Sensors and Actuators B 257 (2018) 766–771

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

Research paper

Technique of dual-wavelength micro-lens imaging which can eliminate thermal noise for accurate on-site concentration measurement

Jiang He, Guang-Yun Jiang, Xue-Cen Zhao, Yao-Xiong Huang*

Department of Biomedical Engineering, Ji Nan University, Guang Zhou, China

ARTICLE INFO

Article history:
Received 8 August 2017
Accepted 25 October 2017
Available online 26 October 2017

Keywords:
Accurate on-site concentration measurement
Thermal noise
Mixing or inhomogeneous solutions
Dual-wavelength micro-lens imaging

ABSTRACT

The present paper reports a novel dual-wavelength micro-lens imaging technique which uses micro-lens as the sensor and can eliminate thermal noise for on-site real time and continues accurate concentration detection in mixing or inhomogeneous solutions. By simply immersing micro-lenses into sample solution and deducing the refractive indices of the solution from their images taken with two wavelengths, the technique can eliminate random thermal noise for accurate solution concentration measurement. With the technique, the accuracy and precision of refractive index detection was improved to $\pm 10^{-6}$. Detections on NaCl and glucose solutions demonstrated that the measured concentrations were just about 0.005%–0.01% away from true values for one centigrade temperature fluctuation, and can catch the temporal concentration variation at a speed of two measurements per second.

1. Introduction

Nowadays on-site measurement of solution concentration is required in many branches of chemistry, physics and biology as well as in industry [1–3]. Especially in some separation and reaction processes and microfluidics processes, the stream or micro fluid is usually desired to enter into processing units with precise compositions; otherwise there will be undesirable variation in product stream composition [4–6]. One effective method to measure the composition or concentration of the solutions in the processes is refractive index (RI) measurement, for the detection of refractive index is quick and simple. However, the conventional methods of refractive index measurement such as Abbe refractometers [7] and interferometry [8,9] cannot be used in the cases in which on-site refractive index/concentration measurement is desired. The reason is that these refractometers need to introduce the solution into the refractometers for measurement. Therefore, to meet the requirement of on-site refractive index/concentration measurement, we have to develop new method.

We have previously developed a microsphere imaging technique [10] which uses microsphere as the sensor, can monitor the instant refractive index variation in an inhomogeneous medium or fluid mixtures with the imaging of the microsphere. The method is simple and easy, just needs to immerse a microsphere into the medium, and then measure the radius r of the central bright spot in the image of the microsphere and the sphere's radius R, the refractive index of the medium can be deduced from the ratio r/R. Since the used microspheres can be as small as several hundred nanometers to several hundred microns in diameter, they can be put into a processing unit and even a microsystem of microfluidics process for on-site measurement while without disturbance on the fluids. Therefore, microsphere imaging can be a candidate sensing technique of performing on-site real time and continues concentration monitoring in a processing unit or microfluidics systems.

However, refractive index is not only a function of concentration, but also a function of temperature and wavelength [11,12]. Generally one centigrade variation in temperature corresponds to 1.0×10^{-4}–2.0×10^{-4} RI changes in aqueous solutions[13]. Such a temperature dependency is usually higher with other solvents. In comparison, one percent of concentration corresponds to approximately 0.0015–0.002 change in RI, so a change of one centigrade corresponds typically to a change of 0.05%–0.1% in concentration. Therefore, to have an accurate concentration measurement, we have to eliminate the thermal noise induced by the environmental temperature fluctuation from the RI detection. Though the processing unit can be under thermostatic control, temperature fluctuation of 1–2 °C would still often happen and in some cases, the stream or micro fluid gets into the unit for mixing so fast that it has no enough

* Corresponding author at: Department of Biomedical Engineering, Ji Nan University, Guang Zhou, 510632, China.
E-mail address: tyxhuang@jnu.edu.cn (Y.-X. Huang).

https://doi.org/10.1016/j.snb.2017.10.148
0925-4005/

time to be in equilibrium with the temperature of the unit. Hence we need to develop a new method which is based on the technique of microsphere imaging but can eliminate the influence of thermal noise on concentration measurement. On the other hand, in the image of a microsphere, the edge of its central bright spot and its radius is not focused at the same focal plane; the optical quality of the microsphere's image is not satisfied for high accuracy concentration measurement. Therefore, the imaging technique itself also needs to be improved.

Here we report a novel dual-wavelength micro-lens imaging technique which uses micro-lens as the sensor for better optical imaging quality and two wavelengths for imaging to eliminate the thermal noise. By the method, the RI detection accuracy and precision was improved to $\pm 10^{-6}$ and thermal noise was largely eliminated so that accurate on-site concentration determination is possible. Measurements on NaCl and glucose solutions with the method showed that the measured concentrations was just 0.005%–0.01% deviating from true values for one centigrade temperature fluctuation.

2. Theoretical background

The refractive index of a solution is a function of solute concentration, temperature and wavelength. The RI of a medium as a function of wavelength and temperature can be expressed as [14]:

$$n(\lambda, t) \approx 1 + N_A \rho(t) \alpha(\lambda)/(2M\varepsilon_o). \quad (1)$$

Where t is temperature, N_A is Avogadro constant, ρ is density, α is molecular polarizability, M is molecular weight, and ε_0 is vacuum permittivity. The molecular polarizability is a molecular property that is largely independent of temperature but strongly dependent on wavelength. The density is a bulk property that is independent on wavelength but dependent on temperature[15]. For small temperature variations, the density is considered as a linear function of temperature. Thus, for a given wavelength, Eq. (1) can be simplified as:

$$n(\lambda, t) = n_0(\lambda) + \gamma(\lambda)\Delta t. \quad (2)$$

Where n_0 is the RI at reference temperature, γ is a temperature coefficient, but at the same time, it is also a wavelength-dependent factor. Δt is the temperature deviation from the reference temperature.

On the other hand, the dependence of RI of a solution on the solute concentration at a certain temperature can be expressed as:

$$n(\lambda, c) = n_0(\lambda) + R(\lambda)\Delta c. \quad (3)$$

Where c is the concentration, n_0 in here is the RI of the pure solvent, and $R(\lambda)$ is the (molar) refractive index increment for a given solvent/solute mixture at a certain wavelength. For dilute solutions, the RI of a solution is linearly dependent on concentration. Since both temperature and concentration are independent properties, Eqs. (2) and (3) can be combined as:

$$n(\lambda, t, c) = n_0(\lambda) + \gamma(\lambda)\Delta t + R(\lambda)c \quad (4)$$

Now n_0 is the refractive index at reference temperature and concentration. This equation was proved to be valid for different kinds of aqueous solutions in our previous experiments [3]. When two wavelengths are considered, we have:

$$n(\lambda_1, t, c) = n_0(\lambda_1) + \gamma(\lambda_1)\Delta t + R(\lambda_1)c, \quad (5)$$

$$n(\lambda_2, t, c) = n_0(\lambda_2) + \gamma(\lambda_2)\Delta t + R(\lambda_2)c. \quad (6)$$

From Eqs. (5) and (6), we can obtain the following equation:

$$c = \frac{\gamma_{12}[n(\lambda_1, t, c) - n_0(\lambda_1)] - [n(\lambda_2, t, c) - n_0(\lambda_2)]}{\lambda_{12}R(\lambda_1) - R(\lambda_2)}. \quad (7)$$

Where $\gamma_{12} = \gamma(\lambda_1)/\gamma(\lambda_2)$. The temperature coefficient γ (λ) for a given wavelength can be obtained by the derivative dn/dT in Eq. (3), while $R(\lambda)$ can be obtained by the derivative dn/dc in Eq. (4). It should be noted that the temperature term (Δt) has been already eliminated from Eq. (7). Therefore, by using two wavelengths to measure the refractive indices n (λ_1, t, c) at λ_1 and n (λ_2, t, c) at λ_2 respectively, we can eliminate the "thermal noise" that is connected with conventional RI detection to obtain accurate values of concentration c.

As described previously that, to monitor the instant variation of local concentration in solution and have better optical imaging quality for accurate concentration detection, we used micro-lens imaging for the measurement. The reason we replaced microsphere with micro-lens was that in the imaging of a micro-lens, the images of the central bright spot and the lens' periphery are located at the same focusing plane, so micro-lenses imaging would have better image optical quality [16]. It can be proved that, by immersing a micro-lens with RI of n_2 into a solution and illuminating it with parallel light, a dark ring would appear in its image as shown in Fig. 1. By measuring the radius r of the central bright spot of the image and the radius R of the micro-lens to obtain the ratio X (r/R), the RI of its surrounding medium n_1 can be deduced from the following equation:

$$X = \sin\alpha - \left[\cos\alpha + \frac{h}{R}\right] \frac{\sin\alpha\sqrt{1 - \left(\frac{n_1}{n_2}\right)^2 \sin^2\alpha} - \left(\frac{n_1}{n_2}\right)\sin\alpha\cos\alpha}{\cos\alpha\sqrt{1 - \left(\frac{n_1}{n_2}\right)^2 \sin^2\alpha} + \left(\frac{n_1}{n_2}\right)\sin^2\alpha}. \quad (8)$$

As aforementioned that, since the edge of the central bright spot and the lens' radius were focused at the same focal plane, the optical image quality of a micro-lens is much better than that of a microsphere as shown in Fig. 1.

3. Experimental

3.1. Materials

Aqueous NaCl and glucose solutions were prepared using NaCl (99.9%, Guangzhou Chemical Reagent Factory) and glucose (99.9%, Guangzhou Chemical Reagent Factory) respectively. The employed water for the solutions was purified with a Milli-Q de-ionization system. Both the NaCl and glucose sample solutions were prepared with the purified water to become100 mL in volume with 1, 5, 10 and 20 mass% concentrations respectively.

3.2. Experimental setup

The experimental setup of the dual-wavelength micro-lens imaging is shown in Fig. 2. It was equipped with a red LED parallel light source of 660 nm and a purple LED parallel light source of 405 nm. The reason to choose these two wavelengths was that both the wavelengths are visible, providing a significant advantage for alignment and optical imaging. Furthermore, the r of the dark ring in the image of the micro-lens is significantly different at these two wavelengths so that measuring error can be reduced. The lights illuminated to the sample cell via an optical beam splitter. The two light sources were alternately switched on and off using an electronic aperture and the time to switch one light source to another can be less than 0.5 s. A digital camera (PCO, Germany) with a 10× objective was used for imaging. The image of the micro-lens was then sent to a computer with a homemade intelligent image analyzing software for intelligent image recognition and r and R detection to have the value of n_1. Theoretically, the detection limit of the refractive index measurement is about $\pm 10^{-6}$ when using a CCD camera of 5472 × 3678 pixels for imaging and with the super-resolution method to measure both r and R [17]. The temperature of the solu-