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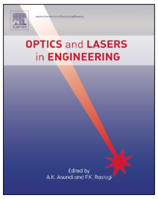

Determining the concentration of methanol within a liquid mixture of ethanol and methanol using a laser interferometer

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ABSTRACT

This paper investigates using an optical measurement method to determine the concentration ratio in a liquid mixture of methanol and ethanol. To better understand the relative mixture solution concentration, the dilution method is used to determine slight variations in the refractive index of the variable mixture concentration. The test concentration range of both methanol and ethanol is between 0–90%. The results of our analysis indicate that the refractive index of a mixture of methanol and ethanol lies in the interval between the refractive index of pure ethanol and methanol. The optical property of the mixture is similar to that of the solution material with the highest quantity. Regression analysis using a quadratic function resulted in an error of 25%. Regression analysis using a cubic function reduced the error to 6.25%. Therefore, the regression analysis function used in this study is the cubic function, as the mixture solution includes the methanol liquid. Combining the optical measurement and dilution methods can yield the solution concentration of the liquid mixture.

1. Introduction

Alcohol is a compound of both industrial and human importance. It is used in a variety of applications. It has two forms, i.e., ethanol and methanol. Methyl alcohol (CH_3OH) is an organic compound. Because methyl alcohol can lead to the formation of formaldehyde and formic acid in the human body, it is poisonous to humans. Importantly, the toxicity of certain solutions depends on the amount of methyl alcohol that they contain, and reliable and straightforward techniques should thus be developed that are capable of measuring the concentration of methyl alcohol. In general, such measurements are performed using stereometry techniques. However, these methods exhibit relatively poor measurement resolution. Optical methods offer the potential of obtaining higher-resolution concentration measurements by relating the alcohol concentration of a liquid sample to its refractive index. Various methods have been proposed for measuring the refractive indeces of liquids. For example, Feng et al. [1] determined the refractive index and phase of glucose using the heterodyne polar meter of the variable phase. While this method can reduce external perturbation, the system is very complex. Lin and Su [2] used the laser heterodyne interference method and the optical polar meter to determine the refractive index and chiral properties of a liquid. Yeh and Lin [3] developed a high-precision, non-destructive measurement technique based on a laser interferometer for determining the alcohol concentration of a liquid solution from its refractive index. Yeh et al. [4] developed a high-precision, non-destructive optical metrology system based on a position-sensing detector for measuring the refractive index of a liquid solution such that its alcohol concentration can be derived. Mitsuhiro Fukuta et al. [5] investigated the refractive index of oil using a laser displacement sensor to detect a change in the optical path. It was determined that the difference in refractive index between the refrigerant and oil was sufficient for measuring the mixing concentration of the refrigerant/oil mixture. From the literature, it is known that the surface plasmon resonance (SPR) method is a highly sensitive technique for measuring the refractive index of a liquid. Mart et al. [6] used the SPR method to distinguish three types of tequilas according to their respective SPR curves. The authors found that the resonant angle of the SPR curve produced by silver tequilas is larger than that produced by the aged and extra-aged tequilas from the same producer. The resonant angle of the SPR curve can employed to distinguish the different tequilas. Lee and Tsai [7] investigated measuring the refractive index variation of liquids using the SPR method. In their paper, the resolving power of the refractive index is 1.5×10^{-6}. However, the SPR method exhibits a highly sensitive performance. The experimental device is very complex. [7]. Accordingly, the current study employs a laser interferometer as the basis of a simple yet highly accurate optical metrology system designed to

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evaluate the alcohol concentration of a liquid solution. The literature [3] indicates that this method can be employed to easily determine the concentration of a one-component liquid. If two- or multi-component solutions are applied, however, the interferometer alone cannot distinguish the individual components from the solution mixture to determine their respective concentrations. Therefore, it is necessary to increase the capability of the measurement. Regression analysis is applied to determine the multi-material solution concentrations.

The proposed system has the advantage of a straightforward optical setup and experimental procedure. After verifying its measurement performance, the metrology system is then used to measure the refractive indeces of solutions with known methyl and ethyl alcohol concentrations ranging from 10–90%. Based upon the experimental results, an analytical expression is derived to describe the relationship between the refractive index and alcohol concentration. The feasibility of using this analytical expression to derive the alcohol concentration of liquid mixture samples, given knowledge of their refractive index values, is experimentally demonstrated.

2. Measurement system

2.1. Structural design and experimental procedure

Fig. 1 presents a schematic illustration of the optical metrology system. The system is comprised of a measuring length host, a polarization beam splitter (Agilent 10706A), two corner cube retro-reflectors, a stepping motor, a quarter-wave plate, a plane reflector and a rectangular cell containing the liquid sample.

The objective of the optical system, shown in Fig. 1, is to measure the refractive index of a liquid solution such that the concentration of the liquid components can be derived. The measurement procedure is shown in a previous study [3].

2.2. Mathematical analysis

Rotating the sample cell changes the length of the optical path in the interferometer system. Assuming that the cell has a perfectly rectangular shape, the change in the optical path length is dependent on the rotational angle, the refractive index and the thickness of the two glass plates in the cell, as well as the refractive index and thickness of the liquid layer within the sample cell. Fig. 2 presents a schematic illustration of the relationship between the optical path length difference through the liquid sample cell and its angle of rotation.

The change in length of the optical path, L, when the rectangular liquid cell is rotated through an angle θ, is given mathematically by

$$L=2\left[\frac{T_1}{\cos\theta_{T1}}-T_1\right]_{glass}+\left[\frac{d}{\cos\theta_d}-d\right]_{liquid},$$

$$-2\left[\frac{T_1\cos\phi_{T1}}{\cos\theta_{T1}}-T_1\right]_{air}-\left[\frac{d\cos\phi_d}{\cos\theta_d}-d\right]_{air} \tag{1}$$

where T_1 is the glass thickness; d is the liquid thickness; θ_{T1} is the refractive angle of the glass; θ_d is the refractive angle of the liquid; and $\phi_{T1}=\theta-\theta_{T1}$ and $\phi_d=\theta-\theta_d$, where θ is the angle of rotation. From Snell's law, it can be shown that

$$n_0\sin\theta=n_1\sin\theta_{T1} \tag{2}$$

$$n_1\sin\theta_{T1}=n_2\sin\theta_d, \tag{3}$$

where n_0, n_1 and n_2 are the refractive indeces of air, glass and the liquid sample, respectively.

Substituting Eqs. (2) and (3) into Eq. (1), the change in the optical path length can be expressed as

$$L=2\left[\frac{T_1}{\left(1-\left(\frac{n_0\sin\theta}{n_1}\right)^2\right)^{0.5}}-T_1\right]_{glass}+\left[\frac{d}{\left(1-\left(\frac{n_0\sin\theta}{n_2}\right)^2\right)^{0.5}}-d\right]_{liquid}$$

$$-2\left[\frac{T_1\cos\left[\theta-\sin^{-1}\left(\frac{n_0\sin\theta}{n_1}\right)\right]}{\left(1-\left(\frac{n_0\sin\theta}{n_1}\right)^2\right)^{0.5}}-T_1\right]_{air}-\left[\frac{d\cos\left[\theta-\sin^{-1}\left(\frac{n_0\sin\theta}{n_2}\right)\right]}{\left(1-\left(\frac{n_0\sin\theta}{n_2}\right)^2\right)^{0.5}}-d\right]_{air} \tag{4}$$

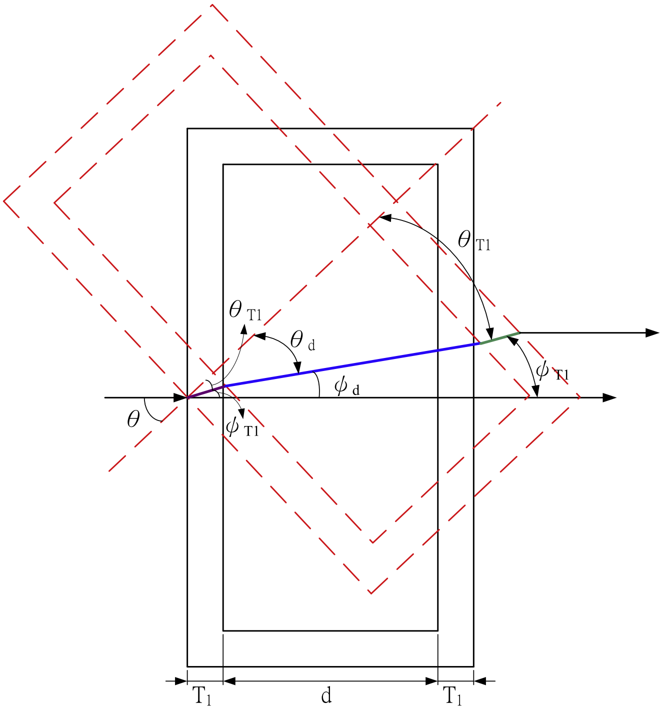

Fig. 2. Relationship between the optical path length difference through the liquid sample cell and the rotational angle.

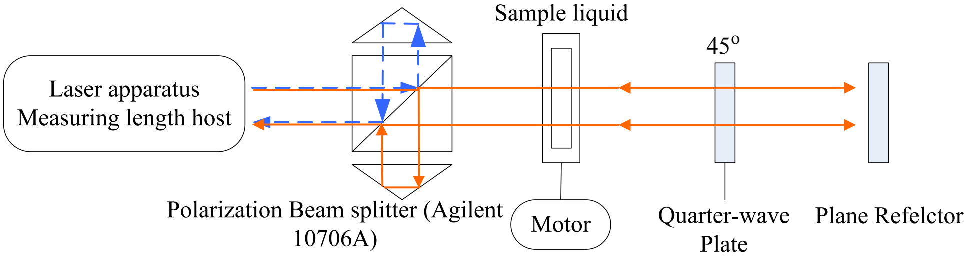

Fig. 1. High-precision optical metrology system for determining the refractive index of a liquid solution.