Exploring the Anomalous Temperature Dependence of the Speed of Sound in water: An Undergraduate Ultrasonic Interferometry Experiment

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Abstract

A pedagogical approach through which students can investigate the anomalous behaviour of water through the temperature dependence of ultrasonic velocity using a simple ultrasonic interferometer experiment has been reported in the article. We examine the variation of the speed of sound in water and compare it with that in a commercially available groundnut oil. The measurements were performed using an ultrasonic interferometer operating at 1 MHz over a temperature range of 30–70 °C.

The speed of sound in groundnut oil exhibits linear decrease with increase in temperature, a trend commonly observed in liquids. In contrast, water exhibits a non-monotonic behaviour: the speed of sound initially increases with temperature, reaches a maximum, and subsequently decreases with further increase in temperature. This characteristic response reflects the competing effects of density and bulk modulus, governed by water's extensive hydrogen-bonding network.

The study not only highlights a fundamental acoustic property of liquids but also offers an engaging experiment for undergraduate students to explore water's anomalous behaviour and the molecular forces responsible for its unique characteristics.

1. Introduction

This study focuses on measurement of speed of sound, a property intrinsically linked to a liquid's density (ρ) and bulk modulus (K) through the fundamental relation $v=\sqrt{\frac{K}{\rho}}$. Both quantities K and ρ are temperature-dependent, their independent variations may lead to linear or non-monotonic variation in the speed of sound as a function of temperature. The bulk modulus of liquids is governed by molecular structure and interactions.

We have studied speed of sound in water and a groundnut oil, as a function of temperature. We have established their different acoustic behaviours. It is a practical and easy way to understand and appreciate anomalous behaviour in water.

2. Experimental

The speed of sound in liquid samples is measured using an ultrasonic interferometer procured from Optiregion pvt ltd. The schematic diagram of experimental set up used for carrying out measurements is provided in Figure 1. In this set up, ultrasonic waves are generated using Quartz crystal at the bottom of a cylindrical cell of ultrasonic interferometer. The waves are reflected by a movable metallic reflector fitted in the cell, parallel to the crystal. The superposition of the incident waves of 1 MHz, gets reflected from the surface and results in standing wave. The movable reflector is attached with a screw gauge of 0.01 mm least count to facilitate the measurement of a position. The acoustic resonance is seen by electrical reaction on a generator driving the quartz crystal and results in increase in anode current of the generator. A position of ten to twelve successive antinodes is measured using screw gauge attached to the instrument. A difference between two alternate antinodes lead to wavelength. Thereafter, speed of sound is calculated using wavelength and frequency.

A high temperature water is circulating around the cell, for taking readings at higher temperature. A temperature was controlled with accuracy of ±1°C. After waiting for sufficient time to attain the temperature equilibrium higher temperature readings are recorded.

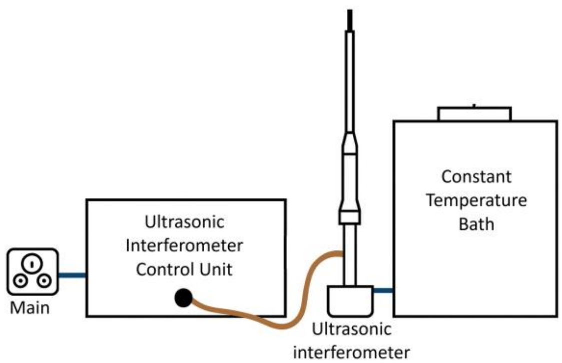

Figure 1: Schematic diagram of the experimental set up

3. Result and Discussion Conclusion

The speed of sound computed for the oil and water is exhibited in Figure 1 and 2 respectively. Figure 2 depicts that speed of sound in the oil decreases linearly with increase in temperature. Figure 3 exhibits that the speed of sound in water increases with initial increase in temperature, attends a maximum value and decreases with further increase in temperature.

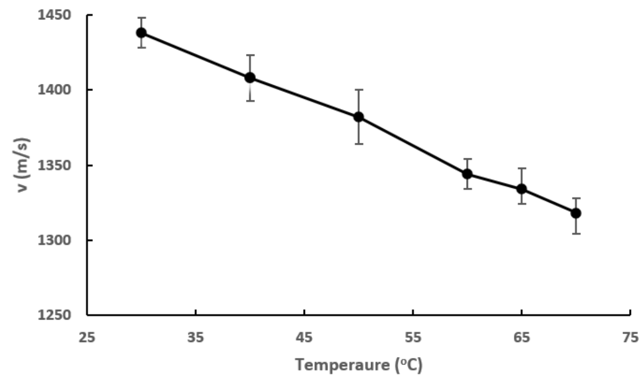

Figure 2: Speed of sound in the oil as a function of temperature

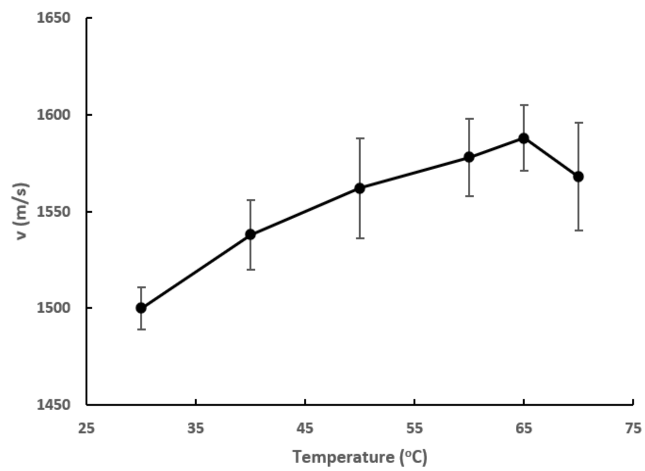

Figure 3: Speed of sound in water as a function of temperature

In general density of liquid decreases with increase in temperature [1]. Therefore, it is imperative that the difference in trend in speed of sound in water and oil is due to difference in variation in bulk modulus. In oil, compressibility increases with temperature because the thermal kinetic energy of the molecules rises, weakening the intermolecular forces. As a result, the liquid becomes easier to compress. Since the bulk modulus is the reciprocal of compressibility, an increase in compressibility implies that the bulk modulus decreases with increase in temperature. Because the decrease in bulk modulus with temperature is much larger in magnitude than the corresponding decrease in density, the speed of sound in the oil decreases as temperature increases. The trend observed in our measurements is consistent with results reported for other oils in the literature. [2] The anomalous behavior of speed of sound in water is probed since long time and is explained using two state theory. [3-5] The early seminal work has reported a trend in variation in compressibility as a function of temperature. [6-7] The anomalous change in bulk modulus has been of great interest since its discovery and addressed from inter molecular interactions perspective in the recent work. [8] It has been reported that the bulk modulus of water increases with initial increase in temperature, attains a maximum and decreases with further increase in temperature. This implies that with increase in temperature, speed of sound increases up to certain temperature and decreases with further increase in temperature.

An initial increase in the speed of sound with temperature, reaching a maximum value at a certain temperature, followed by a decrease with further temperature rise is in agreement with all reported literature.[3,5] The range of values of speed is in good agreement with the literature. However, a temperature at which the speed of sound is maximum at around 74–76 °C [3,5].

4. Conclusion

The present study demonstrates the anomalous temperature dependence of the speed of sound in water, in contrast to the behaviour observed in oil. In oil, the speed of sound decreases monotonically with an increase in temperature. However, in water, the speed of sound initially increases with temperature, attains a maximum, and subsequently decreases with further increase in temperature. Even without a detailed exploration of the temperature corresponding to the maximum sound speed and its subsequent decrease in water, the contrasting trends observed in water and oil are sufficient to establish the anomalous behaviour of water. These observations provide valuable insights into the variation of the bulk modulus with temperature and can be effectively incorporated as an undergraduate laboratory experiment. Further work is warranted to confirm the attainment of a maximum in sound speed at a specific temperature and its subsequent decrease at higher temperatures. Such confirmation would require experimental arrangements capable of operating at elevated temperatures with improved temperature control and measurement accuracy.

Acknowlegements

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