ISSN 2706-655X Vol.6, Issue 6: 72-76, DOI: 10.25236/IJFET.2024.060611

Measurement of liquid concentration based on the speed of sound in saturated solutions

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Abstract: *Ultrasonic waves propagate at different speeds in liquids of different concentrations or temperatures. The speed of sound in a solution varies with the concentration of the solution when the temperature is constant. When the solution is saturated, the speed of sound almost no longer changes with the increase of that solute. Based on this characteristic, the use of time difference method of measuring the speed of sound in different concentrations of solutions, the establishment of the speed of sound and the increase in the mass of the solute as a function of the relationship, the mutation point that indicates that the solute has been saturated, according to the solubility table can be deduced from the original concentration of the solute in the solution. In order to minimize the effect of temperature change on the speed of sound in solution, the ZKY-SS type sound speed measuring instrument is improved by adding temperature monitoring and measuring device, insulation device, water circulation device, which greatly reduces the systematic error of the experiment and improves the accuracy of the measurement.*

Keywords: *Speed of Sound, Concentration, Time Difference Method, Solution Saturation, Temperature*

1. Introduction

With the continuous rise of the processing industry, the high-precision measurement of liquid concentration in the production and processing process is pivotal, the measurement of liquid concentration is an important task in chemical, medical, food and other production and scientific research. How to be able to conveniently and quickly, but also accurately measure the concentration of the inherent components of the liquid has become a hot spot of current research, especially the detection of the concentration of the components of the mixture has an important significance for the process control and quality management. At present, the commonly used experimental methods include chemical analysis, chromatography, photorefractive index method, polarization method, light intensity absorption method, etc. However, these measurement methods are either very time-consuming or of poor accuracy, the most important of which is the inability to achieve real-time dynamic measurement, the promotion of which is restricted in industrial production. The propagation speed of ultrasound in a medium is closely related to the characteristics of the medium and state factors. The speed of sound at a certain temperature is generally linear with the solution concentration. Based on this characteristic, we measured the speed of sound in different concentration solutions by time difference method, and processed the data by using origin to establish the functional relationship between the speed of sound and the increased mass of solute, and the mutation point indicates that the solute has been saturated, and according to the solubility table, we can infer the concentration of the solute in the original solution, which provides a new way of thinking for the dynamic measurement of the concentration of the soluble substance, and it can be used to detect the content of a major component in liquid food, which has important practical significance[1-3].

2. Experimental setup and methods

2.1 Laboratory Instruments

The instruments chosen for this experiment were ***a***. ZKY-SS type sound velocity meter; ***b***. water bath; ***c***. homemade foam lid; ***d***. aluminum foil; ***e***. electronic balance; ***f***. measuring cups, cylinders, and

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droppers; **g**. thermocouple thermometer; ***h***. NaCl; ***i***. distilled water; ***j***. temperature-controlled heating device; ***k***. water pump; and ***l***. artificial ice (as shown in Fig.1).

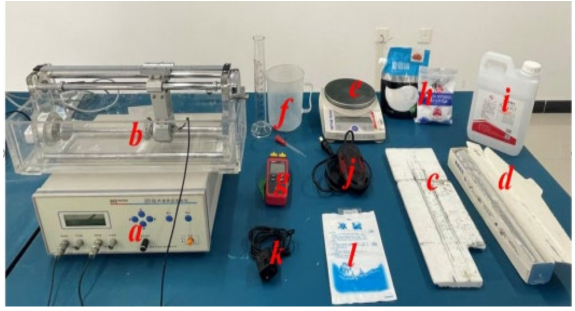

Figure 1: Introduction to the experimental apparatus

2.2 Experimental principle

The speed of sound is measured using the time difference method. The time difference method is used as a pulse wave, between a certain distance by the control circuit timing an acoustic pulse wave, after a distance L propagation to the receiving transducer (as shown in Fig.2). The received signal is amplified, filtered by a high-precision timing circuit to find out the acoustic wave from the issue to receive this in the medium propagation of the elapsed time t, so as to calculate the propagation speed v in a certain medium, i.e., v = L/t.

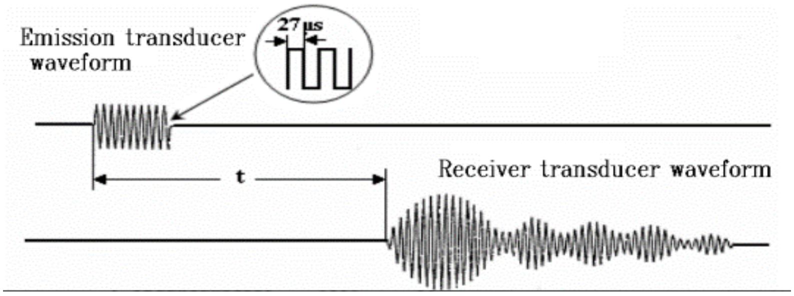

Figure 2: Waveform of sound velocity measurement by time-difference method

In this experiment each time the speed of sound was measured, the position and time readings were recorded at 15mm intervals for a total of 8 points, and each velocity was measured and obtained by the difference-by-difference method:

$$\frac{L_5-L_1}{t_5-t_1}=v_1,\ \frac{L_6-L_2}{t_6-t_2}=v_2\ ,\cdots,\ \frac{L_8-L_4}{t_8-t_4}=v_4 \tag{1}$$

The average value of the speed of sound is then found to be:

$$\bar{v}=\frac{v_1+v_2+v_3+v_4}{4} \tag{2}$$

2.3 Experimental Methods

When the solvent and the temperature is certain, the solute solubility in which is certain, when the concentration of the solute saturated speed of sound no longer changes, the establishment of the speed of sound and the concentration of the solute as a function of the relationship between the mutation point that is, indicating that the solute has been saturated, according to the solubility table can be deduced from the original solution the concentration of the solute. Compared to observing the precipitation of a solute by the naked eye, the sudden change point in the curve of the speed of sound versus solute mass indicates solution saturation and provides a more accurate inversion of the initial solution concentration. For example, if you want to measure the concentration of a solute in the solution, from which a small amount of solution can be extracted, measured the quality of the solution *m* and volume *V*, set the solution dissolved in the mass of this solute for m_0, and then gradually add the solute, and at the same time measure the speed of sound, make the speed of sound *v* and the added solute mass Δ*m* relationship map, the image slope mutation that is saturated, the horizontal coordinate corresponds to the added solute mass Δ*m*, when the speed of sound no longer increase that is Just for the saturated solution, query the temperature of the saturated concentration of the solute in water for $a\%$, then the following relationship can be obtained:

$$a\% = \frac{m_0+\Delta m}{m_0+\Delta m+\rho_{water}V_{water}} \tag{3}$$

In the above equation ρ_{water} (ρ_{water}=1g/cm^3) is the density of the solvent water and V_{water} is the volume of water. The mass of this solute dissolved in the original solution can be found using Equation (3):

$$m_0 = \frac{(\Delta m+\rho_{water}V_{water})a\%-\Delta m}{1-a\%} \tag{4}$$

This gives the mass concentration of that solute in the original solution.

When there is only one solute in the solution, $m_0 + \rho_{water}V_{water} = m$ is satisfied and Equation (4) can be simplified to:

$$m_0 = (m + \Delta m)a\% - \Delta m \tag{5}$$

For a mixed solution satisfying the inequality $m_0 + \rho_{water}V_{water} \neq m$, And in general the volume of solute added to water increases so that the volume V of the original solution is not equal to the volume V_{water} of the solvent water, so the volume of solvent water needs to be calculated. Let η denote the mass of solute added when increasing the unit volume, i.e.

$$\eta = \frac{\Delta m}{\Delta V} = \frac{m-\rho_{water}(V-\Delta V)}{\Delta V} \tag{6}$$

In the above equation$V - \Delta V = V_{water}$. The value of η can be obtained experimentally by substituting into the above equation to obtain ΔV and calculating the volume of the aqueous solvent V_{water}. Substituting into the equation gives m_0, which allows the concentration of the solute in the original solution to be calculated[4-6].

3. Improvement of experimental apparatus

3.1 Design of heating and cooling devices

Aluminum foil is laid flat on the bottom and inner wall of the sink, put into the solution to be measured, and then put into the double probe thermocouple thermometer, the heating device, the water circulation device in turn, and finally cover the homemade foam cover containing the track, which allows the acceptance of the transducer to move freely to make the whole device in a basically closed state. The overall structure of the experimental apparatus is shown in Fig.3.

Figure 3: Overall structure of the experimental apparatus

3.2 Improvement of temperature measuring device

The temperature is accurately raised by a temperature-controlled heating device to a minimum of 0.5 ℃. Cooling is carried out by means of artificial ice packs.

3.3 Design of the insulation device

The traditional device uses a glass bubble thermometer to measure the temperature, which can only

ISSN 2706-655X Vol.6, Issue 6: 72-76, DOI: 10.25236/IJFET.2024.060611

measure the local temperature. We have changed to use a dual-probe thermocouple thermometer to measure the temperature at the corresponding ends of the sink, and the heating device used at the same time can also display the temperature of the liquid, which can realize multi-point measurement and ensure a more uniform and accurate temperature.

3.4 Design of circulating flow device

The use of aluminum foil has good thermal insulation properties, so that the test sample solution in the cooling process is closer to the quasi-static process. At the same time with the foam homemade sink cover, in the measurement of the liquid and the outside world can be minimized to minimize the heat transfer, both measures can be made to make a longer period of time basically keep the solution at a constant temperature, thus improving the accuracy of the data.

4. Data processing

The following table shows the speed of sound in a solution of 15% standard NaCl at 20 ℃ after increasing the mass of solute NaCl in the solution:

Table 1: Changes in the speed of sound

Increased mass*Δm*(g)	**Velocity(m/s)**
0	1643.8
100	1679.5
200	1708.8
300	1734.1
400	1764.6
500	1775.2
600	1775.1

Based on the table 1 above use ORIGIN to draw a graph of the speed of sound versus added mass as shown below:

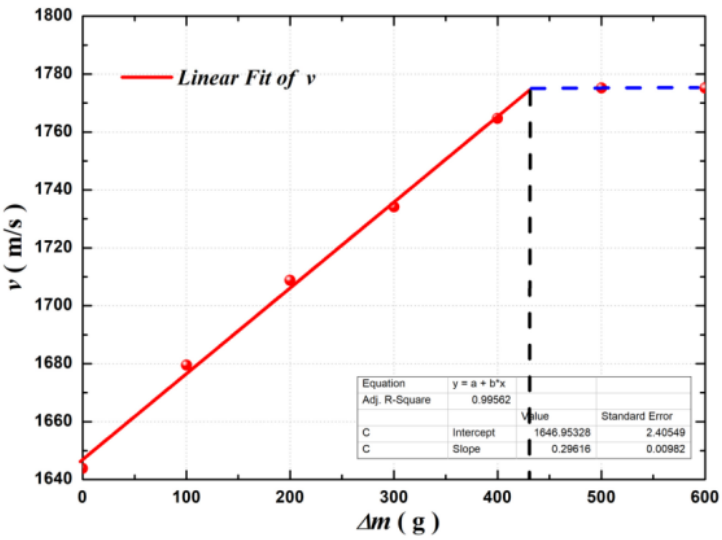

Figure 4: Velocity of sound versus mass increase of NaCl solute at 20 ℃

The linear fit of points in Fig.4 correspond to the speed of sound of the solution after the solute is added, and it can be seen that once the NaCl solution is saturated, the speed of sound no longer increases, so we can invert the graph to show the concentration of NaCl in the original solution[7].

The speed of sound v as a function of the added mass Δm (before saturation of the solution) was firstly established by using the method of one-dimensional linear fitting (red solid line in the figure), and the linear relationship was obtained from the fitting results as:

$$v = 0.29616\Delta m + 1646.95328 \quad (R^2 = 0.99562) \tag{7}$$

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The blue dashed line in Fig.4 represents the speed of sound when the solution is saturated, and from Table 1, we know that the speed of sound when the NaCl solution at 20 °C is saturated is about v=1775.2 m/s. Substituting into the formula, we can calculate themass of solute added when the solution is just saturated to be Δm=433.032g (i.e., it is the horizontal coordinate corresponding to the intersection of the corresponding red solid line and the blue dashed line in the figure).

The original solution taken is the configuration of 2600 ml concentration of 15% (can be regarded as an unknown quantity, as a standard value) of NaCl solution, using the balance to weigh its mass m = 2810.15 g, after consulting the information can be known as 20 ℃ when the saturation concentration of NaCl is 26.47%, and then the use of the formula can be calculated as the mass of the original solution in the NaCl m_0 = 425.438 g. Thus, it can be predicted the original solution concentration is:

$$c = \frac{m_0}{m} \times 100\% = \frac{425.438}{2810.15} \times 100\% = 15.14\% \tag{8}$$

The absolute error of the prediction results compared to the standard value of 15% is 0.14% and the relative error is 0.94%.

5. Conclusions

At the same time, this experiment improves the original ZKY-SS-type sound velocity measurement device by adding temperature monitoring and measurement device, insulation device, heating device and water circulation device, which greatly reduces the system error. The method of measuring the concentration of solution designed in this experiment can be used for the detection of the concentration of the components of the mixture, which is of great significance in medical, food and chemical industries. Because the speed of sound is also related to other factors such as pressure, medium flow rate and direction of flow, the accuracy of concentration measurement can be improved by further improving the experimental setup.

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