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Expand the measurement range of a critical angle refractometer by a centroid method for transparent fluids

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ABSTRACT

A simple approach to expand the measurement range of a critical angle refractometer (CAR) is demonstrated. Our method is based on measuring the centroid point of the angular reflective ratio of the CAR. According to the Snell's reflective law, the CAR with a divergent beam source has a limited measurement range. When the refractive index (RI) is higher than the upper limit, the reflective ratio curve is gradual changing without cutoff edge between the total internal reflection (TIR) and non-TIR. We find that the centroid point of the gradual changing curve is associated with the RI value of a liquid. Theorectical analysis and experimental results on sugar solutions with RI that varying from 1.359 to 1.3766 show that this method is effective and accurate to expand the measurement range.

1. Introduction

Most commonly the refractive index (RI) is widely used as an indirect measuring parameter of salinity, acidity and Brix in chemical analysis, food engineering, liquid quality monitoring and many other science and engineering fields. The RI of a liquid always has a linear correlation with some liquid parameters difficult to be measured on line. A digital critical angle refractometer (CAR) measures the RI of a liquid by measuring the reflective ratio of a divergent light beam from the surface between the prism and the liquid sample. The digital CAR is based on finding the critical angle point between the total internal reflection (TIR) region and non-TIR region [1]. According to Snell's law and the Fresnel reflective model, the measurement range is determined by the maximal incident angle on the sample surface and the RI of the optical prism [2]. When the RI of a liquid is higher than the upper limit, the reflective ratio curve does not have a cutoff edge between TIR and non-TIR. It means that the critical angle based algorithms by many digital CARs are no longer applicable. Thus, it is important to provide an algorithm to expand the measurement range of the CAR and to measure the RI accurately.

Traditionally, the digital CAR is comprised of a divergent light source, an optical prism, a lens and a CCD camera. The measurement range is determined by the divergent angle and the RI of the prism. Previous attempts to expand the measurement range focus on the hardware improvement such as using a large divergent angle beam and an optical prism with high RI [3]. These attempts are unreliable in practical applications due to the chemical properties of the liquid. When the RI of a liquid is higher than the upper limit, the angular reflective ratio of the CAR contains the RI information of the liquid. It is possible to extract the RI from the reflective ratio by some algorithms without any additional cost.

In the CAR, the liquid sample to be measured is always smaller than the measuring prism of transparent glass. Furthermore, the light rays with incident angles less than the critical angle cause a partial reflection on the dielectric surface between the liquid sample and the prism, whereas others cause total internal reflection (TIR). The CAR is ineffective when the RI of the liquid sample is beyond the upper limit of the refractometer. The RI information is mainly extracted from the cutoff edge near the critical angle between the bright and dark regions using existing algorithms, such as the differentiation [4,5], threshold [6], and the curve-fitting algorithms [7–12]. The differentiation algorithm is a representative and straightforward algorithm for commercial CAR. Mohammadi demonstrated the differentiation algorithm by defining the presentational critical angle as the maximum change of the slope of the relative reflective curve [4]. Guo, in our group, applied the differentiation algorithm in a two-reflection CAR to improve the accuracy of RI measurement [5]. The threshold algorithm was introduced by Bali, who suggested that the pixel point of a fixed percentage of the maximal reflective light intensity be taken as the critical-angle point [6]. The curve-fitting algorithm utilizes the regression analysis between the experimental reflective curve and the Fresnel reflective model to obtain RI information. None of these algorithms have the potential to increase the measurement range of the CAR.

Multiple-reflection is an effective technique to increase the angel measuring sensitivity in an optical system and improve the RI measurement in the CAR. Huang and Ni introduced multiple

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reflections in an angle measuring system with elongated critical angle prism to increase the measurement sensitivity and got an excellent linear correlation [13]. Garcia-Valenzuela et al. analyzed the angle-sensitive device by the critical angle effect, and demonstrated an angle measuring method with a maximum sensitivity close to the diffraction limit [14]. Zheng et al. proposed an improved angle method to measure a small angular displacement with high accuracy by a parallel plated interferometer [15].

In this paper, we present a simple algorithm based on a centroid method to expand the measurement range of the triple-reflection CAR. The main difference of the proposed algorithm from the aforementioned algorithms is that the centroid method obtains RI information from the centroid point of the reflection rather than finding the critical-angle point between the non-TIR and TIR. When the RI of a liquid is beyond the upper range, the incident beam causes partial reflection. The centroid point of the angular reflective curve is different when the RI changes. Using a numerical analysis and experiment on sugar solutions, we find that the centroid point corresponds to the RI of the liquid. Notably, we demonstrated that the centroid algorithm can simply expand the upper range of the CAR. Our algorithm can be simply applied to the digital Abbe-type CAR.

2. Theory

2.1. Principle of the CAR

The general model of the CAR makes a divergent light beam incident on the interface between the prism of known RI n_{prism} and the liquid of unknown RI. The reflection from the interface is modulated with the RI information of the liquid. The reflection of a CAR with a fixed incident angle range and a fixed RI prism n_{prism} has its possibilities in different RI samples. When the RI of a liquid is less than $n_{prism}\sin(\theta_{min})$, all the incident beams cause TIR and the reflectance can be regarded as the light background of the RI determining system. When the RI of a liquid is less than $n_{prism}\sin(\theta_{max})$ and higher than $n_{prism}\sin(\theta_{min})$, the reflection is comprised of a bright region and a dark region as shown in Fig. 1(a). The incident angle ranges $[\theta_{min},\theta_{max}]$are associated with the measurement range $[n_{prism}\sin(\theta_{min}),n_{prism}\sin(\theta_{max})]$ by Snell's law. The critical angle point, which is the abrupt boundary between these regions corresponds to the RI of the liquid. When the RI of a liquid is more than $n_{prism}\sin(\theta_{max})$, the reflection is a gradual dark region as shown in Fig. 1(b). As illustrated, all the incident beams are partially reflected on the dielectric surface. Not unexpectedly, the critical angle based algorithms such as differentiation, threshold, and curve fitting algorithms are ineffective, when the reflection does not possess a step changing character. The reflective ratio of the CAR is obtained through dividing the reflectance of the sample by the system background.

For an unpolarized light beam, the reflective ratio $R(\theta,n_{liquid})$ of third possibility in our experimental setup accords with the well-known Fresnel model and can be expressed as

$$R(\theta,n_{liquid})=\left\{\frac{\sin^2(\theta-\theta_2)}{\sin^2(\theta+\theta_2)}+\frac{\tan^2(\theta-\theta_2)}{\tan^2(\theta+\theta_2)}\right\}^m \quad (1)$$

where θ is the incident angle on the surface, n_{liquid} denotes the RI of the liquid sample, $\theta_2=\arcsin(n_{prism}\sin(\theta)/n_{liquid})$, and m denotes the number of reflections between the prism and the liquid sample. In our system, the incident light beam causes triple reflections. The multiple internal reflections between the parallel measuring surfaces in the prism can greatly improve the angle measurement accuracy.

2.2. Centroid method

The aforementioned algorithms get the RI information by the step changing of a localized reflective curve around the critical angle. When the RI of a sample is beyond $n_{prism}\sin(\theta_{max})$, $R(\theta,n_{liquid})$ is a gradual increasing curve without any step change. The centroid method is a simple algorithm to analyze the angular reflective ratio curve of a CAR. It utilizes the centroid point to represent the distribution of $R(\theta,n_{liquid})$. As for the CAR, the angular reflective ratio is a function of the incident angle θ and the RI value of the liquid n_{liquid}. The range of θ is always constant. The reflective ratios in each θ is disparate with different RI liquid samples. According to Fresnel's reflective law, the distribution of the angular reflective ratio corresponds to the RI of the sample n_{liquid}. When n_{liquid} changes, the distribution of $R(\theta,n_{liquid})$ also changes. So the centroid point $C(n_{liquid})$ is related to the RI of the sample and can be expressed as

$$C(n_{liquid})=\frac{\int_{\theta_{min}}^{\theta_{max}} R(\theta,n_{liquid})\theta\, d\theta}{\int_{\theta_{min}}^{\theta_{max}} R(\theta,n_{liquid})d\theta} \quad (2)$$

where θ_{min} is the minimal value of the incident angle and θ_{max} is the maximal value of the incident angle. Here we calculate the angular reflective ratio curves of different RI value liquids, when $m=1$, $n_{prism}=1.52427$, $\theta_{min}=53.5^\circ$ and $\theta_{max}=62.5^\circ$. The reflective ratio curve with black color in Fig. 2 is composed by non-TIR region and TIR region, when $n_{liquid}=1.345$. The reflective ratio curves with $n_{liquid}>n_{prism}\sin(\theta_{max})$ are gradual changing without any step such as the red curve, blue curve, plum curve and green curve. And the rising velocity of the curve is monotonically decreasing, when n_{liquid} increases. The centroid point value can represent the change of the rising velocity of the curve. So, it is possible to use the centroid point of the reflective curve to represent the RI value and establish the function between the centroid point and RI.

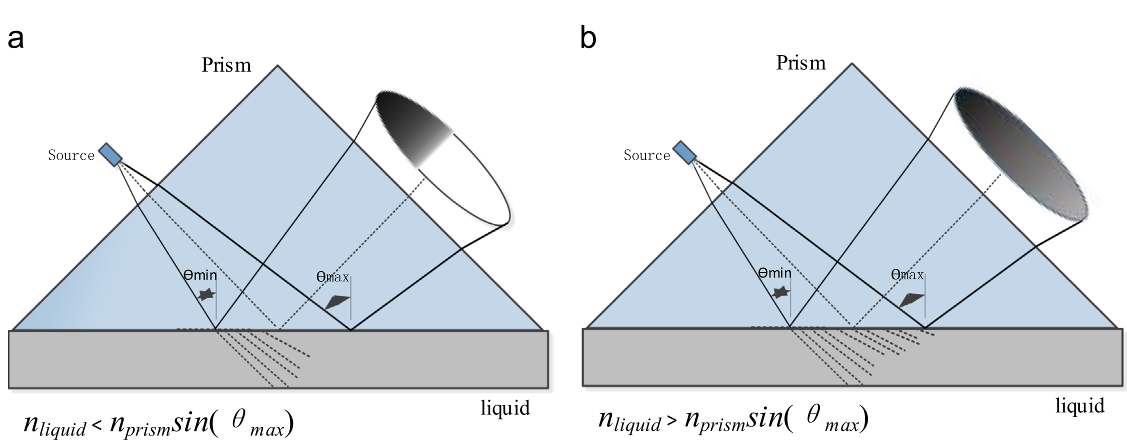

Fig. 1. Two possibilities of the reflection in liquids with different RI values.