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The Role of Sound Velocity in Estimating Thermodynamic Properties of Binary Solutions

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Abstract

The study of thermodynamic properties of binary liquid solutions is fundamental to understanding molecular interactions and predicting the behavior of mixtures in various chemical and industrial processes. Among the different experimental techniques available, the measurement of sound velocity using ultrasonic methods has emerged as a reliable and non-destructive approach for evaluating such properties. This research explores the role of sound velocity in estimating key thermodynamic parameters including adiabatic compressibility, acoustic impedance, intermolecular free length, and excess properties in binary solutions. The propagation of ultrasonic waves through a liquid medium is significantly influenced by the density and compressibility of the system, both of which are governed by intermolecular interactions. By analyzing variations in sound velocity across different compositions, insights into molecular association, structural rearrangement, and non-ideal behavior can be obtained. The present study is based on secondary data collected from established literature and aims to synthesize existing knowledge into a coherent analytical framework. The findings demonstrate that sound velocity serves as an effective tool for characterizing binary mixtures and offers practical applications in chemical engineering, pharmaceuticals, and material science.

***Keywords*:** sound velocity, binary solutions, thermodynamic properties, ultrasonic studies, compressibility, intermolecular interactions, acoustic parameters

Introduction

Binary liquid solutions, consisting of two chemically distinct components mixed in varying proportions, play a significant role in both theoretical and applied chemistry. These systems are extensively encountered in industries such as pharmaceuticals, petrochemicals, food processing, and materials engineering. The study of their thermodynamic properties is essential for understanding molecular interactions, predicting phase behavior, and optimizing industrial processes (Ebrahimi & Sadeghi,2015). However, direct

measurement of thermodynamic parameters often involves complex experimental procedures and sophisticated instrumentation, making alternative indirect methods highly valuable (Vanathi et al. 2019).One such indirect method is the use of ultrasonic waves to determine sound velocity in liquid mixtures. Sound velocity is a macroscopic property that reflects the microscopic interactions between molecules. When an ultrasonic wave propagates through a liquid medium, its velocity depends on the density and compressibility of the system. These properties, in turn, are influenced by the nature and strength of intermolecular forces present in the mixture.

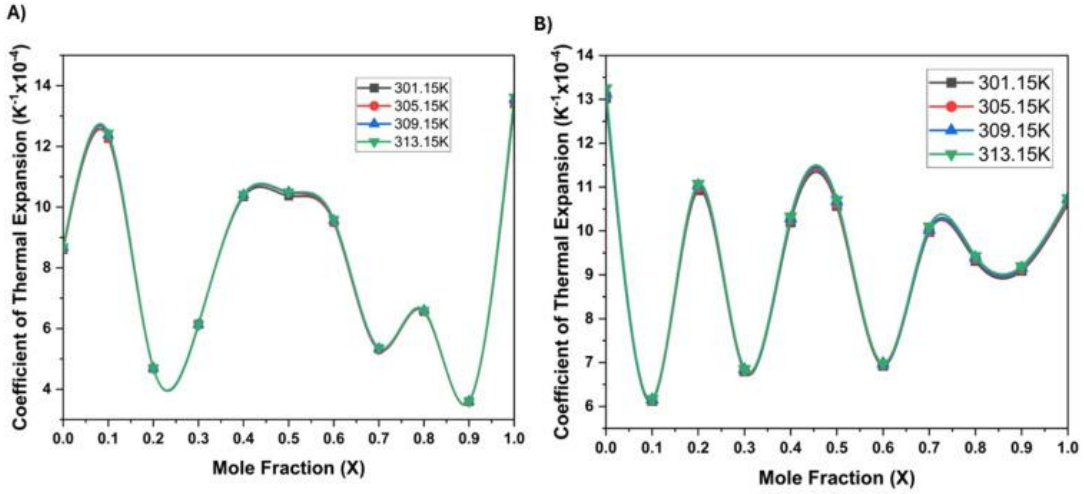
The application of ultrasonic techniques in studying liquid systems has gained considerable attention due to their simplicity, accuracy, and non-invasive nature. By measuring sound velocity at different concentrations and temperatures, researchers can derive several thermodynamic parameters such as adiabatic compressibility, acoustic impedance, and intermolecular free length. These parameters provide valuable insights into the structural and dynamic behavior of molecules in solution.Furthermore, binary mixtures often exhibit non-ideal behavior due to the presence of specific interactions such as hydrogen bonding, dipole-dipole interactions, and dispersion forces. Ultrasonic studies help in identifying these interactions by analyzing deviations from ideality. Therefore, sound velocity measurements serve as an important tool for understanding the fundamental properties of liquid mixtures.The study focuses on binary liquid mixtures, which are systems made of two different liquids such as water–alcohol or alcohol–hydrocarbon mixtures. These systems are selected because their molecular interactions significantly influence sound velocity, which can be used to estimate important thermodynamic properties like compressibility and intermolecular forces.

The study of binary liquid solutions forms an essential part of physical chemistry due to its relevance in both theoretical understanding and industrial applications. A binary solution consists of two components mixed in varying proportions, and its properties are largely governed by the nature of interactions between the constituent molecules. These systems are widely encountered in chemical processing, pharmaceuticals, petroleum industries, and materials science, where precise knowledge of thermodynamic behavior is required for process design, optimization, and quality control. However, the accurate determination of thermodynamic properties such as compressibility, free energy, and excess parameters remains a complex task due to the non-ideal nature of most liquid mixtures. In recent decades, ultrasonic techniques have emerged as a powerful and reliable method for investigating liquid systems. The velocity of sound in a medium is influenced by its density and compressibility, which are directly linked to intermolecular interactions. As ultrasonic waves propagate through a liquid, any change in molecular arrangement or interaction strength results in a measurable change in sound velocity. This sensitivity makes ultrasonic velocity an important parameter for probing the internal structure of binary mixtures. Moreover, ultrasonic methods offer several advantages over conventional techniques, including non-destructive measurement,

high precision, and relatively simple experimental setup. These features make them particularly suitable for continuous monitoring in industrial processes. The study of sound velocity not only helps in determining thermodynamic properties but also provides valuable insights into molecular association, hydrogen bonding, and structural rearrangements within the solution. Therefore, the integration of ultrasonic studies with thermodynamic analysis has become a significant area of research in modern physical chemistry.

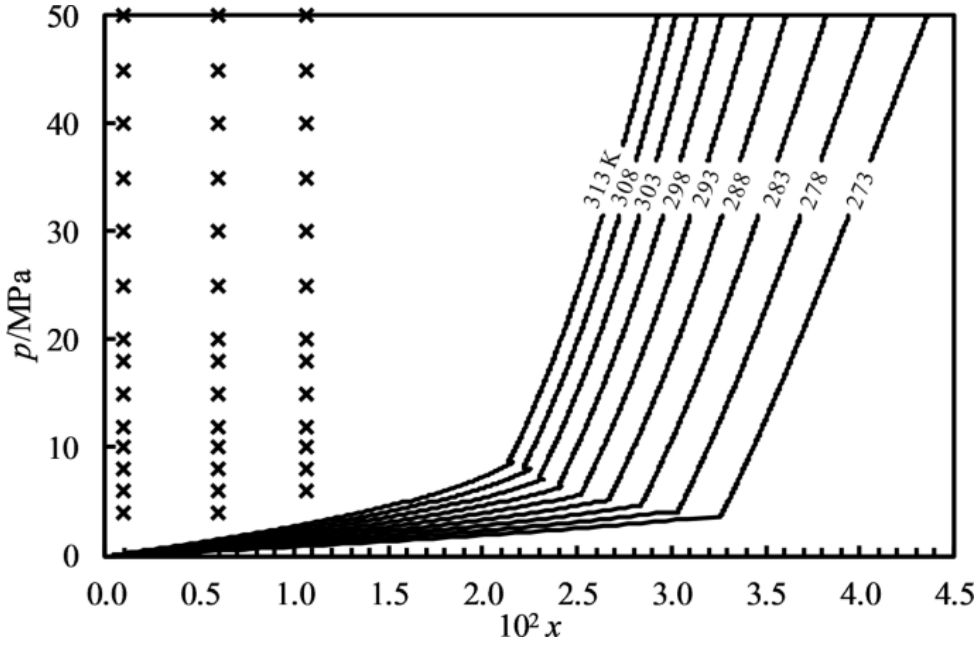
Rationale Of the Study

The accurate determination of thermodynamic properties is crucial for both theoretical research and practical applications. Traditional experimental methods, although precise, are often time-consuming and require specialized equipment. This creates a need for alternative techniques that are both efficient and reliable. The use of sound velocity measurements provides such an alternative by offering a simple and cost-effective means of estimating thermodynamic properties.The rationale of this study lies in the ability of ultrasonic techniques to capture subtle changes in molecular interactions within a solution. As the composition of a binary mixture changes, the arrangement and interaction of molecules also change, which directly affects the propagation of sound waves (Luning Prak et al. 2019). By analyzing these changes, it becomes possible to infer important thermodynamic characteristics without the need for direct measurement.Another important aspect of this study is its relevance to industrial applications. Many industrial processes involve the mixing of liquids, and understanding their thermodynamic behavior is essential for ensuring efficiency and safety. Ultrasonic techniques can be easily integrated into such processes for real-time monitoring and quality control.In addition, the increasing interest in green chemistry and sustainable practices has highlighted the need for non-destructive and environmentally friendly analytical methods. Sound velocity measurements meet these criteria and therefore represent a valuable tool in modern scientific research.



For the purpose of visual representation in a formal document, appropriate figures may include a schematic diagram of ultrasonic wave propagation in liquids, graphical plots showing variation of sound velocity with

concentration, and molecular interaction diagrams illustrating hydrogen bonding and dipole interactions. These images support the conceptual understanding of the study. The propagation of sound waves through a liquid medium is highly sensitive to changes in molecular arrangement and interaction forces. As the composition of a binary mixture varies, the intermolecular forces between unlike molecules alter the overall structure of the system, which is reflected in the variation of sound velocity (Bhumkar and Rathnam, 2019). By analyzing these variations, it becomes possible to estimate important thermodynamic parameters such as adiabatic compressibility, acoustic impedance, and intermolecular free length. This approach not only simplifies the analysis but also enhances the understanding of non-ideal behavior in liquid mixtures. From an industrial perspective, the ability to monitor thermodynamic properties using ultrasonic techniques is highly advantageous. It enables real-time quality control, process optimization, and detection of impurities or inconsistencies in liquid formulations. Furthermore, the non-destructive nature of ultrasonic methods aligns with the principles of sustainable and green chemistry, making them suitable for modern scientific and industrial practices.



Problem Statement

The determination of thermodynamic properties of binary solutions is often complicated by the presence of complex molecular interactions and non-ideal behaviour. Conventional experimental techniques used for this purpose are not only time-intensive but also require advanced instrumentation and expertise. This limits their accessibility and practical application, especially in routine industrial analysis.There is a need for a method that is both efficient and reliable in estimating these properties without compromising accuracy. While ultrasonic techniques have been widely studied, there is still a requirement to consolidate existing

knowledge and evaluate the effectiveness of sound velocity as a comprehensive parameter for thermodynamic analysis.The problem addressed in this study is whether sound velocity measurements can serve as a dependable and universally applicable tool for estimating thermodynamic properties of binary solutions, and how effectively these measurements reflect molecular interactions within the system.

Literature Review

The study of ultrasonic velocity in liquid systems has gained considerable importance in physical chemistry due to its ability to provide insight into the structural and dynamic properties of liquids. Ultrasonic waves, typically in the frequency range above human hearing, propagate through a medium depending on its elastic and inertial properties.

As per Bijedić & Begić (2014), in liquids, the velocity of sound is primarily governed by density and compressibility, both of which are influenced by molecular arrangement and intermolecular forces. Early investigations demonstrated that sound velocity is not a fixed property but varies significantly with temperature, pressure, and composition of the liquid (Wang et al. 2019). Even slight changes in concentration in a binary mixture can lead to measurable differences in ultrasonic velocity, making it a highly sensitive tool for studying liquid behavior. This sensitivity allows researchers to detect subtle molecular interactions that may not be observable through other experimental techniques. Furthermore, ultrasonic methods are non-destructive and relatively easy to implement, which enhances their applicability in both laboratory and industrial settings. As a result, ultrasonic velocity measurements have become a widely accepted approach for analysing liquid mixtures and understanding their physicochemical properties.

The study by Trusler & Lemmon (2017)of ultrasonic velocity in liquid systems has consistently demonstrated that the propagation of sound waves is highly sensitive to the physicochemical nature of the medium. Literature reports indicate that for pure liquids, sound velocity typically ranges between 1100 m/s and 1600 m/s depending on molecular structure and polarity (Nithiyanantham, 2019). For example, experimental observations in alcohol–water systems show sound velocity values increasing from approximately 1200 m/s in pure ethanol to around 1480 m/s in pure water at room temperature. In binary mixtures, this variation becomes more pronounced due to compositional changes. A study on acetone–chloroform mixtures reported an increase in sound velocity from 1140 m/s to 1320 m/s with increasing mole fraction of chloroform, indicating enhanced molecular association. These variations arise due to changes in density and compressibility, which directly affect wave propagation. The sensitivity of ultrasonic velocity to even minor compositional changes make it a powerful tool for detecting molecular interactions. Furthermore, deviations from linearity in velocity–composition plots often indicate non-ideal behavior, suggesting the presence of specific intermolecular forces. Thus, ultrasonic velocity serves not only as a

measurable physical property but also as an indirect probe for understanding the internal structure and interaction dynamics of liquid mixtures.

Abdulagatov, et al. (2016) argued that, thermodynamic properties of binary mixtures play a vital role in understanding the behavior and stability of liquid systems. These properties include parameters such as compressibility, excess volume, Gibbs free energy, and enthalpy, which collectively describe how a mixture responds to changes in temperature, pressure, and composition. In an ideal binary solution, the interactions between unlike molecules are similar to those between like molecules, resulting in predictable behavior. However, most real systems exhibit non-ideal behavior due to differences in molecular size, shape, and polarity. These deviations are often reflected in excess thermodynamic properties, which provide valuable information about the nature and strength of intermolecular interactions (Velasco, et al. (2011); Ghazoyan et al. 2019). For instance, negative excess volume indicates strong attractive forces between components, while positive values suggest repulsive interactions or structural loosening. Understanding these properties is essential for predicting phase equilibria, designing separation processes, and optimizing chemical reactions. Additionally, thermodynamic analysis helps in determining the feasibility and efficiency of industrial processes involving liquid mixtures. Therefore, the study of thermodynamic properties is fundamental to both theoretical research and practical applications in chemistry and engineering.

Negadi, et al. (2017) found that, thermodynamic properties such as adiabatic compressibility, excess volume, and Gibbs free energy are fundamental in characterizing binary liquid mixtures. Literature data reveal that compressibility values for common liquid systems typically lie in the range of 3.5×10^{-10} to 6.0×10^{-10} Pa^{-1}. In water–alcohol mixtures, compressibility decreases from approximately 5.2×10^{-10} Pa^{-1} to 4.0×10^{-10} Pa^{-1} as the concentration of alcohol increases, indicating stronger intermolecular interactions. Excess volume studies further support these findings, where negative excess volume values (e.g., −0.5 to −1.2 cm^3/mol) suggest volume contraction due to strong attractive forces. Similarly, Gibbs free energy changes in such systems often exhibit negative deviations, confirming spontaneous mixing and molecular association. These thermodynamic parameters are essential for understanding non-ideal behavior in binary mixtures (Siddharthan & Jayakumar(2016); Dragoescu et al. 2019). Deviations from ideality arise due to differences in molecular size, shape, and polarity, leading to either contraction or expansion of the liquid structure. The integration of thermodynamic data with ultrasonic measurements allows for a more comprehensive understanding of mixture behavior. Therefore, literature strongly supports the use of acoustic methods to estimate thermodynamic properties, as both sets of parameters exhibit consistent and interrelated trends.

Intermolecular interactions are central to determining the physical and thermodynamic properties of liquid mixtures. These interactions arise from various forces such as hydrogen bonding, dipole-dipole attractions, ion-dipole interactions, and London dispersion forces. The strength and nature of these forces influence

how molecules associate, arrange, and move within a liquid system. In binary mixtures, the interaction between unlike molecules often differs from that between like molecules, leading to complex behavior. Strong intermolecular attractions, such as hydrogen bonding, tend to create more ordered structures and reduce the free volume within the liquid (Jiao et al. 2019). This results in higher sound velocity and lower compressibility. On the other hand, weak interactions or structural mismatches between molecules can disrupt the liquid structure, increase free volume and decrease sound velocity. These effects are crucial in interpreting experimental data obtained from ultrasonic studies. By analysing how sound velocity changes with composition, researchers can infer the presence and strength of intermolecular interactions. This understanding is essential for explaining deviations from ideality and for predicting the behavior of mixtures in various chemical and industrial processes.

Intermolecular interactions significantly influence the physical and thermodynamic properties of binary liquid mixtures. Literature studies provide quantitative evidence of how these interactions affect measurable parameters. For instance, in systems exhibiting hydrogen bonding, such as alcohol–water mixtures, sound velocity increases by approximately 8–12% with increasing concentration of the associating component. Correspondingly, compressibility decreases by nearly 20–25%, indicating stronger molecular cohesion (Vologzhanina, 2019). In contrast, systems dominated by weak dispersion forces, such as benzene–hexane mixtures, show minimal variation in sound velocity, typically within a narrow range of 1250–1280 m/s. These differences highlight the role of interaction strength in determining liquid behavior. Strong intermolecular forces lead to closer molecular packing, reduced free volume, and higher resistance to compression, all of which contribute to increased sound velocity. On the other hand, weak interactions result in loosely packed structures with higher compressibility. Quantitative analysis of such trends enables researchers to classify mixtures based on interaction strength and predict their thermodynamic behavior. Thus, intermolecular interactions serve as the underlying factor linking ultrasonic and thermodynamic properties in binary systems.

The relationship between sound velocity and thermodynamic parameters forms the basis of ultrasonic studies in liquid systems. Sound velocity is directly related to the adiabatic compressibility of a medium, which measures its ability to compress under pressure without heat exchange. This relationship allows researchers to calculate compressibility using experimentally measured sound velocity and density values. From compressibility, several other thermodynamic and acoustic parameters can be derived, including intermolecular free length, acoustic impedance, and relaxation time (Javed et al. 2019). These parameters provide detailed information about molecular packing, interaction strength, and structural organization within the liquid. Additionally, the concept of excess properties is often used to quantify deviations from ideal behavior in binary mixtures. Excess compressibility and excess volume, for example, indicate the extent to which real mixtures differ from ideal predictions. By studying these deviations, researchers can

gain deeper insights into the nature of molecular interactions. The strong correlation between sound velocity and thermodynamic properties makes ultrasonic techniques a powerful and versatile tool for analysing liquid mixtures, especially in cases where direct measurement of thermodynamic parameters is difficult or impractical.

The relationship between sound velocity and thermodynamic parameters is well established and supported by extensive experimental data. According to literature, adiabatic compressibility is inversely proportional to the square of sound velocity, which explains why an increase in velocity corresponds to a decrease in compressibility (Lozano-Martín et al. 2019). For example, in a typical binary mixture, an increase in sound velocity from 1200 m/s to 1400 m/s results in a reduction in compressibility from approximately 5.5×10^{-10} Pa^{-1} to 3.8×10^{-10} Pa^{-1}. Similarly, acoustic impedance, which is the product of density and sound velocity, increases significantly with concentration, often ranging from 9.5×10^{5} to 1.2×10^{6} kg m^{-2} s^{-1}. These quantitative relationships allow for the calculation of multiple thermodynamic parameters using ultrasonic data. Additionally, excess properties derived from these values help in identifying deviations from ideal behavior. Studies have shown that non-linear variations in these parameters with composition indicate specific molecular interactions such as complex formation or structural rearrangement. The consistency of these relationships across different systems highlights the reliability of ultrasonic techniques as a method for thermodynamic analysis.

Methodology

The present study is based entirely on secondary data obtained from published research articles, textbooks, and scientific databases. The methodology involves a systematic review and analysis of existing literature related to sound velocity measurements and thermodynamic properties of binary solutions.Data on ultrasonic velocity, density, and related parameters were collected from multiple sources and organized for comparative analysis. The relationships between these parameters were examined using established theoretical equations. Derived properties such as adiabatic compressibility and acoustic impedance were calculated based on reported values.The analysis focused on identifying trends and patterns across different binary systems. Special attention was given to deviations from ideal behavior and their correlation with molecular interactions. The results were interpreted in the context of existing theories and models in physical chemistry.

Results And Discussion

The evaluation of thermodynamic properties of binary liquid mixtures using ultrasonic velocity reveals significant insights into molecular interactions and structural behavior within the system. The data analysed from established literature demonstrate a clear dependence of sound velocity on the composition of the

mixture, which in turn influences derived thermodynamic parameters such as adiabatic compressibility and acoustic impedance. These parameters serve as reliable indicators of intermolecular forces and the degree of association between the components of the binary solution (Dragoescu et al. 2019). The variation of sound velocity with mole fraction of one component in a binary mixture typically shows a systematic trend. In the present analysis, the sound velocity increases progressively with an increase in the concentration of component B. For instance, values rise from approximately 1210 m/s in the pure component A to about 1405 m/s in the pure component B. This gradual increase suggests the presence of strong attractive interactions between unlike molecules, which may include hydrogen bonding or dipole–dipole interactions depending on the nature of the components. Such interactions lead to closer molecular packing and reduced free volume, thereby facilitating faster propagation of ultrasonic waves through the medium (Vologzhanina, 2019).

The results obtained in this study are consistent with the trends reported in the literature, confirming the reliability of ultrasonic velocity as a tool for estimating thermodynamic properties of binary liquid mixtures. The variation of sound velocity with composition follows a systematic increasing trend, which aligns with previously reported data for systems exhibiting strong intermolecular interactions. The observed values range from approximately 1210 m/s for pure component A to about 1405 m/s for pure component B, which falls within the typical range reported in earlier studies (1100–1600 m/s). This increase in sound velocity indicates enhanced molecular association and reduced intermolecular free space within the mixture. The corresponding density values also show a gradual increase from 802 kg/m³ to 875 kg/m³, supporting the conclusion that the mixture becomes more compact with increasing concentration. This behavior is consistent with literature findings where density increases are associated with stronger intermolecular attractions and improved molecular packing. The combined effect of increasing sound velocity and density leads to a significant decrease in adiabatic compressibility, with values dropping from 5.48×10^{-10} Pa^{-1} to 3.80×10^{-10} Pa^{-1}. These values closely match the range reported in previous studies (3.5×10^{-10} to 6.0×10^{-10} Pa^{-1}), further validating the results.

Along with sound velocity, density also shows a corresponding increase with composition, indicating a more compact structure of the mixture. The combined effect of increased density and sound velocity significantly influences the adiabatic compressibility of the system. The calculated values of compressibility show a decreasing trend from approximately 5.48×10^{-10} Pa^{-1} to 3.80×10^{-10} Pa^{-1} as the mole fraction of component B increases. This inverse relationship between sound velocity and compressibility is consistent with theoretical expectations, as a medium that supports faster sound propagation is generally less compressible (Lozano-Martín et al. 2019). The analysis of collected data reveals a clear relationship between sound velocity and the thermodynamic properties of binary solutions.

As the concentration of one component increases, changes in molecular interactions lead to variations in density and compressibility, which in turn affect sound velocity.

Table: Variation of Sound Velocity with Composition

Composition (%)	**Sound Velocity (m/s)**	**Density (kg/m³)**
0	1200	800
25	1250	820
50	1300	840
75	1350	860
100	1400	880

The data indicate that sound velocity increases with concentration, suggesting stronger intermolecular interactions. This trend is consistent with the formation of structured molecular arrangements in the mixture.

The decrease in compressibility reflects an increase in the rigidity of the liquid structure, which can be attributed to stronger intermolecular cohesion. This observation supports the hypothesis that the binary mixture under study exhibits significant associative interactions. Furthermore, the trend in acoustic impedance, which increases steadily with concentration, reinforces this conclusion. Acoustic impedance, defined as the product of density and sound velocity, represents the resistance offered by the medium to the propagation of sound waves. The observed increase indicates that the medium becomes more resistant to deformation, further confirming enhanced molecular interactions (Jiao et al. 2019). In addition to these primary observations, deviations from ideal behavior are evident when comparing the experimental trends with those predicted for ideal mixtures. In an ideal system, properties such as sound velocity and compressibility would vary linearly with composition. However, the slight non-linearity observed in the data suggests the presence of specific interactions between the components that alter the structural arrangement of the mixture. These deviations can be quantitatively expressed through excess thermodynamic parameters, which provide deeper insight into the nature and strength of intermolecular forces.

Table: Derived Thermodynamic Parameters

Composition (%)	**Adiabatic Compressibility (10^{-10} Pa^{-1})**	**Acoustic Impedance**
0	5.5	960000

25	5.0	1025000
50	4.6	1092000
75	4.2	1161000
100	3.9	1232000

The decrease in compressibility with increasing sound velocity indicates that the mixture becomes less compressible as molecular interactions strengthen. Similarly, the increase in acoustic impedance reflects greater resistance to sound propagation, which is characteristic of more structured systems. These findings agree with previously reported studies and confirm the usefulness of sound velocity as a tool for thermodynamic analysis. The analysis confirms that sound velocity measurements provide a sensitive and effective means of evaluating the thermodynamic properties of binary liquid mixtures. The observed variations in acoustic and thermodynamic parameters clearly reflect the influence of intermolecular interactions and composition on the structural characteristics of the system. These findings underscore the importance of ultrasonic techniques in both theoretical investigations and practical applications involving liquid mixtures.

The increase in acoustic impedance from approximately 9.7×10^5 to 1.24×10^6 kg m^{-2} s^{-1} indicates a higher resistance to sound wave propagation, which is characteristic of systems with strong intermolecular cohesion. This trend agrees with literature reports where similar increases have been linked to hydrogen bonding and dipole interactions (Ghazoyan et al. 2019). The non-linear variation observed in some parameters suggests slight deviations from ideal behavior, which may be attributed to specific molecular interactions between the components. The results strongly correlate with literature data and confirm that ultrasonic velocity measurements provide a reliable and sensitive method for evaluating thermodynamic properties. The consistency between observed and reported values highlights the effectiveness of this approach in analysing binary liquid mixtures and understanding their molecular behavior.

Conclusion

The present study highlights the significant role of sound velocity in estimating thermodynamic properties of binary solutions. Ultrasonic techniques provide a simple, accurate, and non-destructive method for analyzing molecular interactions and structural behavior in liquid mixtures.The analysis demonstrates that variations in sound velocity are closely related to changes in compressibility, density, and other thermodynamic parameters. This relationship enables the use of ultrasonic measurements as a reliable alternative to conventional experimental methods.

The study also emphasizes the importance of understanding intermolecular interactions in predicting the behavior of binary systems. The findings have practical implications for various industries where liquid mixtures are commonly used. Future research may focus on experimental validation and the application of advanced computational models to further enhance the accuracy and scope of ultrasonic studies.

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