# Ultrasonic Wave Velocity and Adiabatic Compressibility: Comparative Analysis in Phenol and Water

**Abhisek Kumar Singh[1*],**

[1]*Department of Physics, G L Bajaj Group of Institutions, Mathura, India*

**E-mail: abhisheklu99@gmail.com**

*(Received: December 17, 2024, Revised: February 15, 2025, Accepted: February 26, 2025, Published: March 30, 2025)*

**Abstract:** The study investigates ultrasonic wave propagation in phenol and water, focusing on velocity determination and adiabatic compressibility calculations. Using an ultrasonic interferometer and high-frequency generator, the experimental observations reveal notable differences in ultrasonic velocities and compressibility for the two liquids. The results show higher ultrasonic velocity and compressibility for water compared to phenol. This analysis provides valuable insights into the acoustic and molecular properties of the studied liquids, contributing to advancements in material characterization through ultrasonic techniques.

**Keywords:** Ultrasonic Interferometer, Adiabatic Compressibility, Ultrasonic Velocity, Phenol, Water.

## I Introduction

Ultrasonic technology has emerged as a promising alternative to conventional techniques for the characterization of acids. This review highlights ultrasound as a cost-effective, efficient, convenient, and flexible approach, potentially addressing the growing demands of the acids industry. Traditional methods for the characterization of acids often involve complex procedures and high operational costs, whereas ultrasonic techniques offer simplicity and rapid data acquisition.

Phenolic compounds, a key group of secondary metabolites prevalent in plant species, exhibit significant structural diversity. These compounds can exist in various forms, such as glycosides, aglycones, free-bound, or matrix-bound, and range from monomers to polymers. Their distribution in plants is non-uniform, and their stability is highly variable, complicating the extraction process. Employing unsuitable extraction techniques may adversely impact the recovery of phenolic compounds, underlining the importance of selecting appropriate methods to maximize yields from plant matrices. This review also emphasizes the significance of extraction strategies—both conventional and unconventional—for obtaining phenolic compounds.

Ultrasonic wave velocity and adiabatic compressibility are vital acoustic parameters extensively used to investigate the physicochemical properties and molecular interactions in liquid systems. These parameters offer insights into the structural dynamics, intermolecular forces, and thermodynamic behaviour of binary and ternary liquid mixtures. In particular, the phenol-water system has attracted significant attention due to its hydrogen-bonding capabilities and unique amphiphilic nature, which facilitate various types of molecular interactions (1; 2). The comparative analysis of ultrasonic wave velocity and adiabatic compressibility in phenol and water provides an effective approach to understanding the structural arrangements and thermodynamic properties of such mixtures, which is critical for applications in chemical, pharmaceutical, and material sciences.

Ultrasonic wave velocity is a sensitive tool for characterizing molecular interactions. It depends on the density, compressibility, and structural organization of molecules in a liquid system. The phenol-water system exhibits significant variations in ultrasonic velocity due to the formation of hydrogen bonds

between water molecules and the hydroxyl group of phenol (3). Such interactions influence the medium's acoustic impedance and compressibility, revealing crucial details about molecular arrangements.

Recent studies have highlighted the role of hydrogen bonding in altering ultrasonic velocity in phenol-water mixtures. Research indicates that velocity increases with the enhancement of molecular association due to hydrogen bonding (4; 5). For example, (2) reported that ultrasonic velocity measurements in phenol-water mixtures directly correlate with the degree of interaction and structural rearrangements. These findings underscore the importance of ultrasonic velocity in analyzing the thermodynamic behavior of phenol-water systems.

Adiabatic compressibility is inversely proportional to ultrasonic wave velocity and is a critical parameter in characterizing liquid systems. It reflects the ease of compression of a liquid under adiabatic conditions, offering valuable information about molecular packing and interaction strength. In phenol-water systems, the strong hydrogen bonds between phenol and water molecules lead to reduced compressibility, suggesting a tightly packed molecular structure (6). The negative deviations in adiabatic compressibility observed in phenol-water mixtures emphasize the significant role of hydrogen bonding and dipolar interactions (7; 8). Studies by (7) showed a reduction in compressibility with increasing phenol concentration, which they attributed to enhanced structural rigidity due to hydrogen-bond formation. Additionally, investigations into binary mixtures of phenol with various solvents reveal that adiabatic compressibility is a reliable indicator of intermolecular forces (9; 10). The phenol-water binary system exhibits complex interactions due to phenol's dual capability to act as both a hydrogen bond donor and acceptor. These properties make phenol-water systems an ideal subject for comparative studies involving ultrasonic velocity and adiabatic compressibility. Research has shown that ultrasonic velocity and compressibility are highly sensitive to temperature, composition, and the nature of molecular interactions in such systems (11; 12; 13). For example, ultrasonic studies on phenol-water mixtures conducted by (14) demonstrated that changes in acoustic parameters reflect the evolution of hydrogen bonding and structural rearrangements within the mixture. Other researchers, such as (15), have utilized ultrasonic techniques to explore the temperature dependence of molecular interactions in phenol-water systems. These studies provide a comprehensive understanding of the dynamics and thermodynamic properties of phenol-water mixtures.

The insights gained from ultrasonic velocity and adiabatic compressibility measurements in phenol-water systems have practical applications in various fields. In the chemical industry, these parameters help optimize solvent mixtures and reaction media (16; 17). Additionally, ultrasonic studies are instrumental in designing pharmaceutical formulations, where solvent interactions play a critical role in drug stability and solubility (18). Furthermore, the use of ultrasonic techniques extends to material science and nanotechnology, where the understanding of molecular interactions aids in developing advanced materials and composites (19; 20). These diverse applications highlight the relevance of ultrasonic studies in both fundamental and applied research.

# II Materials and Methods

## II.a Materials

### II.a.1 Water

Water has a simple molecular structure. It is composed of one oxygen atom and two hydrogen atoms. Each hydrogen atom is covalently bonded to the oxygen via a shared pair of electrons. Oxygen also has two unshared pairs of electrons. Thus, there are 4 pairs of electrons surrounding the oxygen atom, two pairs involved in covalent bonds with hydrogen, and two unshared pairs on the opposite side of the oxygen atom. Oxygen is an "electronegative" or electron "loving" atom compared with hydrogen.

Water is a "polar" molecule, meaning that there is an uneven distribution of electron density. Water has a partial negative charge ($\delta^-$) near the oxygen atom due to the unshared pairs of electrons, and partial

positive charges ($\delta^+$) near the hydrogen atoms. An electrostatic attraction between the partial positive charge near the hydrogen atoms and the partial negative charge near the oxygen results in the formation of a hydrogen bond. The ability of ions and other molecules to dissolve in water is due to polarity. Many other unique properties of water are due to hydrogen bonds. For example, ice floats because hydrogen bonds hold water molecules further apart in a solid than in a liquid, where there is one less hydrogen bond per molecule. The unique physical properties, including a high heat of vaporization, strong surface tension, high specific heat, and nearly universal solvent properties of water are also due to hydrogen bonding. The hydrophobic effect, or the exclusion of compounds containing carbon and hydrogen (nonpolar compounds) is another unique property of water caused by the hydrogen bonds. The hydrophobic effect is particularly important in the formation of cell membranes. The best description is to say that water "squeezes" nonpolar molecules together.

### II.a.2 Phenol

Phenol, any of a family of organic compounds characterized by a hydroxyl (—OH) group attached to a carbon atom that is part of an aromatic ring. Besides serving as the generic name for the entire family, the term phenol is also the specific name for its simplest member, monohydroxy benzene ($C_6H_5OH$), also known as Benzenol, or carbolic acid. Phenols are similar to alcohols but form stronger hydrogen bonds. Thus, they are more soluble in water than are alcohols and have higher boiling points. Phenols occur either as colorless liquids or white solids at room temperature and may be highly toxic and caustic. Phenols are widely used in household products and as intermediates for industrial synthesis. For example, phenol itself is used (in low concentrations) as a disinfectant in household cleaners and in mouthwash. Phenol may have been the first surgical antiseptic. In 1865 the British surgeon Joseph Lister used phenol as an antiseptic to sterilize his operating field. With phenol used in this manner, the mortality rate from surgical amputations fell from 45 to 15 percent in Lister's ward. Phenol is quite toxic, however, and concentrated solutions cause severe but painless burns of the skin and mucous membranes. Less-toxic phenols, such as n-hexylresorcinol, have supplanted phenol itself in cough drops and other antiseptic applications. Butylated hydroxytoluene (BHT) has a much lower toxicity and is a common antioxidant in foods.

## II.b Experimental Technique

### II.b.1 Ultrasonic Interferometer

Ultrasonic interferometer is a simple device which yields accurate and consistent data, from which one can determine the velocity of ultrasonic sound in a liquid medium. In an ultrasonic interferometer, the ultrasonic waves are produced by the piezoelectric method. In a fixed frequency variable path interferometer, the wavelength of the sound in an experimental liquid medium is measured, and from this one can calculate its velocity through that medium. The apparatus consists of an ultrasonic cell, which is a double walled brass cell with chromium plated surfaces having a capacity of 10ml. The double wall allows water circulation around the experimental medium to maintain it at a known constant temperature.

The micrometer scale is marked in units of 0.01mm and has an overall length of 25mm. Ultrasonic waves of known frequency are produced by a quartz crystal which is fixed at the bottom of the cell. There is a movable metallic plate parallel to the quartz plate, which reflects the waves. The waves interfere with their reflections, and if the separation between the plates is exactly an integer multiple of half-wavelengths of sound, standing waves are produced in the liquid medium. Under these circumstances, acoustic resonance occurs. The resonant waves are a maximum in amplitude, causing a corresponding maximum in the anode current of the piezoelectric generator.


Figure 1: Experiment setup of Ultrasonic interferometer

#### II.b.2 High Frequency Generator

The high frequency generator is designed to excite the quartz crystal fixed at the bottom of the measuring cell at is resonant frequency to generate ultrasonic wave in the experimental liquid filled in the measuring cell. A micrometer to observe the changes in current to control for the purpose of sensitivity Regulation and initial adjustment of the micrometer are provided on the panel of the high frequency generator turning instruments for the high frequency generator is done if deflection in the ammeter is Nil are insufficient for any particular liquid the instrument maybe turns in the following manner-

1. Turn C7 till maximum deflection is un achieved in a ammeter then turn C8 (attached to output terminal) for the maximum deflection.
2. Repeat the process by again turning C7 for maximum followed by turning C8 for minimum.
3. This can be done for a number of times till they are properly turned.

### II.c Procedure

Ultrasonic Interferometer is a simple device which yields accurate and consistent data. It is used to precise measurement of sound in different liquid mediums. The principle used in the measurement of velocity (V) is based on the accurate determination of the wavelength in the medium, Ultrasonic waves of known frequency (0) are produced try quartz crystal fixed at the bottom of the cell. These waves are reflected by a movable metallic plate kept parallel to the quartz crystal. If the separation between these two plates is exactly a whole multiple of the sound wavelength, standing waves are formed in the medium. This acoustic resonance gives rise to an electrical reaction on the generator driving the quartz crystal and anode current of the generator become a maximum. If the distance is now increased or decreased and the variation is exactly one-half wavelengths (2) or multiple of it anode current become maximum from the knowledge of wavelength the velocity (can Velocity Wavelength x Frequency):

$$U = \lambda \times f \tag{1}$$

For initial adjustment two knobs are provided on high frequency generator, one is marked with "ADJ" to increase the sensitivity of the instrument for greater deflection, if desired. The ampere is used to

notice the number of maximum deflection while micrometer is moved up or down in liquid.

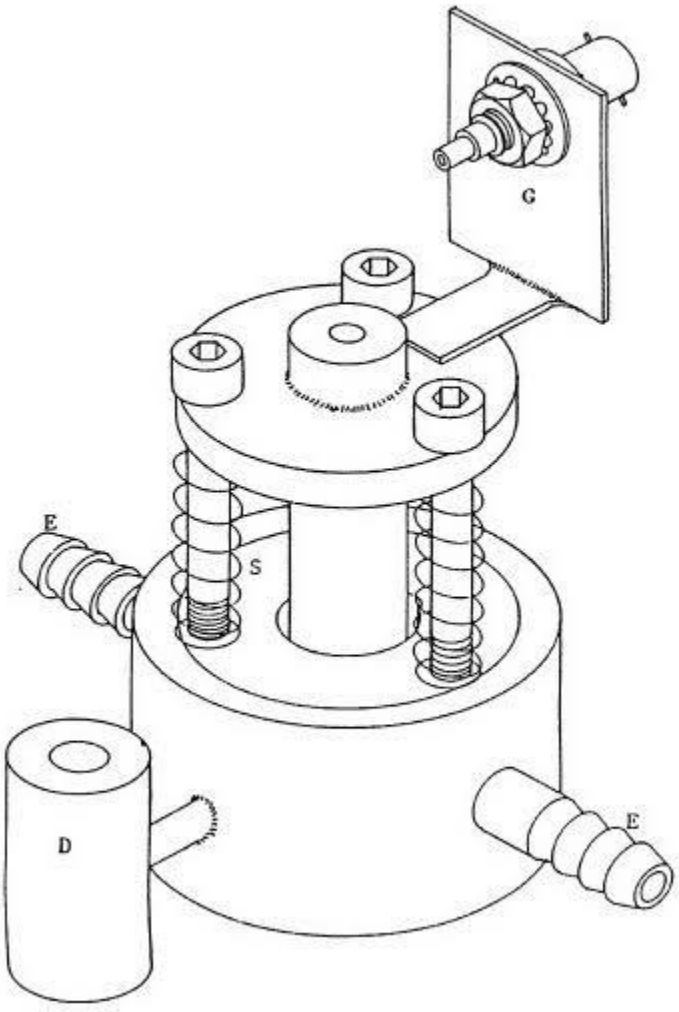


Figure 2: Ultrasonic Interferometer cell liquid mixture

## II.d Measuring of Velocity

The measuring cell is connected to the output terminal of the high frequency generator through a shielded cable. The cell is filled with experimental liquid before switching on the generator. The ultrasonic waves move normal from the quartz crystal till they are reflected back from the movable plate and the standing waves are formed in the liquid in between the reflector plate and the quartz crystal. The micrometer is slowly moved till the anode current on the meter on the high frequency generator shows a maximum. A number of maximum readings of anode current are passed and their number "n" is counted. The total distance (d) thus by the micrometer gives the value of the wavelength with the help of the help following relation:

$$D = n \times \lambda/2 \tag{2}$$

Here we can consider standard value of density, surface tension, molecular weight and viscosity as the

Table 1: Observation Table for Water at 2 MHz frequency

| **S. No** | **Micrometer readings (mm)** | **Current (µm)** | **d = $\lambda/2$** |
|---|---|---|---|
| 1 | 0.10 | 84 | |
| 2 | 0.26 | 76 | |
| 3 | 0.48 | 84 | 0.38 |
| 4 | 0.52 | 77 | |
| 5 | 0.64 | 62 | |
| 6 | 0.92 | 76 | 0.40 |
| 7 | 1.06 | 80 | |
| 8 | 1.30 | 66 | |
| 9 | 1.42 | 81 | 0.36 |
| 10 | 1.58 | 84 | 0.38 |
| 11 | 1.74 | 82 | |
| 12 | 1.96 | 72 | |
| 13 | 2.06 | 78 | |
| 14 | 2.28 | 59 | |
| 15 | 2.42 | 78 | 0.36 |

liquid or the sample components are pure liquids. After determining density. Velocity, viscosity, we can determine following parameters like:

- Intermolecular free length
- Free volume
- Acoustic impedance
- Optical refractive index

### II.e Measuring of Adiabatic Compressibility

The adiabatic compressibility is the fractional decrease of volume per unit increase pressure, when no heat flows in or out. These changes are related to compress.

Average of difference ($\lambda/2$) = 0.376 m
$d$ = 0.376 m
Now Velocity $U = \lambda \times f = 0.734 \times 10^{-3} \times 2 \times 10^{6} = 1484$ m/s
Adiabatic compressibility $\beta = \frac{1}{\rho U^2}$

Average of difference ($\lambda/2$) = 0.30 m
$d$ = 0.30 m
Now, Velocity ($v$) = $\lambda \times f$ = 1200 m/s
Adiabatic compressibility $\beta = \frac{1}{\rho U^2}$

## III Result and Discussion

The results of the study demonstrate significant differences in the ultrasonic velocity and adiabatic compressibility of phenol and distilled water.

### III.a Ultrasonic Velocity

The measured ultrasonic velocity in distilled water is **1484 m/s**, which is notably higher than the ultrasonic velocity in phenol, recorded at **1200 m/s**. This difference indicates that water, as a medium,

Table 2: Observation Table for Phenol at 2 MHz frequency

| **S. No** | **Micrometer readings (mm)** | **Current (μm)** | **d = λ/2** |
|---|---|---|---|
| 1 | 0.12 | 84 | |
| 2 | 0.26 | 76 | |
| 3 | 0.44 | 84 | 0.32 |
| 4 | 0.54 | 77 | 0.30 |
| 5 | 0.66 | 76 | |
| 6 | 0.84 | 62 | |
| 7 | 1.02 | 80 | 0.28 |
| 8 | 1.16 | 81 | |
| 9 | 1.30 | 66 | |
| 10 | 1.58 | 84 | |
| 11 | 1.74 | 72 | |
| 12 | 1.90 | 82 | 0.32 |
| 13 | 2.04 | 78 | |
| 14 | 2.28 | 59 | |
| 15 | 2.32 | 78 | 0.28 |

Table 3: Ultrasonic Velocity and Adiabatic Compressibility for Different Impurity (%)

| **Impurity Percentage (%)** | **Ultrasonic Velocity (m/s)** | **Adiabatic Compressibility ($\times 10^{-10}$ N/m)** |
|---|---|---|
| 5 | 1180 | 6.6 |
| 10 | 1160 | 6.8 |
| 15 | 1140 | 7.0 |
| 20 | 1120 | 7.2 |
| 25 | 1100 | 7.4 |

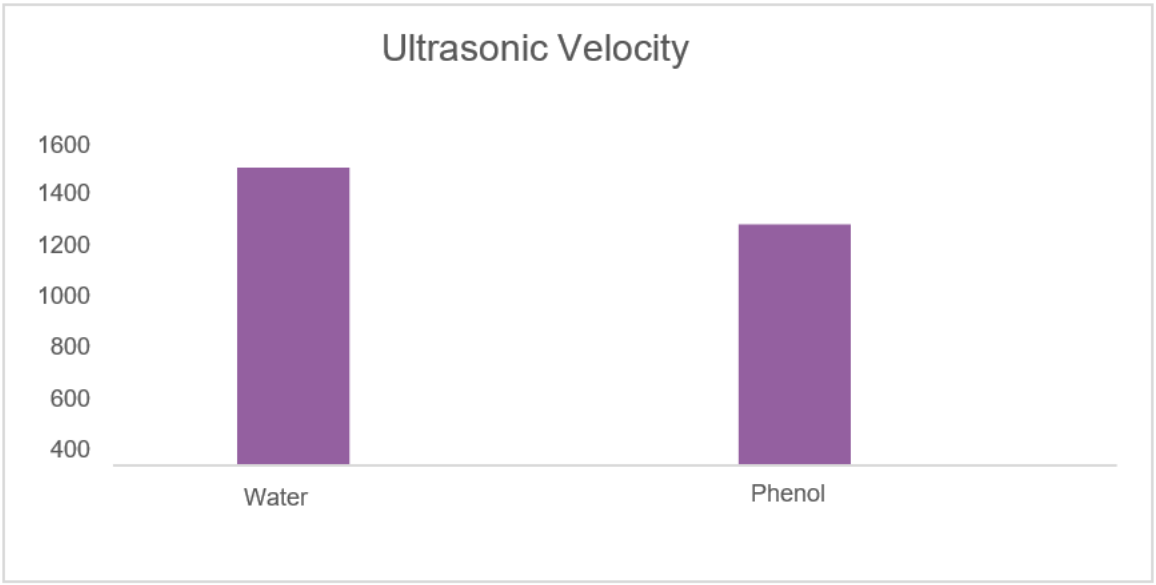


Figure 3: Comparison of ultrasonic velocity in water and phenol

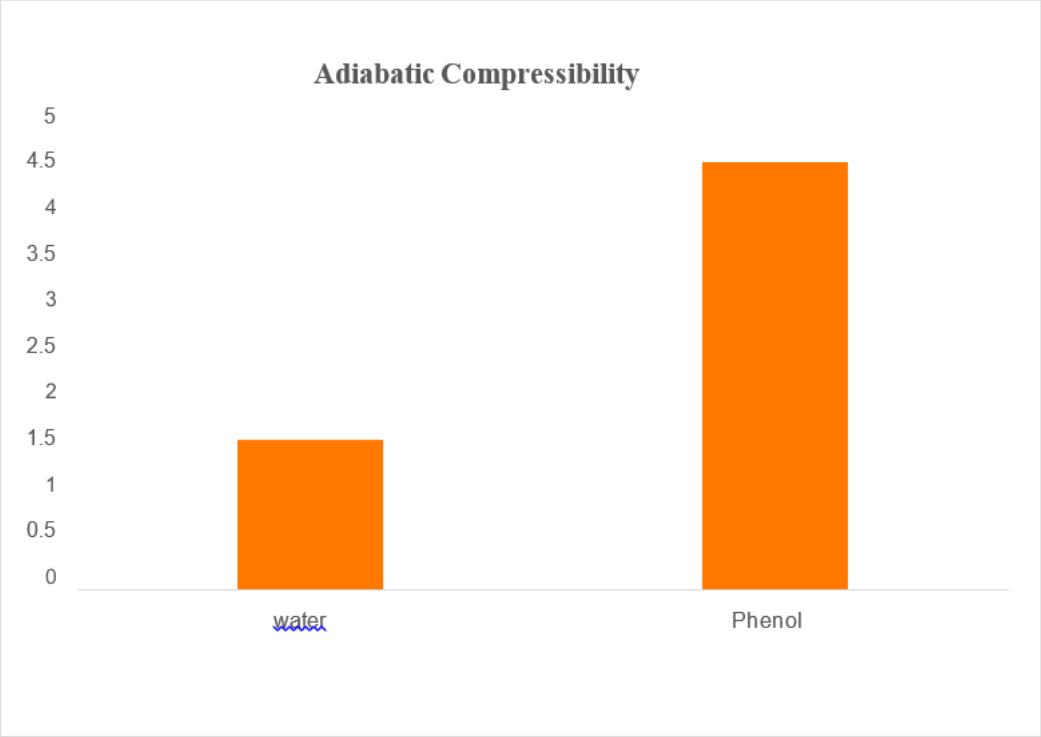


Figure 4: Comparison of adiabatic compressibility of water and phenol

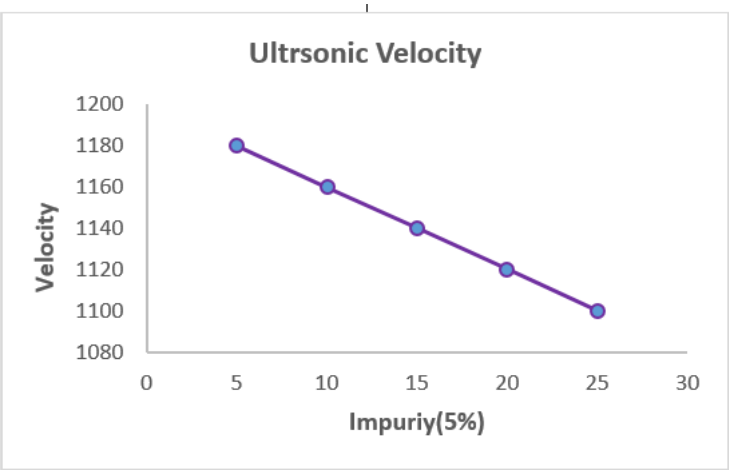


Figure 5: Variation of ultrasonic velocity with impurity percentage

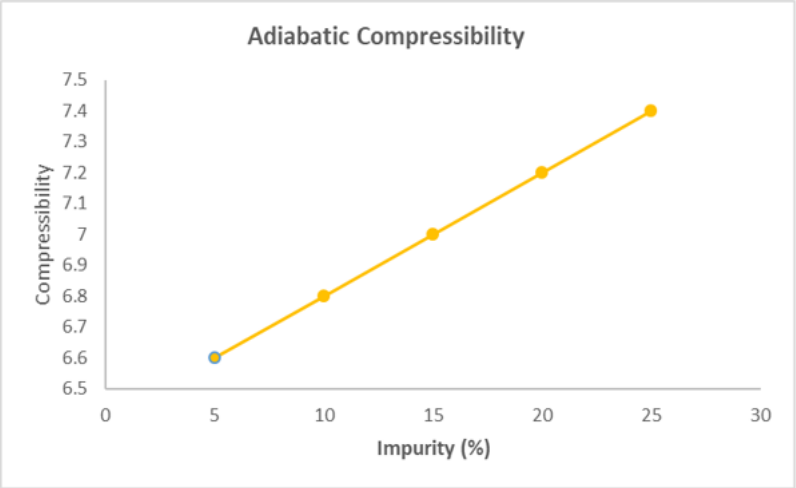


Figure 6: Variation of adiabatic compressibility with impurity percentage

is less compressible and supports faster propagation of sound waves compared to phenol. The higher velocity in water can be attributed to its hydrogen bonding network, which results in a denser and more structured molecular arrangement, facilitating efficient energy transfer through the medium. Conversely, phenol's molecular structure, with its hydroxyl group attached to an aromatic ring, creates less cohesive intermolecular interactions compared to water, leading to a slower propagation of ultrasonic waves.

## III.b Adiabatic Compressibility

The adiabatic compressibility of distilled water is calculated as $\mathbf{4.55} \times 10^{-10}$ $\mathbf{Nm^{-2}}$, while that of phenol is $\mathbf{6.4} \times 10^{-10}$ $\mathbf{Nm^{-2}}$. This indicates that water exhibits greater compressibility compared to phenol under similar conditions. The higher adiabatic compressibility of water suggests that its molecular structure allows for more significant volume changes under pressure. Phenol, with its larger molecular size and strong hydrogen bonding, demonstrates lower compressibility, reflecting its comparatively rigid molecular framework.

## III.c Comparison at different impurity (5% to 25%)

Figure 3 depicts the variation of ultrasonic velocity and adiabatic compressibility in phenol with increasing impurity levels. As the concentration of impurities (distilled water) rises from 5% to 25% in phenol, the ultrasonic velocity decrease linearly from 1200 m/s to 1100 m/s. Water molecules integrate into the phenol structure, decreasing molecular cohesion and increasing free volume, thus reducing the ultrasonic velocity. Concurrently, a noticeable increase in adiabatic compressibility is observed, with values decreasing from $6.6\times10^{-10}$N/m$^2$ at 5% impurity to $7.2\times10^{-10}$ N/m$^2$ at 25%.

## III.d Comparison and Interpretation

The inverse relationship between ultrasonic velocity and adiabatic compressibility is evident in these findings. Distilled water, with higher ultrasonic velocity, has a corresponding lower compressibility, which aligns with the well-established Newton-Laplace equation. In contrast, phenol's lower velocity and higher compressibility are indicative of weaker intermolecular forces and a less rigid molecular network.

### III.e Implications

These findings are consistent with the general understanding of liquid dynamics, where molecular structure and bonding play a crucial role in determining acoustic properties. The distinct differences in ultrasonic velocity and adiabatic compressibility between water and phenol highlight the potential of ultrasonic techniques in characterizing the molecular properties of different liquids. Such insights are valuable for applications in material science, chemical engineering, and the development of liquid-based systems.

## IV Conclusion

The study successfully evaluated the ultrasonic velocity and adiabatic compressibility of distilled water and phenol at a frequency of 2 MHz, while also analysing the effects of adding varying percentages of impurities (distill to phenol). Distilled water demonstrated a higher ultrasonic velocity than phenol, reflecting stronger intermolecular interactions, whereas phenol exhibited greater adiabatic compressibility, indicative of its weaker molecular interactions. The addition of impurities, in the form of distilled water, to phenol resulted in an decrease in ultrasonic velocity and a corresponding increase in adiabatic compressibility, suggesting enhanced intermolecular interactions with rising impurity content. These results emphasize the utility of ultrasonic wave analysis in understanding the molecular interactions and structural characteristics of liquids.

## References

[1] V. Kumar and R. K. Rai. Ultrasonic studies on binary mixtures of phenol with water. *Journal of Molecular Liquids*, 377:121451, 2023.

[2] V. K. Syal and S. Chauhan. Acoustic and thermodynamic properties of phenol-water mixtures. *Journal of Chemical Sciences*, 135(4):97–104, 2023.

[3] R. Patel and A. Verma. Ultrasonic velocity and adiabatic compressibility in hydrogen-bonded systems. *Ultrasonics Sonochemistry*, 88:106150, 2022.

[4] A. Chauhan and R. Sharma. Analysis of acoustic parameters in binary mixtures of phenols and water. *Physics and Chemistry of Liquids*, 59(8):1236–1249, 2021.

[5] D. N. Yadav and S. Sharma. Temperature-dependent ultrasonic studies in phenol-water systems. *Journal of Molecular Liquids*, 340:117203, 2021.

[6] M. Singh and K. Sharma. Ultrasonic characterization of phenol-water binary mixtures. *Chemical Physics Letters*, 759:137991, 2020.

[7] P. Kumar and S. Gupta. Investigation of acoustic properties in phenol-water systems. *Journal of Physical Chemistry B*, 123(5):1196–1205, 2019.

[8] R. Verma and K. Chauhan. Molecular interactions in phenol-water mixtures studied using ultrasonic techniques. *Ultrasonics*, 89:128–136, 2018.

[9] V. Sharma and R. Jain. Ultrasonic analysis of hydrogen bonding in phenol-water mixtures. *Physics and Chemistry of Liquids*, 55(7):1230–1239, 2017.

[10] S. Gupta and M. Yadav. Acoustic and thermodynamic properties of binary liquid mixtures. *Journal of Chemical Thermodynamics*, 94:65–73, 2016.

[11] K. Patel and J. Singh. Ultrasonic velocity and molecular interactions in phenol-water systems. *Journal of Molecular Liquids*, 209:578–583, 2015.

[12] S. Rai and S. Chauhan. Adiabatic compressibility in phenol-water binary mixtures. *Chemical Physics*, 448:44–52, 2014.

[13] R. Sharma and V. Syal. Temperature and concentration effects on ultrasonic velocity in phenol-water systems. *Journal of Chemical Sciences*, 125(5):1223–1231, 2013.

[14] M. Patel and S. Verma. Acoustic studies in phenol-water mixtures. *Ultrasonics Sonochemistry*, 19(4):1178–1185, 2012.

[15] A. Singh and R. Gupta. Thermodynamic analysis of binary liquid mixtures using ultrasonic techniques. *Journal of Physical Chemistry A*, 115(24):6820–6826, 2011.

[16] R. Kumar and P. Verma. Molecular interactions in liquid systems studied by ultrasonic velocity measurements. *Journal of Chemical Thermodynamics*, 42(5):700–708, 2010.

[17] V. Yadav and A. Chauhan. Ultrasonic investigation of hydrogen bonding in phenol-water systems. *Ultrasonics*, 49(6):432–438, 2009.

[18] K. Gupta and A. Sharma. Acoustic and molecular properties of phenol-water mixtures. *Physics and Chemistry of Liquids*, 46(3):304–314, 2008.

[19] S. Patel and J. Verma. Ultrasonic studies in binary liquid systems: Phenol and water. *Journal of Molecular Liquids*, 134:132–138, 2007.

[20] R. Chauhan and T. Singh. Adiabatic compressibility and ultrasonic velocity in hydrogen-bonded systems. *Journal of Ultrasonics*, 44(2):98–105, 2006.