Lontar Physics Today (e-ISSN: 2828-0970)
Vol. 5 No. 2 June 2026, p 187-198
Available online at http://journal3.upgris.ac.id/index.php/lpt/index
DOI: 10.26877/lpt.v5i2.394

Liquid Refractive Index Measurement via Geometric Analysis of Total Internal Reflection Light Rings

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Article Info:

Article History:
received: 10 February 2026
accepted: 13 March 2026
available online: 4 April 2026

Keyword:
refractive index, total internal reflection, geometric analysis, physics laboratory experiments

https://doi.org/10.26877/lpt.v5i2.394

Abstract:

Refractive index measurement is a fundamental component of geometric optics; however, determining the refractive index of liquids is often constrained by the high cost of standard equipment and the complexity of direct angular measurement procedures. Consequently, this study proposes an alternative method for determining the liquid refractive index based on the geometric analysis of light ring patterns formed by Total Internal Reflection (TIR). From the ray path analysis, a linear relationship was derived between the square of the light ring radius r^2 and the square of the liquid height h^2, whereby the refractive index is determined from the gradient of this relationship. The developed method was validated through two experimental schemes determining the refractive index of water and cooking oil and observing the effect of NaCl concentration on the solution's refractive index. The experimental results demonstrate a linear relationship between r^2 and h^2, consistent with the developed equation. The refractive index values obtained for water and cooking oil were 1.339±0.006 and 1.491±0.013, respectively, with relative uncertainties below 1% and accuracies above 98%. In the second experiment, the refractive index of the NaCl solution increased with concentration, although precision limitations in measuring the ring pattern radius caused deviations at several data points. These findings suggest that the reflection light ring phenomenon resulting from total internal reflection can be effectively utilized as an alternative method for measuring liquid refractive indices through a relatively simple experimental approach, with potential for further development in both research and optical education.

1. Introduction

The refractive index is a critical optical parameter, as it describes how light propagates through a transparent medium, thereby representing the optical properties of the material (Chang et al., 2024; Didik et al., 2021). Consequently, measuring the refractive index is not only significant in theoretical optical studies but also possesses various practical applications, such as determining the purity, concentration, and quality of a liquid (J et al., 2021; Prasetyo et al., 2014). Given the importance of this parameter, various methods have been developed to determine the refractive index of a medium.

In the study of geometric optics, measuring the refractive index of liquids is a commonly performed experiment. Various methods have been developed to determine the refractive index, such as the use of an Abbe refractometer or the measurement of incident and refractive angles in specific optical systems. The Abbe refractometer is capable of providing high-precision measurement results; however, its relatively high cost often limits its availability in educational laboratories (Andriyan et al., 2021; Wang & Jia, 2023).

Another frequently utilized method involves determining the refractive index through the measurement of incident and refractive angles using transparent plates or specific optical configurations. Nevertheless, this method requires meticulous angular measurements, meaning the accuracy of the results is highly dependent on the observer's ability to determine angles precisely (Suhadi & Wiranda, 2019; Zamroni, 2013). These limitations underscore the necessity of developing alternative methods that are simpler, more economical, and easily implemented in laboratory practicum activities.

One optical phenomenon that has the potential to be utilized for this purpose is the formation of a circular light pattern resulting from total internal reflection at the liquid–air interface. When a light beam is directed into a container filled with a shallow liquid and a reflective base, a ring-shaped light pattern appears surrounding the point of incidence. This phenomenon, often referred to as a reflection light ring, contains geometric information related to the critical angle of total internal reflection.

However, in most discussions it is primarily used as a qualitative illustration of refraction and total internal reflection rather than as a method for quantitative measurement. Previous studies have described the geometric formation of these light ring patterns within the framework of geometric optics, particularly in explaining ray paths and the visual representation of total internal reflection (Destefano & Widenhorn, 2024, 2025). Although these studies provide valuable conceptual insights, the potential of this geometric pattern to be utilized as a practical tool for determining the refractive index of liquids has not been extensively explored.

Since the radius of the observed light ring is determined by the geometry of the light path and the critical angle at the liquid surface, geometric analysis offers an opportunity to extract quantitative information about the refractive index without requiring direct angle measurements. By analyzing the relationship between the geometric parameters of the ring pattern and the liquid depth, the refractive index can potentially be determined through a simpler experimental procedure.

Therefore, this study proposes a method for measuring the refractive index of liquids based on the geometric analysis of reflection light ring patterns produced by total internal reflection. The aim of this research is to determine the refractive index of several liquids using this approach and to evaluate the precision and accuracy of the proposed method by comparing the obtained results with reference values from the literature.

2. Theoretical Framework

2.1 Light Refraction and Total Internal Reflection

Light refraction is the phenomenon where the direction of light propagation changes as it crosses the boundary between two transparent media with different refractive indices.

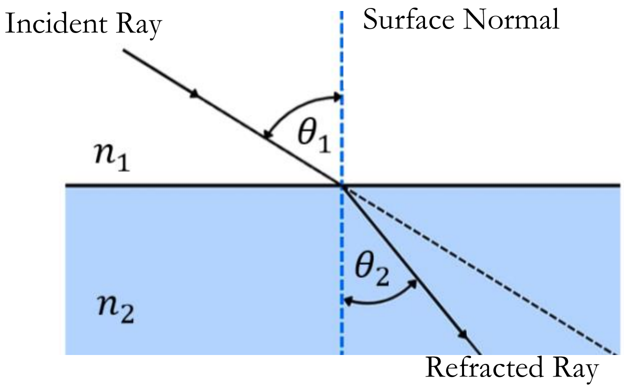

Figure 1. *Schematic of light refraction from air to liquid, illustrating the angle of incidence θ_1, the angle of refraction θ_2, and the normal line relative to the boundary of two media with refractive indices $n_1 < n_2$.*

The refractive index of a medium is defined as the ratio of the speed of light in a vacuum c to the speed of light in that medium v (Respati & Rahardjo, 2017), which is mathematically expressed as

$$n = \frac{c}{v}. \tag{1}$$

The change in the speed of light from the first medium to the second causes its propagation direction to shift relative to the normal (Kurniawati & Suryani, 2023), as illustrated in Figure 1.

The change in the direction of light propagation during refraction is described by Snell's Law, which states that the relationship between the angle of incidence and the angle of refraction satisfies the equation

$$n_1 \sin \theta_1 = n_2 \sin \theta_2, \tag{2}$$

where $n_1$and n_2 represent the refractive indices of the first and second media, while θ_1 and θ_2 are the angle of incidence and the angle of refraction measured relative to the normal.

When light travels from a medium with a lower refractive index to a medium with a higher refractive index, the light is refracted toward the normal. Conversely, when light travels from a medium with a higher refractive index toward one with a lower refractive index, the direction of light propagation is refracted away from the normal (Hendri, 2019).

Under certain conditions, the change in the direction of light propagation can reach a limit where the light is no longer refracted into the second medium. This condition occurs when light travels from a medium with a higher refractive index toward a medium with a lower refractive index at a sufficiently large angle of incidence, causing all the light to be reflected back into the original medium. This phenomenon is called Total Internal Reflection (TIR) (Nasution et al., 2021).

The occurrence of TIR is determined by the critical angle θ_c, which is the minimum angle of incidence that causes light to be entirely reflected rather than refracted (Giancoli, 2014). The θ_c can be calculated using the equation

$$\theta_c = \arcsin\left(\frac{n_2}{n_1}\right), \tag{3}$$

with the requirement that $n_2 < n_1$. There are three conditions for the incident angle of a ray: when $\theta_1 < \theta_c$, when $\theta_1 = \theta_c$, and when $\theta_1 > \theta_c$, as shown in Figure 2.

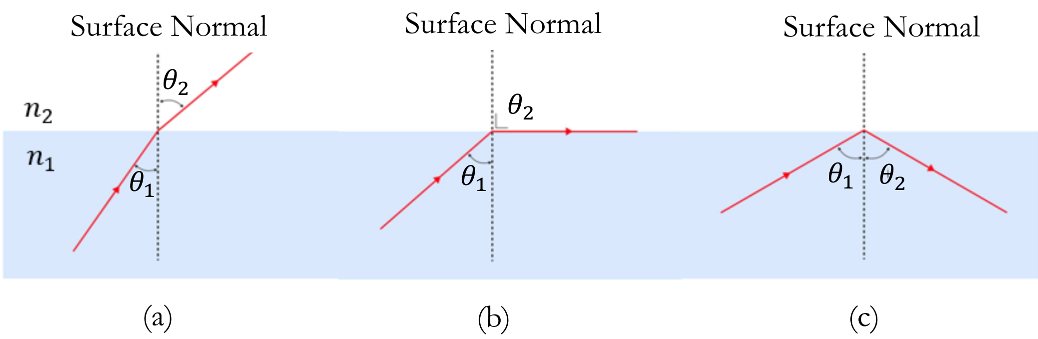

Figure 2. *Light propagation from a medium with a higher refractive index toward a medium with a lower refractive index: (a) when $\theta_1 < \theta_c$, the incident ray is refracted into the second medium; (b) when $\theta_1 = \theta_c$, the ray does not penetrate the second medium but travels parallel to the boundary between the two media; (c) when $\theta_1 > \theta_c$, the incident ray undergoes total internal reflection with the angle of reflection equal to the angle of incidence.*

2.2 Light Ring Patterns due to Total Internal Reflection

When a laser beam is directed into a shallow liquid contained in a vessel with a reflective base, the light undergoes diffuse reflection at the bottom of the container due to micro-textures or minor surface roughness (Huang et al., 2024; Lai et al., 2025). This process causes the initially unidirectional laser beam to transform into a collection of rays propagating in various directions within the liquid. As a consequence of this angular dispersion, the scattered rays reach the liquid–air interface with a wide range of incident angles relative to the normal line. The behavior of these rays depends on their angle of incidence, as illustrated in Figure 3.

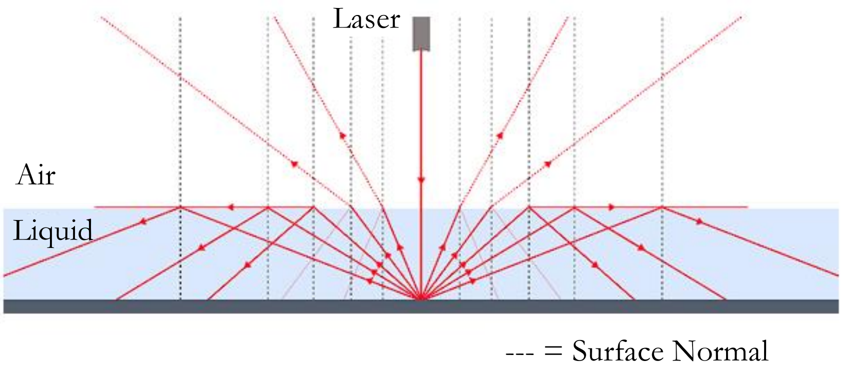

Figure 3. *Propagation of reflected rays within a liquid toward the surface, illustrating variations in the angle of incidence relative to the surface normal in the phenomenon of total internal reflection.*

Rays with an angle of incidence smaller than the critical angle will penetrate the surface and be refracted into the air. Rays with an angle of incidence equal to the critical angle will propagate parallel to the liquid surface, whereas rays with an angle of incidence greater than the critical angle will undergo total internal reflection (Destefano & Widenhorn, 2024, 2025).

As the number of observed rays increases, the bright ring pattern formed around the bright spot can be more easily identified, as shown in Figure 4.

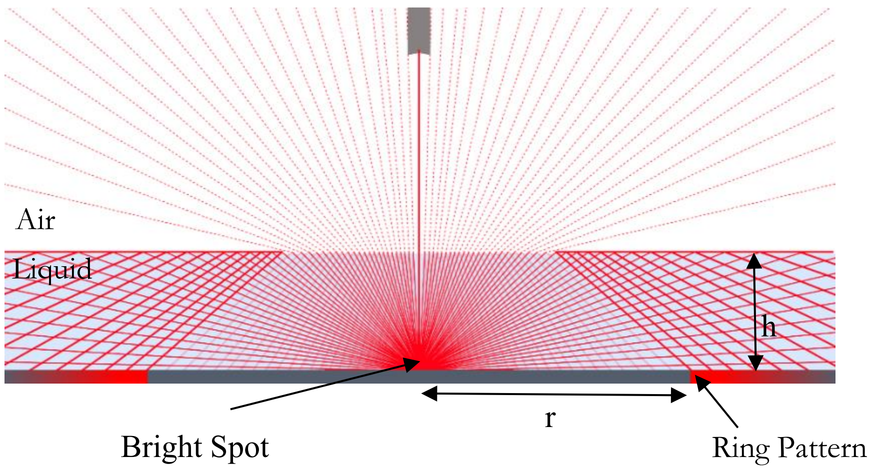

Figure 4. *Formation of the light ring pattern on the base of the liquid as a result of total internal reflection at the liquid-air interface.*

The ring formed on the base of the container is the result of ray paths that satisfy the condition for total internal reflection at the liquid-air interface. These ray paths spread symmetrically in three-dimensional space relative to the central point. Consequently, the points where the rays hit the base are at an equal distance from the center, thus forming a ring pattern, as shown in Figure 5.

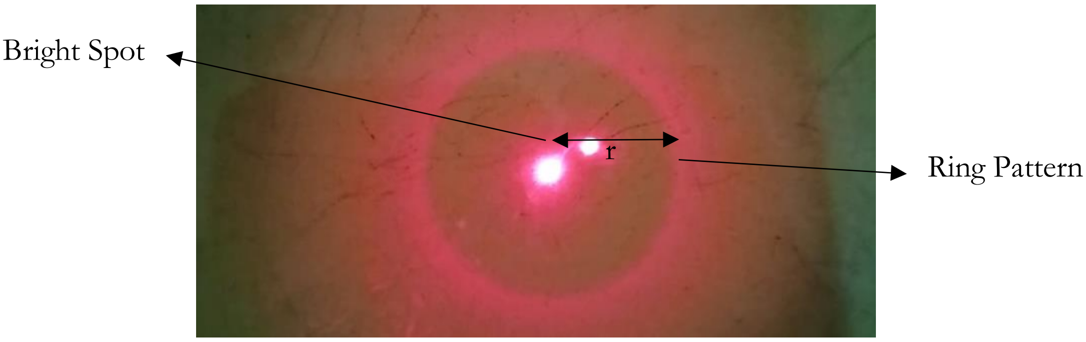

Figure 5. *Experimentally observed light ring pattern from total internal reflection on the liquid base, as viewed from above.*

Observation of the bright ring pattern can be utilized as an experimental method to determine the critical angle, which can then be used to calculate the refractive index of the medium.

2.3 Geometric Analysis of the Ring Pattern

If we consider an incident ray with an angle equal to the critical angle, its propagation path is as shown in Figure 6.

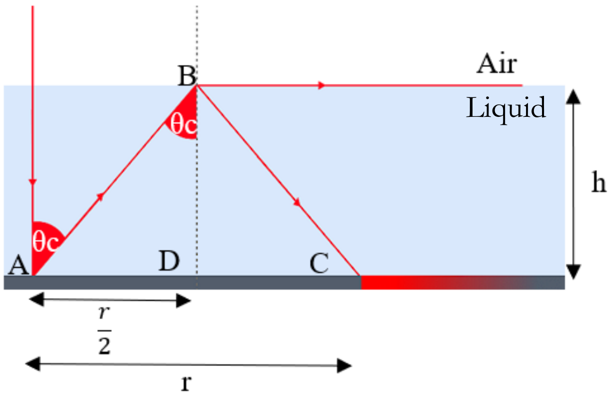

Figure 6. *Geometric analysis of the TIR ring pattern based on an incident ray at the critical angle.*

Triangle ABC is an isosceles triangle resulting from the reflection of the ray, where the angle of reflection equals the angle of incidence. Thus, the length of side AD is half the length of side AC. From triangle ABD, the following geometric relationship is obtained

$$AB = \sqrt{\left(\frac{r}{2}\right)^2 + h^2}. \tag{4}$$

Based on trigonometric identities, the critical angle satisfies the following relationship

$$\sin\theta_c = \frac{AD}{AB}. \tag{5}$$

By substituting Equation (4) into Equation (5), we obtain

$$\sin\theta_c = \frac{r}{2\sqrt{\left(\frac{r}{2}\right)^2 + h^2}}. \tag{6}$$

The relationship between the radius and the liquid height can be implemented into Snell's Law $n_1 \sin\theta_1 = n_2 \sin\theta_2$. According to the behavior of light in total internal reflection, when $\theta_1 = \theta_c$ the ray is refracted along the liquid surface, meaning $\theta_2 = 90°$ relative to the surface normal. The second medium is air, which has a refractive index of $n_2 = 1$. Thus, the equation becomes

$$n_1 \sin\theta_1 = 1. \tag{7}$$

Therefore, the refractive index of the first medium n_1 is expressed as

$$n_1 = \frac{1}{\sin\theta_1}. \tag{8}$$

Substituting Equation (6) into Equation (8) yields

$$n_1 = \frac{2\sqrt{\left(\frac{r}{2}\right)^2 + h^2}}{r}. \tag{9}$$

Squaring both sides and simplifying the equation results in

$$n_1{}^2 = \frac{4\left(\frac{r^2}{4}\right) + 4h^2}{r^2} = 1 + \frac{4h^2}{r^2}. \tag{10}$$

To obtain a linear relationship between the ring radius r and the liquid height h, Equation (10) is rearranged as follows

$$r^2 = \frac{4}{n_1{}^2 - 1} h^2. \tag{11}$$

Thus, a plot of r^2 against h^2 yields a straight line with a gradient m of

$$m = \frac{r^2}{h^2} = \frac{4}{n_1{}^2 - 1}. \tag{12}$$

From Equation (12), the relationship between the refractive index and the gradient of the graph is obtained as

$$n_1{}^2 = 1 + \frac{4}{m} \tag{13}$$

or

$$n_1 = \sqrt{1 + \frac{4}{m}}. \tag{14}$$

3. Method

This study employs an experimental method to test the validity of the developed geometric equations as a basis for determining the refractive index of liquids. The experiment was conducted by observing the formation of light ring patterns when a laser beam was directed into a liquid at specific heights within a container.

The apparatus used consists of a laser pointer with a wavelength of approximately 650 nm, a flat-bottomed container with a reflective base, a ruler, and a digital balance. The liquids used as research objects include water, cooking oil, and NaCl solutions of various concentrations. The parameters measured in this experiment are the liquid height and the radius of the resulting ring pattern.

3.1 Determination of the Refractive Index of Water and Cooking Oil

The first experiment was conducted on water and cooking oil by varying the liquid height. Data analysis in this experiment was performed by determining the gradient of the linear relationship between r^2 and h^2 using Equation (14).

Since the refractive index n depends on the gradient m, the uncertainty of the refractive index Δn was determined through the propagation of the gradient uncertainty using the error propagation method

$$\Delta n = \left|\frac{dn}{dm}\right| \Delta m = \frac{d}{dm}\left|\sqrt{1+\frac{4}{m}}\right| \Delta m = \frac{2}{m^2\sqrt{1+\frac{4}{m}}}\Delta m \,. \tag{15}$$

3.2 Effect of NaCl Concentration on the Refractive Index

The second experiment was conducted on salt solutions by varying the solution concentration. The concentration was calculated as the mass percentage of salt relative to the total mass of the solution using Equation (16).

$$C = \frac{m_g}{m_l} \times 100\%. \tag{16}$$

In this equation, C represents the solution concentration, m_g denotes the mass of the salt, and m_l is the total mass of the solution.

Data analysis was performed by calculating the refractive index directly using Equation (10). The obtained refractive index values were plotted against the solution concentration to determine the relationship between these two parameters.

4. Result

4.1. Experimental Results for Determining the Refractive Index of Water and Cooking Oil

The first experiment was conducted by measuring the liquid height and the corresponding radius of the circular pattern, with variations in liquid height for both water and cooking oil media. The measurement results are summarized in Table 1.

Table 1. *Measurement Data of the First Experiment for Water and Cooking Oil*

No	h (m)$\times 10^{-2}$	h^2 (m²)$\times 10^{-4}$	Water		Cooking oil	
			r (m)$\times 10^{-2}$	r^2 (m²)$\times 10^{-4}$	r (m)$\times 10^{-2}$	r^2(m²)$\times 10^{-4}$
1	0.50	0.25	1.10	1.21	0.60	0.36
2	1.00	1.00	2.20	4.84	1.50	2.25
3	1.50	2.25	3.25	10.56	2.50	6.25
4	2.00	4.00	4.50	20.25	3.50	12.25
5	2.50	6.25	5.50	30.25	4.30	18.49
6	3.00	9.00	6.75	45.56	5.40	29.16

Based on the data in Table 1, the observation results indicate that an increase in liquid height leads to an increase in the radius of the ring pattern for both media. For every identical height variation, the ring radius formed in water tends to be larger than that in cooking oil. This suggests that the differing optical properties of the two liquids influence the dimensions of the resulting light ring pattern. The measurement data were analyzed by plotting the relationship between r^2 and h^2, as shown in Figure 7.

According to Figure 7, the relationship between r^2 and h^2 in both media is linear, with a coefficient of determination R^2 greater than 0.99. This indicates that the experimental data align closely with the geometric relationship predicted by the theoretical model.

The gradient values obtained from the graph were used to calculate the refractive index of each liquid using Equation (14), while the uncertainty of the refractive index was calculated using Equation (15). Theoretical refractive index values from literature were used as references to determine the accuracy of the experimental results. The calculation results are presented in Table 2.

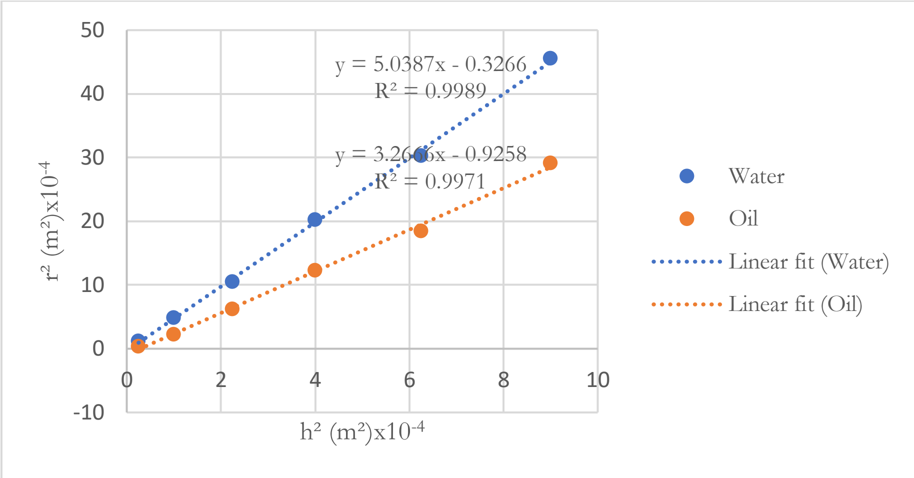

Figure 7. *Linear relationship between r^2 and h^2 for water and cooking oil.*

Table 2. *Gradient m, Gradient uncertainty Δm, refractive index $n \pm \Delta n$, relative uncertainty RU, precision, theoretical refractive index n_{theory}, and accuracy.*

Liquid	m	Δm	$n \pm \Delta n$	RU	Precision	n_{theory}	Accuracy
Water	5.039	0.1097	1.339 ± 0.006	0.48%	99.52%	1.33	99.30%
Cooking oil	3.267	0.1061	1.491 ± 0.013	0.89%	99.11%	1.47	98.54%

Based on the data in Table 2, the experimental results show that the refractive index of water is lower than that of cooking oil. The RU for both media is below 1%, indicating high precision in the experimental data. Although the RU for cooking oil is slightly higher than for water, the accuracy of both measurements remains high and does not differ significantly. This suggests that while the data variation for oil is slightly larger, the obtained average refractive index remains very close to the reference values found in the literature. The higher uncertainty in cooking oil is likely due to the light ring pattern being less sharp compared to that in water, which results in lower precision during the measurement of the ring radius.

4.2. Experimental Results for NaCl Solution Refractive Index

The subsequent experiment was conducted on NaCl solutions by varying the concentration while maintaining a constant liquid height. The refractive index values were calculated using Equation (10), and the experimental data are presented in Table 3.

Table 3. *Refractive Index Measurements of NaCl Solutions at Various Concentrations*

Salt Mass (kg) $\times 10^{-3}$	Solution Mass (kg) $\times 10^{-2}$	Concentration	h (m) $\times 10^{-2}$	h^2 (m²) $\times 10^{-4}$	r (m) $\times 10^{-2}$	r^2 (m²) $\times 10^{-4}$	Refractive Index
0	46.40	0.00%	1.50	2.25	3.25	10.56	1.3609
10	47.40	2.11%	1.50	2.25	3.25	10.56	1.3609
20	48.42	4.13%	1.50	2.25	3.20	10.24	1.3707
30	49.37	6.08%	1.50	2.25	3.20	10.24	1.3707
40	50.35	7.94%	1.50	2.25	3.15	9.92	1.3810
50	51.39	9.73%	1.50	2.25	3.10	9.61	1.3916
60	52.31	11.47%	1.50	2.25	3.10	9.61	1.3916

According to Table 3, it is observed that the radius of the light ring pattern tends to decrease as the solution concentration increases. Consequently, the obtained refractive index values tend to rise with increasing concentration. The relationship between solution concentration and refractive index is illustrated in Figure 8.

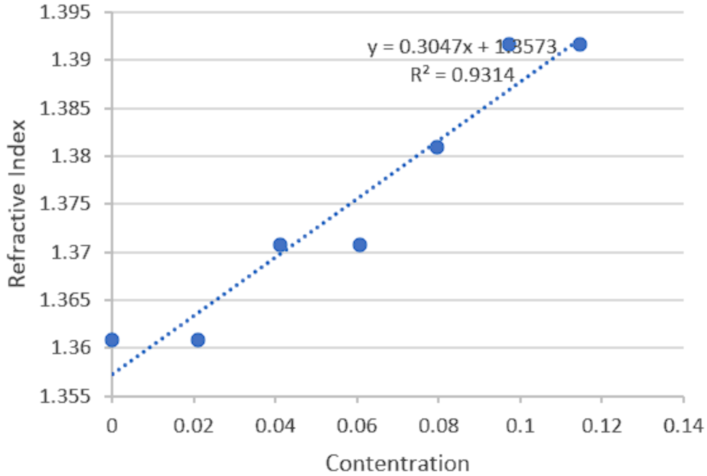

Figure 8. *Graph of refractive index vs. NaCl solution concentration.*

The graph in Figure 8 demonstrates that the refractive index increases proportionally with the solution concentration. The resulting regression equation is $n = 0.3047C + 1.3573$ with a R^2 value of 0.9314. This value indicates that the experimental data follow a linear trend, despite some deviations at certain data points. These deviations are likely caused by limitations in the precision of the visual measurement of the ring pattern radius.

5. Discussion

5.1 Determination of the Refractive Index of Water and Cooking Oil

The experimental results demonstrate that the relationship between r^2 versus h^2 is linear, with a very high coefficient of determination. This indicates that the light ring pattern formed on the liquid surface follows the geometric relationship predicted by the theoretical model. Such linearity suggests that the proposed method effectively represents the theoretical framework.

The difference in refractive index values between water and cooking oil is consistent with the optical properties of the two media. Cooking oil possesses a higher optical density than water, leading to greater light refraction; consequently, its refractive index is higher. These findings are consistent with refractive index values reported in the literature.

The refractive index values for water and cooking oil obtained in this study are in close agreement with reference values reported in previous research using different optical methods, such as Fraunhofer diffraction and the parallel plate method (Pratiwi et al., 2024; Rosmalinda, 2019). The proximity of these results to reference values demonstrates that the light ring pattern analysis is capable of producing refractive index measurements with an accuracy comparable to established methods.

5.2 Effect of NaCl Concentration on the Refractive Index

Experimental data show that the refractive index of the NaCl solution increases with concentration, which aligns with established theory (Barbosa et al., 2011). This phenomenon occurs because the addition of solute increases the optical density of the medium, thereby reducing the propagation speed of light within it and resulting in a higher refractive index.

The relationship between solution concentration and refractive index exhibits a linear trend, despite some deviations at certain data points. These discrepancies are likely attributable to precision limitations in the visual measurement of the ring pattern radius. Subtle changes in the radius are often difficult to distinguish visually. However, even minor reading errors can lead to significant fluctuations in the calculated refractive index.

This study highlights the advantages of the light ring pattern analysis method. Compared to direct calculation methods that rely on a single radius value, the gradient method utilizes multiple data points, allowing small measurement errors to be minimized through linear regression. This approach yields a more stable and precise refractive index value.

5.3 Research Implications

This research demonstrates that observing light ring patterns serves as a simple yet effective approach for determining the refractive index of liquids. This method has the potential to become an alternative experiment in optics education, as it visually illustrates the phenomena of refraction and reflection using simple apparatus. Furthermore, it enables the observation of the relationship between solution concentration and optical properties, thereby deepening the conceptual understanding of refractive index in physics.

5.4 Research Limitations

This study has several limitations that may affect the precision of the results. A primary source of error is the potential for parallax error during the visual measurement of the light ring radius. Additionally, the sharpness of the ring pattern is not uniform across all media, which can make defining the exact boundary of the ring challenging. Consequently, the observer's precision in scale reading and boundary determination significantly influences the measurement outcomes.

6. Conclusion

This research demonstrates that the light ring pattern formed by total internal reflection can be effectively utilized as an alternative approach for measuring the refractive index of liquids. Through a geometric analysis of the relationship between r^2 and h^2, the refractive index can be determined from the gradient of the graph without requiring direct angular measurements. The application of this method to water, cooking oil, and NaCl solutions shows that the reflection light ring phenomenon consistently represents the optical properties of the media. Furthermore, the increase in refractive index corresponding to higher NaCl concentrations aligns with the theoretical trends reported in the literature. These findings confirm that the reflection light ring-based approach holds significant potential as an alternative technique for refractive index measurement, offering a relatively simple experimental procedure. With further development, specifically in enhancing the precision of ring radius measurements, this method has the potential to become an effective experimental approach for both optical research and physics education.

Authors Contribution

Oktaviana Dwi Saputri: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Suharto Linuwih:** Methodology, Supervision, Validation, Writing – review & editing. **Listiyanto:** Methodology, Supervision, Validation, Writing – review & editing.

Ethical statement

This article reports a theoretical and experimental study and does not involve human participants or animals. Therefore, formal ethical approval was not required. The authors confirm that no personal or sensitive data were collected, processed, or analyzed in this study

Declaration of AI use

The authors used ChatGPT (OpenAI) to improve sentence structure and readability in the original draft. Gemini AI was used to translate the revised text into English. All AI-assisted outputs were carefully reviewed, edited, and approved by the authors, who remain fully responsible for the accuracy, originality, and integrity of the final manuscript.

Conflict of Interest

The authors declare that there is no conflict of interest, either financial or non-financial, that could be perceived as influencing the work reported in this manuscript. All authors have reviewed and approved this statement.

Supplementary Materials and Data Availability

No public repository is currently available for the dataset. However, the instruments and key data summaries used in this study can be obtained from the corresponding author upon reasonable request. Any data shared will be anonymized and provided in accordance with the ethical approval.

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