Temperature Dependence of Refractive Index of Water Measured with a Microcontroller Based Optical Interferometric System

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Abstract: A simple, low-cost and high precision method of measuring the refractive index of water using Michelson interferometer in temperature range 38 to 72ºC is reported in this paper,. The aim of the present study was to measure the varition of refractive index of water with temperature. An Arduino UNO microcontroller based data acquisition system was designed and constructed for data gathering. The data was sent to a desktop computer for storage and offline analysis. The system is able to detect relative changes in refractive index of the order of 10^{-4}. The set of values generated through our measurements agreed with other measurements within 10^{-3} and with the standard values as tabulated in Lange's Handbook of Chemistry within **0.1%**.

Keywords: **Michelson interferometer, temperature dependence, Refractive index, Arduino UNO microcontroller, refractive index.**

I. INTRODUCTION

Water is is considered quite common substance which is abundantly available around us. But the fact is that it has unique physical and chemical properties (Hawkins & Stillinger, 1974). The anomalous behaviour of liquid water with temperature has been a matter of speculation as well as intense scientific study. Water plays an important role in the development of life on earth – It encompasses all aspects of Human existence (Mae-Wan ho, 2014). Water has unique chemical and physical properties. One of the important properties of water is its refractive index. The refractive index of water is an optical property and its temperature dependence is of interest in various areas like biomedical optics and optics of tissue (Alexey, 2003). This is also useful for understanding short range molecular interaction in solids, liquids and gaseous material (Rosen, 1947) (Stanley, 1971). Therefore, the goal of this study is to measure the dependence of refractive index of water on temperature. A Michelson interferometer technique with microcontroller based electronic circuit was designed and fabricated which enabled a reliable measurement of the concerned parameters.

II. INSRUMENTATION

A Michelson Interferometer is schematically depicted in figure 1. This instrument uses the principle of interference of electromagnetic waves for precise measurement of various quantities such as wavelength, distances, refractive index, spatial and temporal coherence of optical beams, etc. The working of Michelson interferometer is based on division of amplitude. In the present study, a Michelson Interferometer was used to measure the temperature variation of refractive index of water. A cell containing water was placed in one of its two limbs. The temperature of water in the cell was slowly changed with the help of heating element. A corresponding change occurred in the refractive index of water resulting in a change in the optical path of the laser beam passing through the cell. The variation of this optical path caused a shifting of the fringes formed in front of the interferometer,

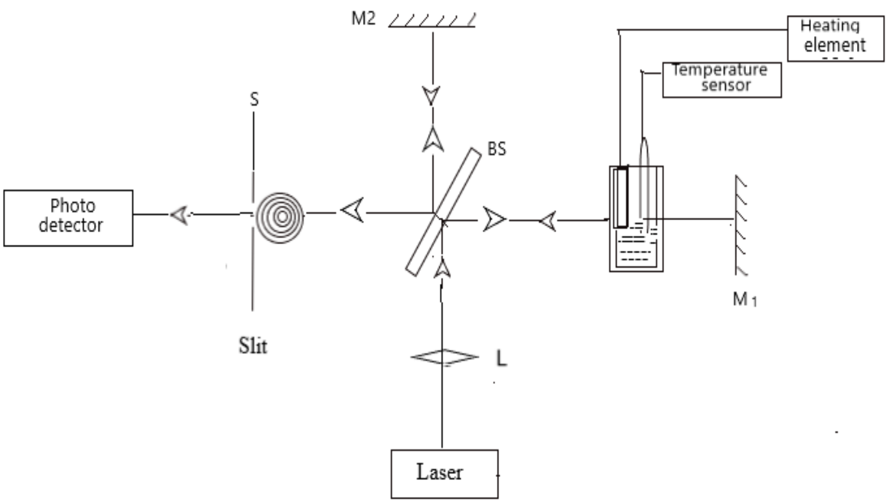

Figure: 1

An indigenously developed microcontroller based data acquisition system was constructed (figure.2) for observation and managing this data. The data recorded consisting of temperature and time at which fringe shift occurred was sent to a desktop computer using serial interface and saved in a computer file for further offline processing and study.

Microcontroller based data acquisition system

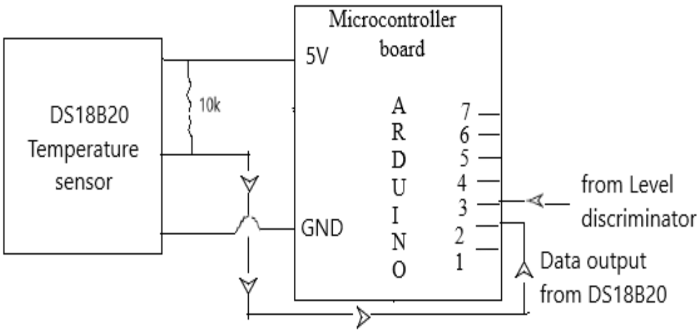

Figure: 2

III. OBSERVATION AND CALCULATION:

If change in temperature is **ΔT** and the corresponding fringe shift is **m**, then change in refractive index **Δn** is given by

$$\Delta n = m\lambda / 2L \qquad (1.1)$$

The rate of change of refractive index with temperature, (**Δn /ΔT**) can now be determined. For obtaining **Δn /ΔT** the number of fringes shifted per unit temperature difference was calculated from the data. Then we have

$$2\Delta nL = m\lambda \qquad (1.2)$$

$$\Delta n = m\lambda /2L$$

$$\Delta n/\Delta T = m\lambda / 2L\Delta T \qquad (1.3)$$

where **λ** is the wavelength of light used. In the present experiment the light source was He-Ne Laser that has wavelength 638.8nm (6.38×10^{-7} m). Path traversed through the glass portion of the cell is 1.3 cm which is equal to 1.30×10^{-2} m, that is very small and can be neglected. Using the above equation (1) the rate of change of refractive index with temperature was obtained. Since the value of n cannot be directly determined by Michelson interferometer, the value of n at a particular temperature (38°C) was obtained using a Mettler Toledo RM40 refractometer. This was used as a reference. Now using the measured values of Δn/ΔT the refractive index values for other temperatures were calculated.

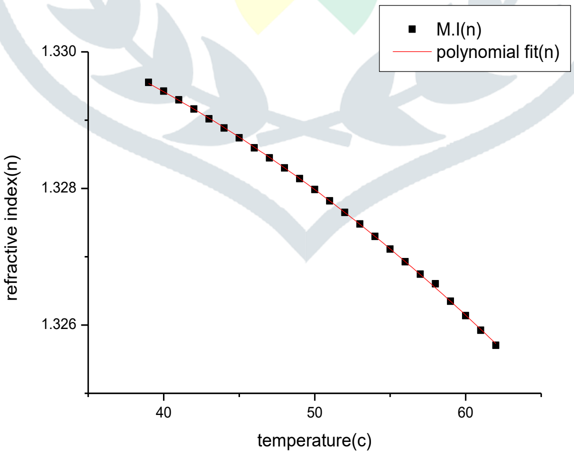

Figure: 3

In this graph, the average of data at different temperatures obtained during different cooling runs has been plotted as a function of temperature. We tried to develop an empirical formula for refractive index on the basis of our measurements. For this we carried out a quadratic best fit on the refractive index data with respect to temperature. On comparing the best fit curve with our data, we found the curve to fit the data very closely. This is also indicated by the correlation coefficient.

VI. RESULT AND DISCUSSION:

Refractive index of pure water for a wavelength of 6328, Temperature from 38 ºC – 71ºC and Atmospheric Pressure

Table I

Temperature T	m (average Fringe shift / deg celsius)	Δn per fringe shift	Δn/ΔT	Ref. Index N	Std Dev σ(n)
71	8.50	2.57701E-05	2.190462E-04	1.325922785	8.60495E-05
70	8.67	2.48065E-05	2.149897E-04	1.326137774	5.06645E-05
65	7.60	2.43385E-05	1.849723E-04	1.327112935	0.000118736
60	6.60	2.5076E-05	1.655015E-04	1.327984252	8.8426E-05
55	6.00	2.45413E-05	1.472477E-04	1.328739962	6.60158E-05
50	5.17	2.4731E-05	1.277769E-04	1.329425495	3.66304E-05
45	5.14	2.40004E-05	1.234308E-04	1.330048154	2.30427E-16
40	4.93	2.46204E-05	1.214605E-04	1.330659861	1.25683E-05
38	4.93	2.43385E-05	1.200697E-04	1.3309	0

Accuracy and Error:
In quadratic best fit measurement of our data, we obtained the r^2 **error** as **0.99982** which is very close to **1.**

The average standard deviation for all the values of refractive index measurement of pure water is $\pm$ **0.00005** while the error calculated in the temperature range by Andy tan (201by 0) was also of same order ($\pm$ **0.000055)** and the error measured by Alexey Bhaskatov (2003) was $\pm$**0.00007** . The present technique is able to detect changes in refractive index of the order of $\mathbf{10^{-4}}$

The agreement of the set of values generated through our measurements with those by other researchers is better than 10^{-3} and the agreement with the standard values as tabulated in Lange's Handbook of Chemistry is within **0.1%**.

The expansion of the cell over 1ºC is 5 X 10^{-9}m. Between the temperatures 38ºC and 72ºC the total increase in path length due to expansion of the cell is 1.7X10^{-7}m. We calculate the fringe shift by dividing this value by the wavelength 632.8 nm. Thus the total error over this range due to expansion of the cell comes out to be **0.268** of one fringe. This can be compared with total fringe shift over this range which is 220. Thus the error due to expansion of the cell thus comes to be 0.12%.

V. COMPARE OUR DATA WITH OTHERS:

Comparison of our data and the empirical model with Lange's Handbook data: The refractive index measured by us was compared with the available values from Lange's data. The comparison is shown below in Figure 4. The measured data tallies quite well in the range 30ºC to 70ºC. The theoretical model based data also tally in this range. But there is a substantial divergence between the model data and data from the handbook as the temperature goes further below 30ºC

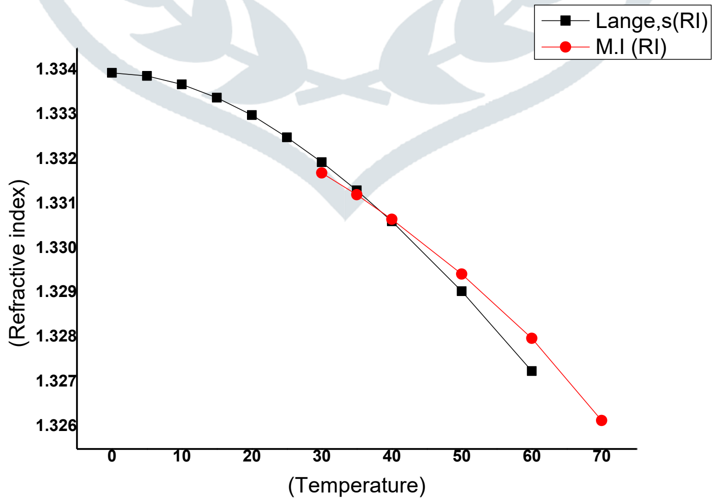

Figure: 4

Comparison with different models and measurements:

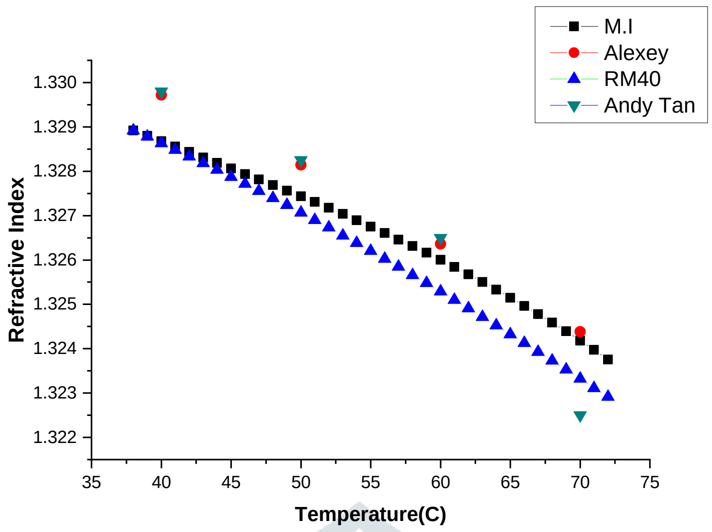

Figure: 5

In figure 5 the Michelson interferometer measurements done by us have been shown as black squares. The error bars have been depicted at 10ºC intervals. These error bars have been calculated on the basis of standard deviation observed when the measurement was repeated in different experimental runs. Thus they represent the random errors mainly. The measurements (using light of wavelength 589.3 nm) by Mettler Toledo RM40 refractometer (Mettler Toledo RM40) are quite accurate (accuracy 10^{-4} in **n**) and We observe that the two measurements tally within 0.09% percent at 72ºC. Andy Tan (2010) who has been obtained the value of refractive index with the help of Michelson interferometer technique. The two data were quite similar and agreed within error limits up to 60ºC. Alexey N. Bashkatov et al.(2003) has modelled the refractive index of water to conform to a temperature dependent Cauchy's equation as given below

$$n(\lambda) = A(t) + \frac{B(t)}{\lambda^2} + \frac{C(t)}{\lambda^4} + \frac{D(t)}{\lambda^6} \qquad (2.1)$$

Our measurement data approximately matched with their formula. Alexy (2003) has used standard values tabulated in CRC Handbook of Chemistry (2001) and Physics as basis of his model calculation. On the other hand we have used measured value.

VI. RELATION WITH DENSITY: An empirical relation of refractive index obtained by us with density and temperature was obtained through curve fitting. We can express the refractive index as a function of density and temperature as

$$\mathbf{RI = D^*(0.001348+5.22\ x10^{-7}\ (T-55.6) + 3x10^{-9}(T-55.6)^2} \qquad (3.1)$$

For the range 39ºc to 72ºc this gives the measured RI within 10^{-5} accuracy. If we compare the coefficient;

$$\mathbf{T^0 = 1.348 * 10^{-3}}$$
$$\mathbf{T^1 = 5.22 * 10^{-7}}$$
$$\mathbf{T^2 = 3.0 * 10^{-9}}$$

This variation is depicted in figure 6. It is nearly linear with density with a good accuracy. Temperature variation coefficient are much smaller **(~10^{-4} and 10^{-6}**). So that we can say that the main cause of refractive index variation is change in density. But there is a very small effect of other causes also, which is observed in temperature variation.

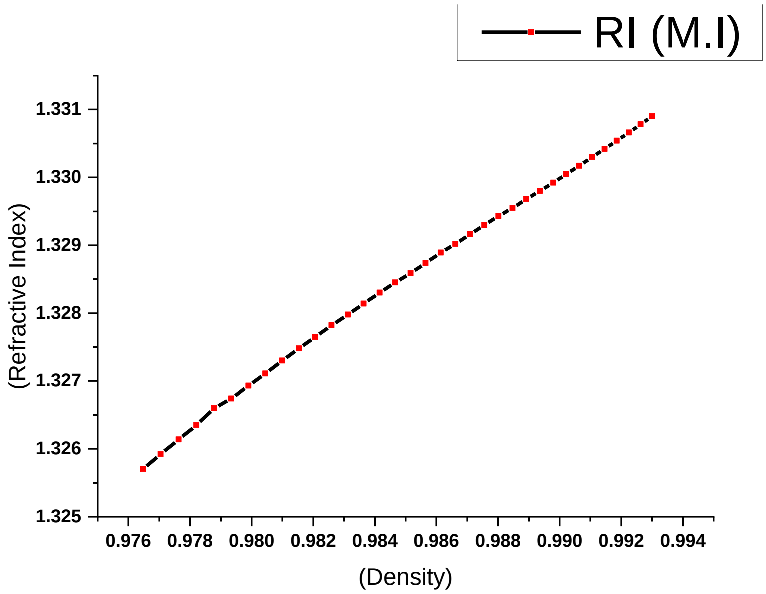

Figure: 6

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