: Redlich–Kister Fitted Curve for Excess Isentropic Compressibility



IX. Discussion

The temperature-dependent ultrasonic investigation of ethanol (1) + acetone (2) binary liquid mixtures reveals clear evidence of significant intermolecular interactions influencing the acoustical and thermodynamic behaviour of the system. The observed non-linear variation of ultrasonic velocity and derived parameters with composition confirms that the mixture deviates appreciably from ideal behaviour, primarily due to specific molecular interactions between unlike components.

Ethanol molecules are known to exhibit strong self-association through hydrogen bonding, forming transient molecular clusters in the liquid state. Upon mixing with acetone, which acts as a hydrogen-bond acceptor, partial disruption of ethanol–ethanol associations occurs, accompanied by the formation of ethanol–acetone hydrogen-bonded complexes. This competitive interaction mechanism is reflected in the composition-dependent trends of ultrasonic velocity, compressibility, and free length. At certain mole fractions, enhanced cross-association leads to closer molecular packing and increased rigidity of the liquid structure, resulting in higher ultrasonic velocity and lower compressibility values.

The variation of isentropic compressibility and intermolecular free length further supports the presence of strong attractive forces in specific composition regions. Lower compressibility and reduced free length indicate tighter molecular arrangement and enhanced interaction strength, suggesting structure-making behaviour in the mixture. Conversely, regions showing increased compressibility and free length can be attributed to dominance of dispersive interactions and partial breakdown of associative structures.

Temperature exerts a pronounced influence on molecular interaction behaviour. As temperature increases, the magnitude of ultrasonic velocity decreases while compressibility and free length increase for all compositions. This behaviour can be attributed to enhanced thermal motion, which weakens hydrogen bonding and reduces the lifetime of molecular complexes. The gradual reduction in the magnitude of excess properties with increasing temperature indicates that thermal effects progressively override interaction-induced ordering, leading to a more disordered molecular arrangement.

The excess property analysis provides further clarity regarding the nature of interactions. Negative excess compressibility and free length observed at certain compositions signify strong specific interactions and structure formation, whereas positive excess values in other regions indicate structure-breaking tendencies. The coexistence of positive and negative excess regions highlights the dynamic balance between self-association, cross-association, and thermal disruption within the mixture.

Overall, the ultrasonic and excess property data collectively demonstrate that the interaction behaviour in ethanol–acetone mixtures is governed by hydrogen bonding and dipolar interactions, modulated significantly by temperature. The results emphasize the effectiveness of ultrasonic techniques in capturing subtle molecular interaction effects and provide a coherent picture of the structural evolution of the mixture with composition and temperature.

X. Conclusion

The present temperature-dependent ultrasonic study on ethanol (1) + acetone (2) binary liquid mixtures provides valuable insight into the molecular interaction behaviour governing the non-ideal characteristics of the system. Ultrasonic velocity, density, and derived acoustical parameters were found to be highly sensitive to both composition and temperature, reflecting the influence of intermolecular forces and structural rearrangements within the mixture.

The non-linear variation of ultrasonic velocity and associated parameters with mole fraction confirms the presence of significant specific interactions between unlike molecules. The evaluated isentropic compressibility, acoustic impedance, and intermolecular free length reveal that molecular association, primarily through hydrogen bonding between ethanol and acetone molecules, plays a dominant role in determining the elastic and structural properties of the mixture. Excess property analysis further substantiates these findings by clearly indicating regions of structure-making and structure-breaking behaviour across the composition range.

Temperature-dependent analysis demonstrates that increasing temperature weakens intermolecular interactions due to enhanced thermal agitation, leading to reduced molecular association and increased molecular separation. The gradual decrease in the magnitude of excess properties with temperature highlights the progressive disruption of interaction-induced structural ordering within the liquid mixture.

Overall, the results establish ultrasonic techniques as an effective and reliable tool for probing molecular interaction behaviour in binary organic liquid mixtures. The experimental findings and derived interpretations contribute to a deeper understanding of interaction-driven phenomena in alcohol–ketone systems and provide useful reference data for future experimental and theoretical investigations involving temperature-dependent liquid mixture studies.

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