

## Refractive Index of liquids by measuring Displacement of Refracted Laser Beam

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### Abstract

A simple method for measuring the refractive index of liquid is described with the help of detailed theory. A laser beam suffers a lateral displacement due to refraction while passing through a liquid. This displacement of laser beam from its incident direction is measured for different angles of incidence to find the refractive indices of oils that are commonly used in the laboratory.

**Keywords:** Refraction, Refractive index of liquids, lateral displacement.

### Introduction

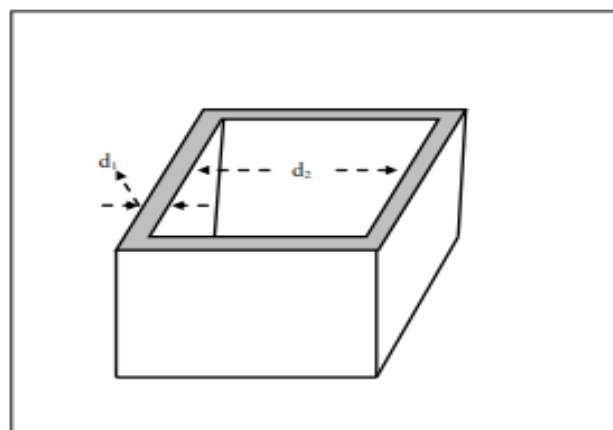
The optical properties of a medium often manage the interaction of electromagnetic wave incident onto it. Thus an electromagnetic wave starts interacting with the electrons in a medium, when the wave is allowed to propagate through it. The electric field associated with the wave causing them to vibrate and this forced oscillations of the electrons in the medium start radiating light by offering secondary sources of radiation. However, the speed of new waves changes accordingly to the optical properties of the medium and it is always smaller than the speed of light in vacuum. All materials are characterized by their ability to slow down the waves, classified as optical refractive index. The refractive index of vacuum is unity and it is higher than unity for any other material (e.g.  $n=1.33$  for water).

Refractive index plays a vital role in many areas of material science with special reference to various optical technologies and measurement of refractive index of liquids is often required in physics and chemistry to determine the concentration of solutions. The refractive index of liquid is determined by various methods and a common method is the measurement of angle of minimum deviation produced by a light beam that passes through the liquid contained in a hollow prism made of glass<sup>1,2</sup>. But, this method can be limited to visible light, because glass is opaque to infrared and ultraviolet radiations. Another versatile instrument commonly used for the determination of refractive index of liquids is the well-known Abbe refractometer<sup>3</sup>. Unfortunately, the Abbe refractometer suits best for the assessment of refractive index of transparent liquids<sup>2</sup>.

The last decade witnessed a giant leap in the design of new optical technology with the use of laser beam due to its high degree of coherence. Thus now it becomes easy to set up basic optical experiments illustrating refraction in a physics laboratory by using a laser beam.<sup>3-7</sup>

This study describes the determination of refractive index of a liquid that does not require conventional optical elements like prism, or wedge. This method employs a He-Ne laser beam impinges obliquely on a rectangular cell containing the liquid whose refractive index is to be measured. Subsequently, the beam is found to be displaced from the direction of the incident beam after refraction. Thus, the displacement of the refracted laser beam depends on the refractive index of liquid in the glass cell and its wall thickness of the glass cell. In order to eliminate the influence of optical parameters of the glass cell, displacements of the laser beam are measured while the glass cell is empty and it is filled with a liquid. By measuring the separation between the two displacements in these two cases, the refractive index of liquid could be determined without accounting the cell parameters. A detailed version of the theory used to retrieve the refractive index of liquid is given below.

**Theory:** A laser beam is allowed to incident on one face of a rectangular glass cell with wall thickness  $d_1$  of refractive index  $n_1$  as shown in figure-1.



**Figure-1**  
Geometry of the glass cell

The distance between the glass walls is  $d_2$  and the liquid of refractive index  $n_2$  is filled in the glass cell which is placed in air of refractive index  $n_0$ . A He-Ne laser beam of wavelength 632.8 nm is made to incident at an angle  $\theta$  and the corresponding displacement of the emerging laser beam at the other face of the cell after refraction is  $\delta$  as depicted in figure-2.

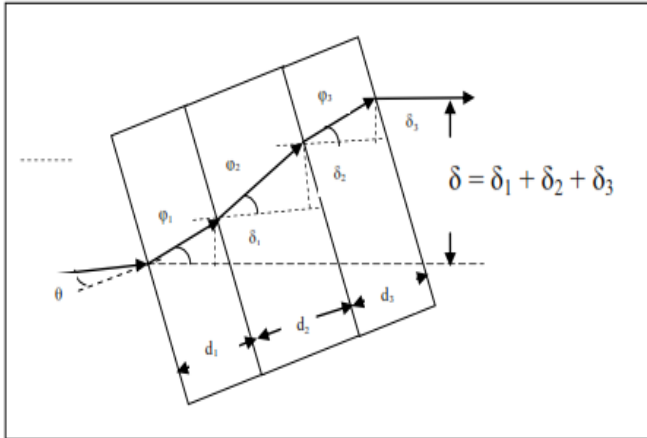


Figure-2  
Schematic layout of the laser beam propagation after refraction through the glass cell

$\delta_1$  and  $\delta_2$  are the lateral displacements of the beam from its original direction after passing through the glass wall and liquid respectively and the expression for the displacement produced by any medium is

$$\delta_i = d_i \left[ \frac{\sin \phi_i}{\cos(\theta - \phi_i)} \right] = \frac{d_i \sin \phi_i}{\cos \theta \cos \phi_i + \sin \theta \sin \phi_i} \quad (1)$$

this can be further simplified to 
$$\delta_i = \frac{d_i}{\sin \theta + \frac{\cos \theta}{\tan \phi_i}} \quad (2)$$

But Snell's law gives:  $n_0 \sin \theta = n_1 \sin(\theta - \phi_i)$ ,  $n_0$  and  $n_1$  are the refractive indices of rarer and denser media respectively. Hence the angle of deviation of light beam from the line of the incident ray after refraction is

$$\phi_i = \theta - \sin^{-1} \left[ \frac{n_0 \sin \theta}{n_1} \right] \quad (3)$$

where  $i=1,2$

From the geometry of rays,  $\phi_i = \theta - \theta_r$ ,  $\theta_r$  is the angle of refraction. Thus the expression becomes

$$\cos \theta_r = \frac{[n_1^2 - n_0^2 \sin^2 \theta]^{1/2}}{n_1} \quad (4)$$

$$\tan \phi_i = \left[ \frac{\sin \theta \cos \theta_r - \cos \theta \sin \theta_r}{\cos \theta \cos \theta_r + \sin \theta \sin \theta_r} \right] \quad (5)$$

and this is further expressed as

$$\tan \phi_i = \frac{[n_c \sin \theta - n_0 \cos \theta \sin \theta]}{[n_c \cos \theta + n_0 \sin^2 \theta]} \quad (6)$$

where  $n_c = [n_i^2 - n_0^2 \sin^2 \theta]^{1/2}$

$$\tan \phi_i = \left[ \frac{(n_c - n_0 \cos \theta)}{n_c \cos \theta + n_0 \sin^2 \theta} \right] \sin \theta \quad (7)$$

Thus the displacement becomes 
$$\delta_i = d_i \left[ \frac{1 - n_0 \cos \theta}{[n_i^2 - n_0^2 \sin^2 \theta]^{1/2}} \right] \sin \theta \quad (8)$$

Thus the expression for the total displacements of refracted beams through the glass wall and the medium are  $\delta(n_0, n_1, n_2) = 2\delta_1 + \delta_2$ .

$$\delta = \left\{ 2d_1 \frac{(1 - n_0 \cos \theta)}{[n_1^2 - n_0^2 \sin^2 \theta]^{1/2}} + d_2 \frac{(1 - n_0 \cos \theta)}{[n_2^2 - n_0^2 \sin^2 \theta]^{1/2}} \right\} \sin \theta \quad (9)$$

The value of  $n_2$  can be obtained from  $\delta$  and fixed value of  $\theta$  from the above equation. In order to eliminate the contribution of  $n_1$ , a new quantity is introduced as  $\Delta$  which is

$$\Delta = \delta(n_0, n_1, n_2) - \delta(n_0, n_1, n_0) \quad (10)$$

the first and second terms in the above equation represent the displacements of refracted laser beam when the cell is filled with a liquid with refractive index  $n_2$  and an empty glass cell. Using equations (9) and (10)

$$\Delta = d_2 \left[ \frac{(1 - n_0 \cos \theta)}{(n_2^2 - n_0^2 \sin^2 \theta)^{1/2}} \right] \sin \theta \quad (11)$$

this finally yields

$$n_2 = n_0 \left\{ 1 + \left[ \frac{\cos \theta}{(\sin \theta - \frac{\Delta}{d_2})} \right]^2 \right\}^{1/2} \sin \theta \quad (12)$$

This equation is independent of  $d_1$  and  $n_1$  and the refractive index of the liquid  $n_2$  can be obtained without the knowledge of cell parameters  $d_1$  and  $n_1$ .

### Methodology

A glass cell with wall thickness  $d_1 = 0.25$  cm and  $d_2 = 5.5$  cm is used for this experiment. A He-Ne laser beam of wavelength 632.8 nm incident on a cell placed on the prism table of a spectrometer which is capable of rotating in order to select the desired angle of incidence. A photograph of the experimental set up used is shown in figure-3.

The prism table is rotated to select the angles of incidence from  $5^\circ$  to  $40^\circ$  with a step of 5 degrees and the respective displacements of the beam with and without liquids are recorded on the screen. Thus the difference between the displacements with and without liquid are measured with a microscope to determine  $\Delta$ . The maximum possible angle of incidence is limited to  $40^\circ$  and beyond this angle the deviations are inconsistent. The experiment is repeated for liquids like water, coconut oil, palm oil and kerosene.

### Results and Discussion

The refractive index of different liquids has been measured using the laser displacement method. The value of  $\Delta$  and the measured refractive indices for water, coconut oil, palm oil and kerosene for different angle of incidence is shown in table 1. The values of refractive indices measured using this method is in good agreement with their standard values. From this table it is evident that the measured values of the refractive indices of liquids at different angles of incidence are nearly equal. But the

deviation observed in the measured values at 40 degree in all cases show a deviation in the magnitude of refractive index. Thus the angle of incidence beyond 40 degrees would affect the accuracy of the result due to the non linear parameters that occur in the equations. Therefore, angle of incidence has a strong dependence on the thicknesses of glass walls  $d_1$  and column of the liquid  $d_2$ . The variations observed in the deviations  $\Delta$  with angles of incidence are shown in figure-4.



Figure-3  
 Photograph showing the experimental set up

Table-1  
 Measured values of  $\Delta$  and refractive indices for various angles of incidence on the front face of the glass cell

Angle of incidence in degrees	Water		Coconut Oil		Palm Oil		Kerosene	
	$\Delta$	Refractive index	$\Delta$	Refractive index	$\Delta$	Refractive index	$\Delta$	Refractive index
5	0.15	1.332	0.2	1.436	0.2	1.455	0.2	1.4446
10	0.26	1.335	0.35	1.443	0.4	1.453	0.4	1.449
15	0.33	1.331	0.5	1.445	0.55	1.456	0.65	1.442
20	0.52	1.334	0.65	1.441	0.65	1.458	0.8	1.446
25	0.65	1.337	0.8	1.445	0.82	1.455	0.9	1.445
30	0.85	1.334	0.95	1.447	0.96	1.457	1	1.442
35	0.96	1.336	1	1.446	1.02	1.459	1.05	1.441
40	1.05	1.303	1.2	1.402	1.2	1.448	1.1	1.430

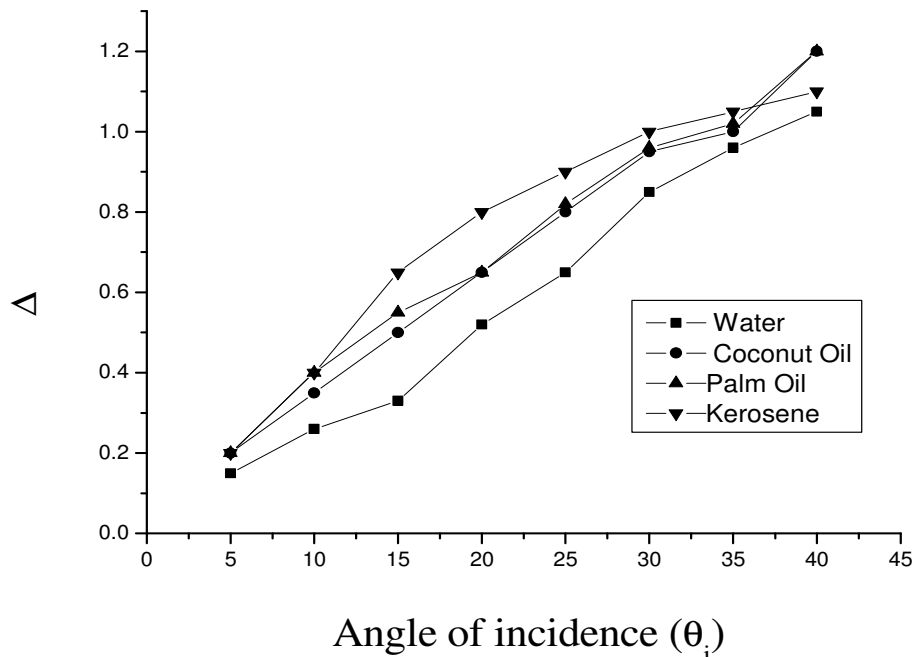


Figure-4

Graph showing the variations observed in the values  $\Delta$  for different angles of incidence

The magnitudes of  $\Delta$  are identical for all angles of incidence and this in turn proves the validity of the theory used for determining the refractive index of liquids using laser beam displacement. However, the range of angle of incidence selected depends on the value of  $\Delta/d_2$  depend on the geometry and size of the glass cell. Hence, the thickness of glass and that of liquid column are so adjusted to select higher values of angles of incidence.

### Conclusion

This describes a simple method for the measurement of the refractive index of liquid by using a He-Ne laser beam. In this scheme, the displacement of laser spot from the direction of incident beam after propagating through a rectangular glass cell in two cases is measured: By taking the difference between the two positions, the refractive index of liquid can be precisely determined without considering the thickness of the glass cell used. The use of a laser beam makes the experiment becomes easy to conduct in laboratory and the lateral shifts can be easily measured using a microscope. However, the range of the angle of incidence to be selected depends on the geometry and dimension of the glass cell and liquid column.

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