Sensors and Materials, Vol. 16, No. 7 (2004) 319–334
MYU Tokyo

S & M 0569

Design of the Optical Fiber Transmission and Geometrical Microoptical Path in the Optical Liquid Drop Sensor

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(Received April 8, 2004; accepted September 8, 2004)

Key words: drop analysis, liquid drop sensor, optical fiber, microoptical path, liquid drop fingerprint

An optical liquid drop sensor detects the light signal passing through the liquid drop during drop growth. A drop head is used to form the drop. A 90° reserve cone angle at its lower end is specially designed based on surface theory, to ensure that the liquid can fully wet the end surface of the drop head. How to transmit the light signal with low loss in both intensity and spectrum is a key technology. Optical fiber transmission is a simple and convenient method if the transmission characteristic of the fiber match the spectral width when studying a specific liquid. The coupled light signal is related to the penetration depth of fibers into the liquid drop. So a fiber height adjuster is desired. A geometrical microoptical path is favorable for studying the absorption spectrum of the multiwavelength light signal passing through the liquid. Spherical lenses inside the drop head are employed as the light injector and collector. They are positioned symmetrically so that the drop profile is not influenced by different contact surfaces. Experimental graphs of some samples are presented.

1. Introduction

The properties of liquids have long been a concern for industrial, agricultural and environmental science. Many theories and methods have been constructed and applied for measuring various natural parameters of liquids. Devices such as the surface tensiometer, viscosity meter, turbidity meter and instruments for measuring BOD and COD are well established and mature. However, if several parameters are expected to be measured

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simultaneously, conventional individual methods seem to be inadequate, and the correlation between data obtained using various instruments is still in doubt.

Moreover, liquid identification and discrimination are key factors for preventing counterfeits prevention in commercial activity. If there is a unique "fingerprint" for a certain liquid, just like the fingerprint for a certain person, it becomes easy to distinguish quality goods from counterfeits, such as fake beverages, fake medicines and fake wines.

Drop analysis technology (DAT) has been introduced under these circumstances. As we know, a great deal of information on the properties of liquid is contained intrinsically, or can be encoded, in the process of a liquid forming into a drop. This makes it possible to analyze a liquid by monitoring its drop growth. The aims of this research are to study the physical and chemical characteristics of the tested liquids and to discriminate among different liquids qualitatively and quantitatively.

DAT has some remarkable features compared with other instrumental methods. Firstly, a variety of physical and chemical parameters of the tested liquids are expected to be obtained directly or indirectly during a measuring cycle, including surface tension, concentration, refractive index, turbidity and chemical constitution. Secondly, a unique and definite liquid drop fingerprint (LDF) can be obtained through drop analysis. LDF is suitable for fine discrimination among different liquids. Thirdly, drop analysis is a pollution-free method for studying liquid properties because there is no chemical reagent and reaction. Fourthly, a drop analyzer is favorable for carrying out real-time online measurements, which makes it particularly useful for monitoring the manufacturing process of liquids. The above advantages make drop analysis an excellent prospect in the fields of environmental quality monitoring, pharmaceutical technology, food and beverage production, and other liquid-related industries.

DAT has been developed recently with the growing modern optoelectronic technology and computer technology. It is the purpose of this paper to introduce the principle of the multidisciplinary and integrated drop analysis technology, including optical, electrical, spectral and image methods. We will also introduce the design of the optical liquid drop sensor in detail, including the structural design of the drop head, the optical fiber transmission and the geometrical microoptical path. Preliminary sampling tests have been carried out and the liquid drop fingerprint (LDF) has been constructed. Qualitative analysis of experimental results will be presented.

2. The Principle of Integrated Drop Analysis Technology

Figure 1 shows the principle of optical capacitive image spectral (OCIS) drop analysis.

The micro-flow feeding pump[1] consists of a stepper motor and its driver, an actuating device, a switching mechanism, a syringe and the control software. The stepper motor is driven by the computer through an I/O card. Both the flow rate and the flow flux can be controlled precisely and flexibly using the program, so that the liquid is slowly delivered under a quasi-equilibrium condition. The liquid is shaped into a satiated and uniform drop after being pumped into the liquid drop sensor (LDS) through a capillary tube. The drop head with a 90° reserve cone angle at its lower end is specially designed to ensure that the liquid can fully wet the end surface of the head without requiring any external stimulation. This will be explained in detail in section 3. 1.

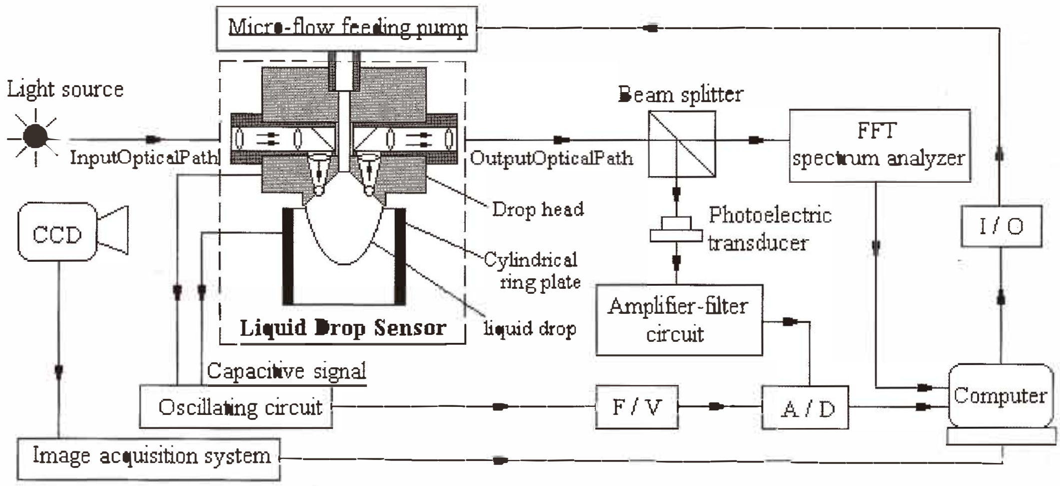

Fig. 1. The principle of optical capacitive image spectral drop analysis.

The signal emitted from the light source is injected into the LDS through an input optical path. The light intensity signal passing through the drop is collected and transmitted along an output optical path, and then sent to the computer in two ways. One signal is transformed into an electrical signal with a photoelectric transducer and is sent to an A/D converter via an amplifier and filter circuit. The other is transferred to a FFT spectrum analyzer, which converts the light intensity signal into the absorption spectrum of the liquid. The design of input and output optical paths will be discussed in section 3. 2 and section 3. 3.

At the same time, a specially designed capacitive sensor[2] uses the drop head as one plate and a cylindrical ring plate, which surrounds the drop head and the space occupied by the formed drop, as another. The drop, which can be seen either as an extension of the drop head plate if the liquid is highly conductive, or as a dielectric material if it is less conductive, changes capacitance as it grows. The variation of the capacitance is converted into a frequency variation of an oscillatory circuit, which is electrically connected to the sensing capacitor. This signal is then sent to the computer after F/V and A/D conversions.[3]

The CCD image processing provides another chance for drop volume measurement and drop growth monitoring by making direct records of the instantaneous drop shape during its formation on the basis of real-time image acquisition and image storage. The drop volume can be determined using a Soble or Laplacian edge detection method and image processing technology.[4]

Generally a monochromatic light source is used in drop analysis. Even though white light is employed, it is considered as an intensity source but not a spectrum source of some spectral width. The coupled light intensity is affected by the mechanical and optical properties of the tested liquids and it is different for different liquids because the profile and volume of the drop during growth are different. However, the collected light intensity is not only dependent on the drop itself and resultant differences in total internal reflection and optical paths inside the drop, but is also dependent on the composition of the liquid, because various liquids consist of various substances which differentially absorb the light at different wavelengths. In other words, if white light is injected into the drop, the collected light may not be white because certain wavelengths are absorbed differentially by the liquid. Therefore, spectral analysis is introduced into drop analysis to study liquid composition by studying the absorption spectrum of the composite light signal passing through the liquid.[5]

Because optical drop analysis is based on the study of the light signal passing through the liquid drop during the drop growth, how to transmit the light signal with low loss in both intensity and spectral width becomes a key technology. The optical liquid drop sensors equipped with optical fibers and a geometrical microoptical path will be introduced in the following sections.

3. Design of the Optical Liquid Drop Sensor

3.1 *Structural design of the drop head*

For a certain liquid to be tested, the drop, on which the drop analysis is based, should be stable and unique in profile. So the drop head which is used to form the drop and position the optical paths, is a significant and key component in the liquid drop sensor. The drop head strongly influences the volume, profile and formation process of the liquid drop. Figure 2(a) shows a common cylindrical drop head.

There is a contact angle when the injected liquid wets the drop head. If the contact angle is relatively large, the liquid cannot cover the end face completely. The drop accordingly becomes variable in profile, position, and volume.

According to the surface theory,[6] when different kinds of liquid drop are dripped on a solid surface with different features, some drops will spread out immediately over the surface of the solid, while some others will keep their original state without expanding. The former phenomenon is called humidification and the latter is called nonhumidification of the liquid on the solid. The degree of humidification is dependent on the molecular attraction between the liquid and the solid. When the molecular attraction between the liquid and the solid is stronger than the internal molecular attraction inside the liquid, the

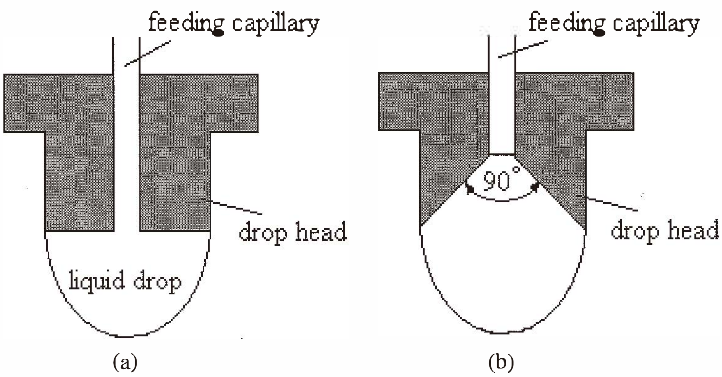

Fig. 2. The drop head. (a) A common cylindrical drop head. (b) The drop head with a reverse cone angle.

liquid will humidify the solid, otherwise it will not humidify the solid. Generally, the liquid will spread and shape into a sessile drop on the solid surface, and there will be a certain contact angle between the liquid phase and the solid phase. As shown in Fig. 3(a), on the solid-liquid-vapor interface, the contact angle is defined as the angle θ formed between the solid-liquid surface and the liquid-vapor surface passing through the liquid interior. Empirically if $\theta > 90°$, it can be said that the liquid does not humidify the solid, and if $\theta <$ 90°, the liquid humidifies. If $\theta = 0°$ and $\theta = 180°$, the states are called complete humidification and complete nonhumidification, respectively.

The humidification process can be represented by the magnitude of the conglutination process. Figure 3(a) shows the incomplete humidification of the liquid pendant drop on the solid surface and the contact angle is θ. If there is a minute displacement dR on the edge of the liquid drop so that the solid-liquid contact area is changed by $\Delta A = 2\pi R\mathrm{d}R$, the variation of the surface free energy is

$$\Delta G^{\mathrm{s}} = 2\pi R\mathrm{d}R(\gamma_{\mathrm{sl}} - \gamma_{\mathrm{sv}}) + 2\pi R\mathrm{d}R\gamma_{\mathrm{lv}}\cos\theta', \tag{1}$$

where G^{s} is the surface free energy, γ_{sl} is the solid-liquid surface tension, γ_{sv} is the solid-vapor surface tension, γ_{lv} is the liquid-vapor surface tension, θ is the contact angle, and R is the humidification radius of the liquid drop.

Since $\theta' = \theta - \Delta\theta$,

$$\Delta G^{\mathrm{s}} = 2\pi R\mathrm{d}R[\gamma_{\mathrm{sl}} - \gamma_{\mathrm{sv}} + \gamma_{\mathrm{lv}}\cos(\theta - \Delta\theta)]. \tag{2}$$

In equilibrium condition

$$\lim_{\mathrm{d}R\to 0}\frac{\Delta G^{\mathrm{s}}}{2\pi R\mathrm{d}R} = 0. \tag{3}$$

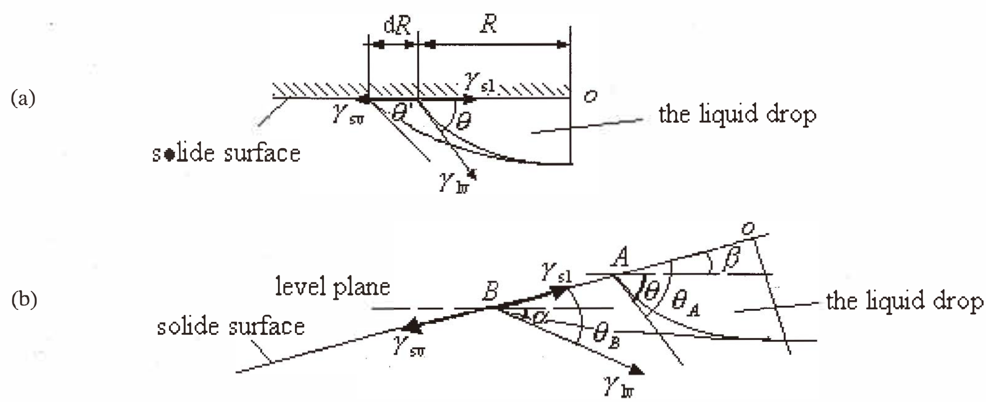

Fig. 3. The contact angle of the liquid pendant drop. (a) When the solid surface is horizontal. (b) When the solid surface is inclined.

When $dR \to 0$, $\Delta\theta \to 0$, and $\theta' = \theta$. Then, the following equation is obtained.

$$\gamma_{sl} - \gamma_{sv} + \gamma_{lv}\cos\theta = 0 \tag{4}$$

So,

$$\cos\theta = \frac{\gamma_{sv} - \gamma_{sl}}{\gamma_{lv}}. \tag{5}$$

As can be seen from eq. (5), if $\gamma_{sv} < \gamma_{sl}$, then $\cos\theta < 0$, therefore $\theta > 90°$. In this case, the liquid cannot humidify the solid. If $\theta = 180°$, it is obvious that the liquid drop has a globular shape and does not humidify the solid completely. If $\gamma_{lv} > \gamma_{sv} - \gamma_{sl} > 0$, then $0 < \cos\theta < 1$, therefore $0° < \theta < 90°$. In this case, the liquid can humidify the solid, and the smaller θ, the stronger the humidification.

A heuristic conclusion is achieved according to above discussion. When the solid surface is horizontal, the contact angle in the equilibrium condition is θ. If the solid surface is inclined as β, as shown in Fig. 3(b), the contact angle at point A is changed to $\theta_A = \theta + \beta$ and the equilibrium condition expressed by eq. (4) is consequently destroyed.

$$\gamma_{sv} > \gamma_{sl} + \gamma_{lv}\cos\theta_A \tag{6}$$

Then, the solid surface will continue to be humidified by the liquid until a new equilibrium condition is obtained at point B.

$$\gamma_{sv} = \gamma_{sl} + \gamma_{lv}\cos\theta_B \tag{7}$$

In the new equilibrium condition, the contact angle is $\theta_B = \beta + \alpha = \theta$. It can be seen that $\theta = \alpha$ when the solid surface is horizontal, and when the solid surface is inclined, $\alpha < \theta$, which means the included angle in the horizontal direction is deminished. The liquid humidification in the original equilibrium condition at point A is expanded to point B and the solid-liquid humidification performance is enhanced.

The drop head with a 90° reverse cone angle at its lower end is then specially designed, as shown in Fig. 2(b), to ensure that the liquid can fully wet the end surface of the head as a result of the inclined end surface. A satiated and uniform drop is prospectively formed through experimental verification.

3.2 *Optical fiber transmission in the optical liquid drop sensor*

Optical fibers provide a simple and convenient method for delivering and collecting the light signal. Figure 4 shows the drop head positioned with two fibers. The Y-type optical fiber is employed to split the collected light signal into two paths: one for intensity analysis after transformation into an analog voltage signal, and the other for spectral analysis after the spectrum analyzer and fast Fourier transform (FFT).

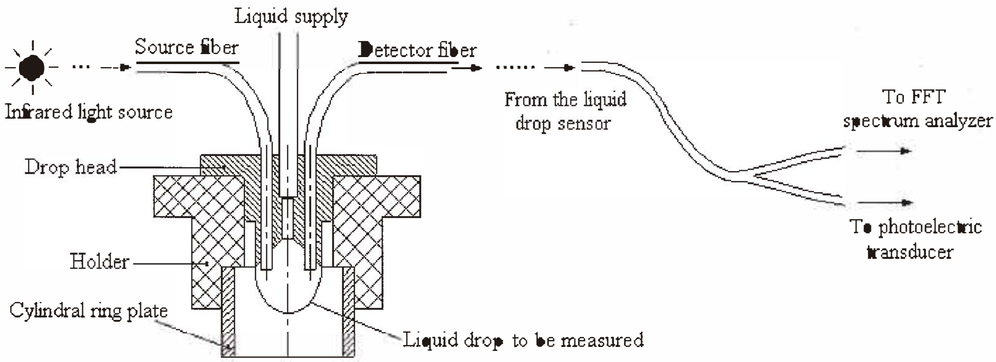

Fig. 4. Optical fiber transmission in the optical liquid drop sensor.

3.2.1 *Light propagation inside the drop*

The instrument described in this paper has been tested with an IR LED, termed SFH450, with a 950 nm spectral peak and a 55 nm spectral bandwidth. Modulated infrared light is injected into the liquid drop using a source fiber positioned in the drop head. A detector fiber, on the opposite side of the drop head, couples some of this injected radiation after various reflections, refractions and absorptions of the optical signal inside the drop, and transmits it to a photoelectric transducer, termed SFH250, which has a maximum photosensitivity wavelength of 850 nm and a photosensitivity spectral range of 400 nm to 1100 nm.

When an optical fiber is used, the light entering the liquid drop is dependent on the emergent cone angle determined by the numerical aperture of the fiber. Figure 5 shows the propagation of the light inside the drop during its growth. The salient end faces on the fibers indicate the effective domains within the emergence or acceptance cone angle. The drawn ray paths are the ones that lead to light coupling from the source fiber to the detector fiber via total internal reflections (TIR) inside the drop. The radiation, which enters the detector fiber within its acceptance angle, is propagated in the fiber with low loss and received by the transducer. During drop growth, the amount of coupled radiation varies reproducibly to produce a curve termed the liquid drop fingerprint (LDF), which is useful for liquid property study and fine discrimination.[7]

3.2.2 *The fiber height adjuster*

It is worth noting that LDF is strongly influenced by the experimental device and testing conditions, such as the mechanical structures of the drop head and drop sensor, the position of fibers inside the liquid drop, the electrical parameters of the processing circuit and the temperature, humidity and pressure. When the fibers are in different height positions, LDFs for a certain liquid are different. This is because for liquid drops of the same volume and profile, when other testing conditions are invariable, the propagation paths of the light signal inside the drops are different if the height positions of the source and detector fibers relative to the end surface of the drops head are different, or if the penetration depths of fibers into the liquid drop are different. This will inevitably lead to the collected light signals being different. The ray paths drawn inside the drop shown in Fig. 5 provide a visual reference. Therefore, in a certain system, the positions of fibers should be fixed after being set up according to the principle of the clearest and strongest light intensity based on an undistorted signal.

In a generalized view, the fiber positions include the horizontal projection positions of the fibers in the drop head and the height positions of the fibers relative to the end surface of the drop head. For the structural reasons, the horizontal positions are difficult to adjust and they are fixed during design and assembly. So only a height adjuster is introduced, as shown in Fig. 6. The device consists of micrometer calipers, a slide block, a slide guide, a fiber holder and a spring. The optical fibers to be adjusted are pressed on the right-hand surface of the fiber holder with a gasket and nut. A fiber holder is connected to the slide block, which is slidable along the guide way. The spring is used to ensure the upward motion of the slide block and to ensure the contact condition between the slide block and the measuring surface of the micrometer calipers. Operation of the micrometer calipers means that the slide block is pressed down by the micrometer calipers or is pushed up by the spring, and accordingly the fiber height can be adjusted. The adjustment precision is dependent on the minimum scale of the micrometer calipers. In addition, the source and detector fibers can be adjusted simultaneously.

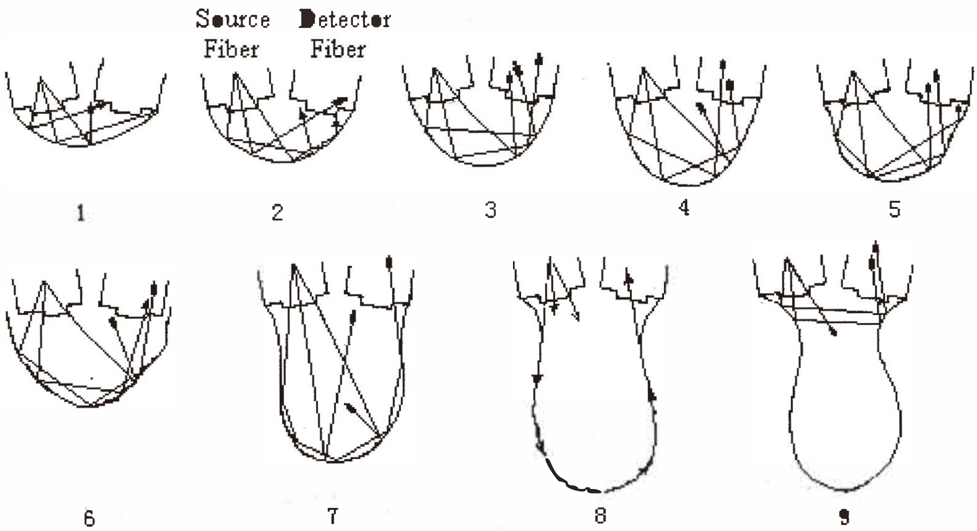

Fig. 5. The propagation of the light inside the drop during its growth (after McMillan[7]).

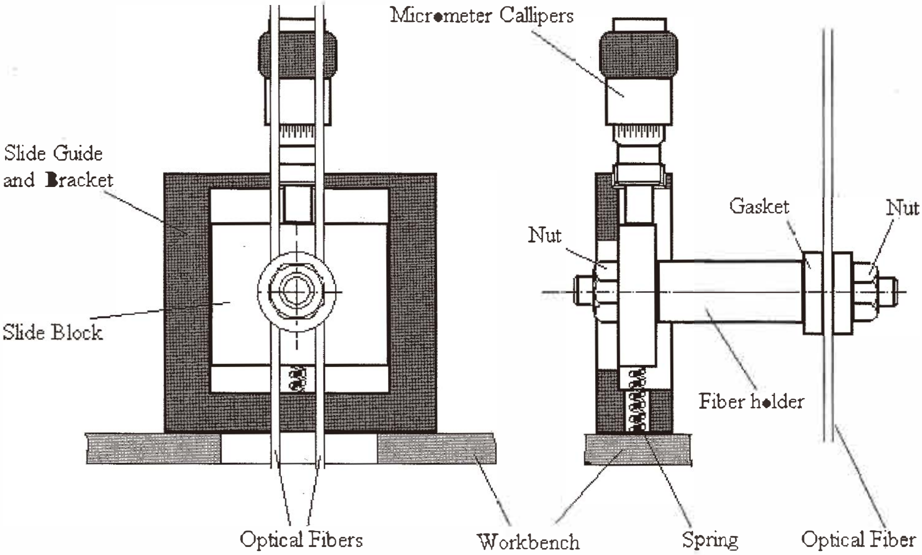

Fig. 6. The fiber height adjuster.

3.2.3 *Limitation of optical fiber transmission*

Optical fiber transmission is a simple method with some disadvantages. Absorption loss and scattering loss occur in optical fiber transmission because of imperfections in manufacturing and materials, and flexure loss also takes place. In fact, for a given optical fiber, light signals of different wavelengths pass through the fiber with different intensities.

Figures 7(a) and 7(b) show the spectral characteristics of the transmitter diode "SFH450" and the photodiode detector "SFH250" employed in our research. A corresponding optical fiber is specially selected and its attenuation characteristic is shown in Fig. 7(c). Obviously, light signals within the entire wavelength range of SFH450 can be transmitted with less intensity attenuation.

However, if a white light source is used, for the special purpose of spectral analysis, as mentioned in section 2, not all the light signal consisting of different wavelengths can pass through the fiber. That is to say, the light signal of a certain wavelength bandwidth is partly lost before entering the liquid drop and consequently the collected signal cannot represent the liquid properties accurately, because the intensity loss in some wavelengths of the collected light signal results neither from the variation of the drop profile nor from absorption by the liquid, but from the transmission characteristics of the optical fiber.

Therefore, if the study of liquid properties except for the absorption spectrum is carried out and the liquid being measured is specific, firstly, the light source must be specially selected so that the emitted light signal is not absorbed by the liquid and the collected light can be used to study the drop profile, volume and related properties. Secondly, the transmission optical fiber must be well matched with the light source in terms of optical wavelength. That is to say, the transmissivity in the range of the emitted spectral bandwidth must be sufficiently high so that the light signal enters the liquid drop com-

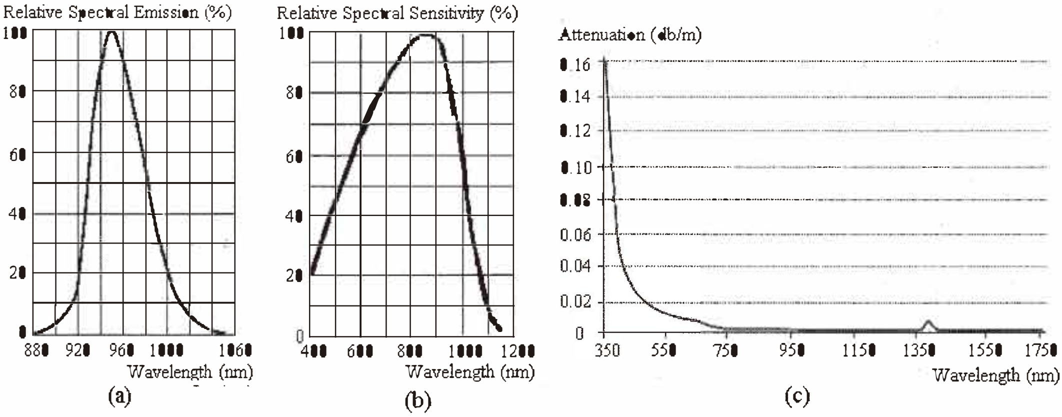

Fig. 7. (a) Relative spectral emission of transmitter diode "SFH450". (b) Relative spectral sensitivity of photodiode detector "SFH250". (c) Attenuation of transmission optical fiber.

pletely in terms of both intensity and wavelength. As for the spectral study, an LED and optical fiber can also be used if they can meet the requirements of the spectral width when a given liquid is studied.

3.3 *Geometrical microoptical path transmission in the optical liquid drop sensor*

The light beam irradiates the internal surface of the liquid drop directly through a geometrical optical path. This principle is shown in Fig. 8(a). Figure 8(b) shows the mechanical structure. Infrared light source 1 is set in the focus of optical lens 2, and the emitted light is collimated with a limiting aperture of ϕ 6 mm. The aperture is narrowed to ϕ 3 mm after optical lens 3 and 4, if they are positioned properly based on geometrical optics. The light enters the drop head with a final aperture of ϕ 1 mm and changes its transmission direction after being reflected by the reflector mirror 5. A spherical lens 6 with a radius of 0.5 mm is positioned in the drop head in contact with the liquid drop and it serves as a point light source which emits light in a cone into the drop. The coupled light signal passing through the drop is collected by another spherical lens 7 set on the opposite side of the drop head. Finally, the light signal is received by a spectrometer via a series of transmissive components including reflector 9 and lenses 8, 10 and 11.

A single optical path tube containing lenses is designed for inputting the light signal and other optical elements are positioned inside the drop head. Because of the small size of the drop head itself, the size of the optical elements is also very small. According to relative materials, the diameter of microoptical elements can be made even smaller than ϕ 1 mm. The focal length of lenses can be adjusted during manufacturing on the basis of the practical requirements. So it is feasible to set optical elements inside the drop head. All the lenses in Fig. 8(b) are covered with a reflection reducing coating, and all the reflector mirrors are plated with aluminum to decrease the light intensity loss in transmission.

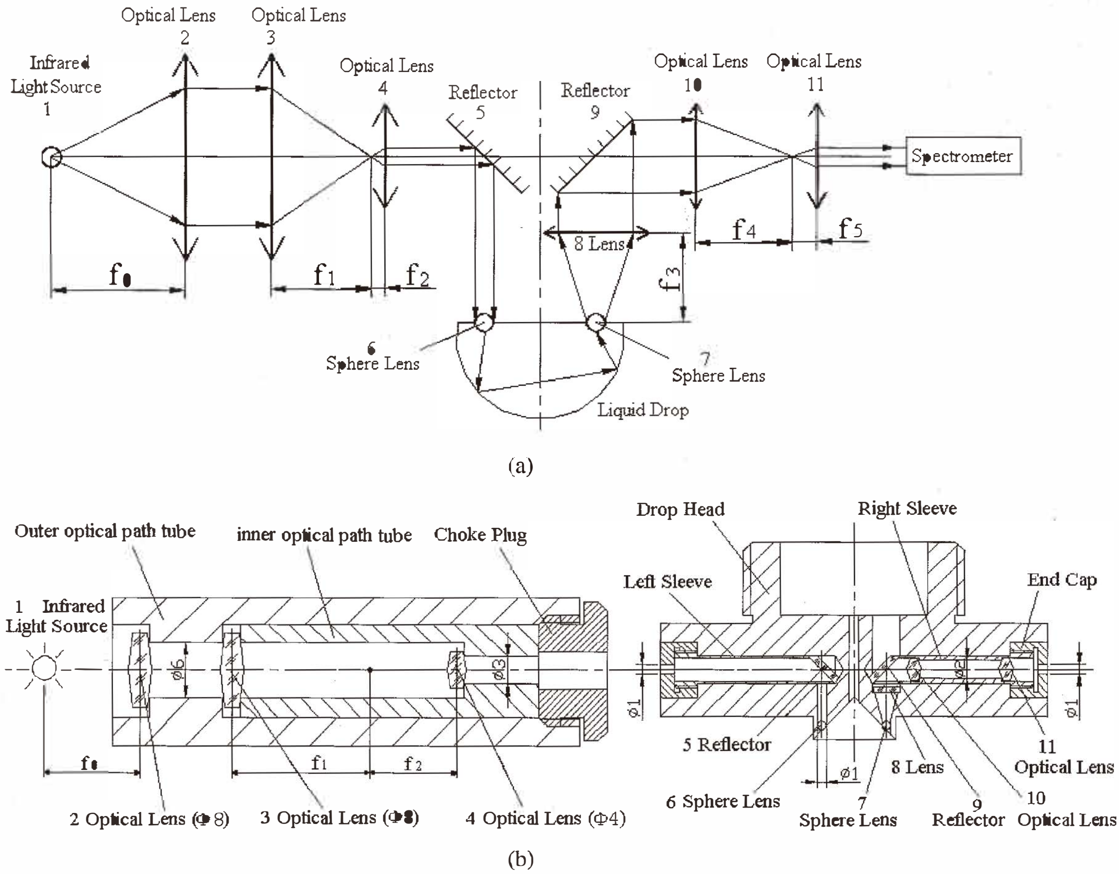

Fig. 8. The geometrical microoptical path in the optical liquid drop sensor. (a) The optical principle. (b) The mechanical structure.

The main technology in the geometrical optical path is the method of injecting and collecting the light signal. A spherical lens is employed as the light collector. Stray light in all directions can enter the spherical lens and be emitted in a cone like a point light source. As for the light injector, there are three options. The first choice is to lead the catoptric light from the reflector into the liquid drop directly. In this case, the incident ray is a parallel cylindrical light beam. The second choice is to add a lens between the reflector and the drop, so that the catoptric parallel light converges through the lens and then emerges when entering the drop. The specific position and fixation method of the lens are worth further discussion. The third choice is to set a spherical lens in the drop head symmetrically to the collecting spherical lens, as shown in Fig. 8. Because the drop profile is different when the drop contacts a different surface, the possible advantage of the third method is that the drop profile is not be influenced by different contacting surfaces because of the symmetrical positions of the injecting and collecting spherical lenses.

4. Experiments and Signal Analysis

Because of the large amount of original data, only diagrammatic results are presented here. Figure 9 shows the experimental graphs of LanTian beer obtained using the fiber capacitive spectral drop analysis system. In Figs. 9(a) and 9(b), the horizontal axis refers to the time series according to the acquisition interval determined by the program, and the vertical axis refers to the uncalibrated output voltage signal from the processing circuits corresponding to the light intensity and capacitance. During drop growth, the amount of coupled radiation varies reproducibly, as shown in Fig. 9(a). Excellent linearity between the capacitor signal and time is achieved, as shown in Fig. 9(b).

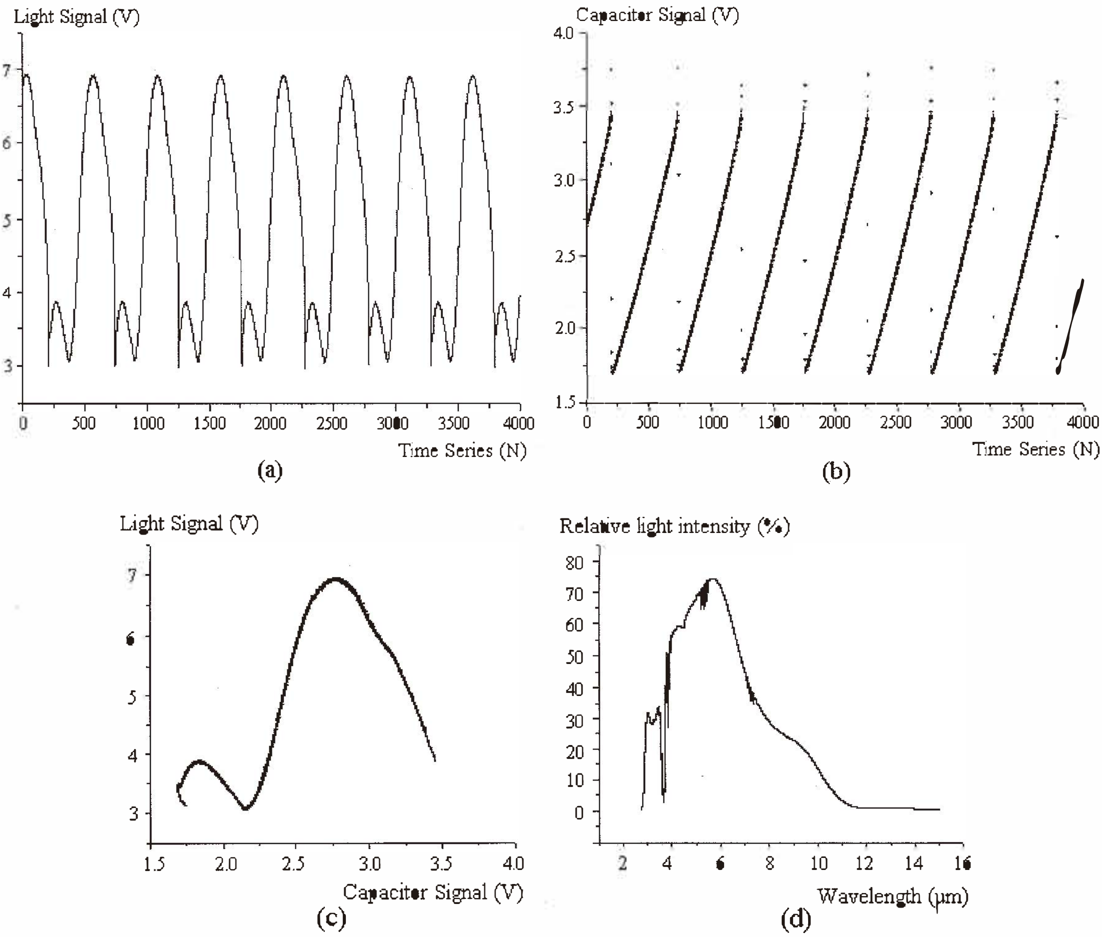

Fig. 9. The experimental results of LanTian beer. (a) Light signal. (b) Capacitor signal. (c) 2-D liquid drop fingerprint. (d) Spectral curve.

Figure 9(c) shows the two-dimensional (2D) LDF, which shows the relation between the light signal passing through the liquid drop collected by the fiber drop sensor and the capacitor signal obtained from the capacitive drop sensor. The LDF is actually an overlapping curve of the light signal in successive periods of drop growth based on the capacitive signal. It can be found that the LDF is of excellent repeatability, which proves the LDF is independent of the speed of drop growth and the feeding speed.

Figure 9(d) shows the spectral curve collected simultaneously using the FFT spectrum analyzer, and shows the relationship between the collected light intensity signal and the incident wavelength.

Figure 10 shows LDFs of several liquids, including pure water, LanTian beer, mature vinegar, LaoChou soy sauce and JianLian rice wine. Visual features and qualitative differences are observed in LDFs of different samples.

In addition, the same liquid with different concentrations also produces different LDFs, as shown in Fig. 11. Samples are seawater with different concentrations of 30%, 50% 60% and 100%.

Why were different curves obtained for different liquids? If liquid absorption is ignored, the light intensity detected by the fiber after TIR (total internal reflection) inside the drop depends on the instant shape or volume of the drop, which determines the optical path, as shown in Fig. 5. Also, the drop shapes during its growth are essentially dependent on the liquid properties. Therefore, the LDF of a liquid is related to the various properties of the liquid and it is unique and definite.

In LDF, the equivalent drop volumes and light intensities of different liquids are different. The peak heights, the peak shapes, and the areas surrounded by the LDF curves and the horizontal axes are different too. In general, LDF is powerful for fine discrimination among different liquids using the information extracted from the LDFs of samples and constructing a mathematical model or database for identification. This is under further study in our laboratory.

The experimental results from Fig. 9 to Fig. 11 are obtained using a monochromatic light source. As mentioned in section 2, if a white light source is employed, the light signal may vary widely. Figure 12 shows LDFs of the same samples shown in Fig. 11, obtained under the condition that the white light enters the liquid drop through a geometrical microoptical path.

Why does the white light experimental data differ so significantly from the monochromatic data? If monochromatic light is injected into the liquid drop and is not absorbed by the liquid, the collected light intensity mainly depends on the drop shape, as explained above. However, if white light is employed, the collected light intensity not only depends on the drop shape, but also depends on the liquid absorption with wavelength.

After introducing spectral analysis into the liquid drop analyzer, a 3D LDF can be obtained by merging the light intensity signal from the fiber drop sensor, the drop volume signal from the capacitive drop sensor and the absorption spectrum from the FFT infrared spectrum analyzer. Figure 13 shows the 3D LDFs of ethanol and propanol. 3D LDF enhances the capability of drop analysis for fine discrimination among different liquids, because it is nearly impossible to obtain the same 3D LDF for two different liquids using the same testing system.

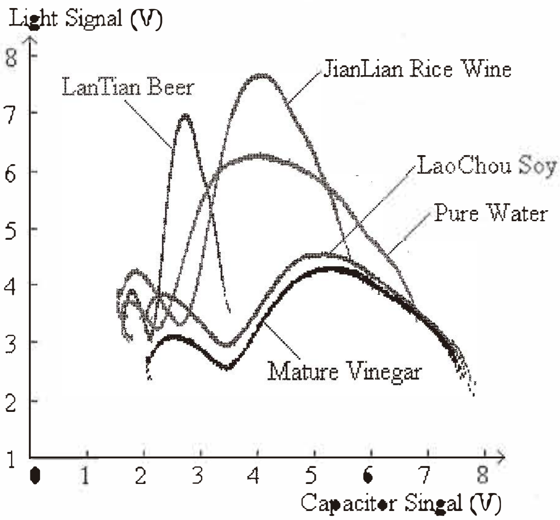

Fig. 10. Liquid drop fingerprints of different liquids.

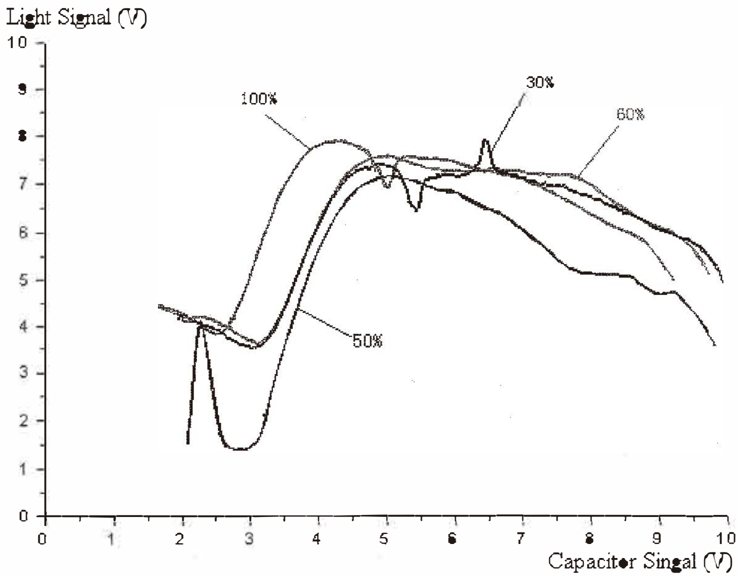

Fig. 11. LDFs of seawater with different concentrations using the monochromatic light source.

5. Conclusions

The key technology in the optical liquid drop sensor is how to transmit a light signal with a low loss in both intensity and spectral width. If a specific liquid is being measured, an optical fiber is favorable for transmission on the condition that its characteristics match

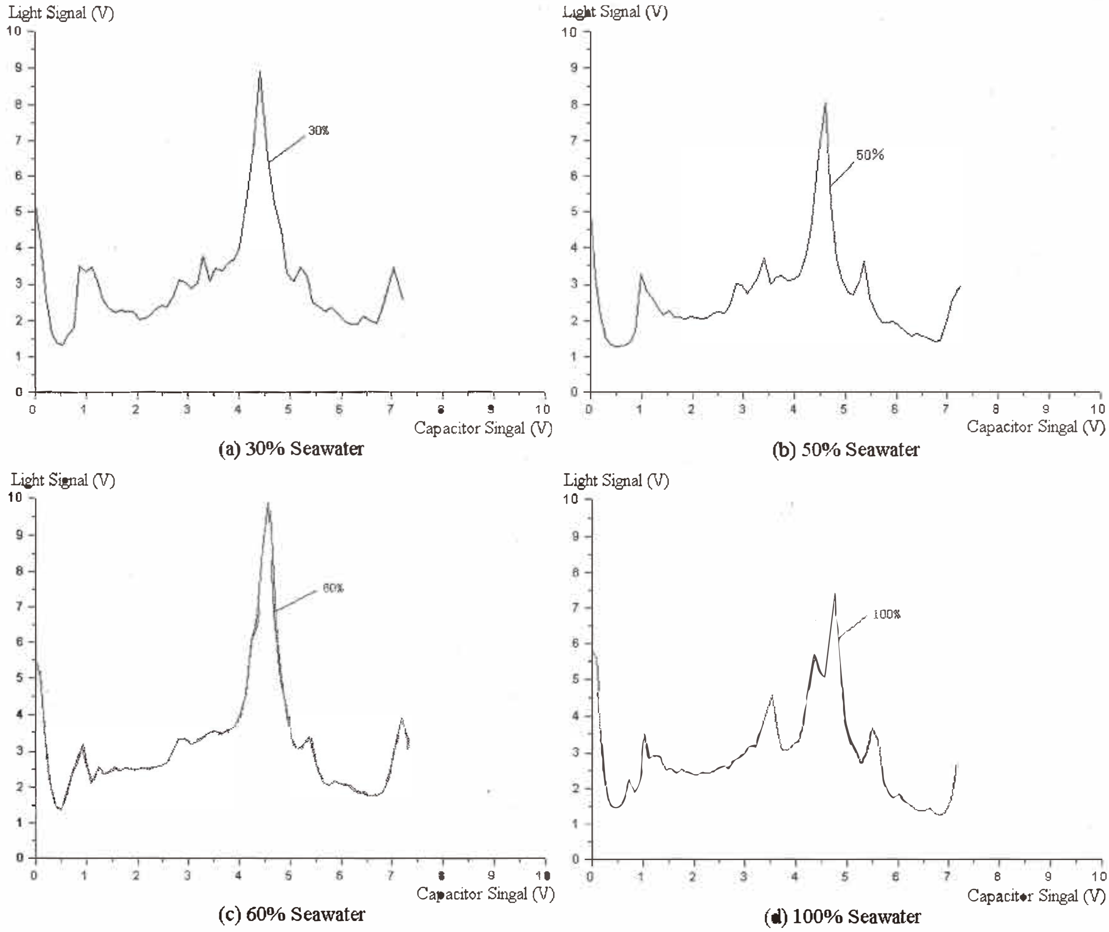

Fig. 12. LDFs of seawater with different concentrations using the white light source.

the requirements of the spectral width of the liquid and also the light source. The coupled light intensity signal from the source fiber to the detector fiber varies along with drop formation. Otherwise a geometrical microoptical path is suitable. It is possible to set the optical elements inside the small drop head. Spherical lenses in the drop head are employed as the light injector and collector. They are positioned symmetrically so that the drop profile will not be influenced by different contact surfaces. All the lenses are covered with a reflection reducing coating, and all the reflector mirrors are plated with aluminum to decrease the loss of light intensity in transmission.

Experiments have been carried out with the sensor. Visual features and qualitative differences can be observed in 2D LDFs of different kinds of liquids and the same liquid with different concentrations. Experimental results prove that it is feasible to measure the properties of liquids and to discriminate among different liquids on the basis of LDF. A 3D

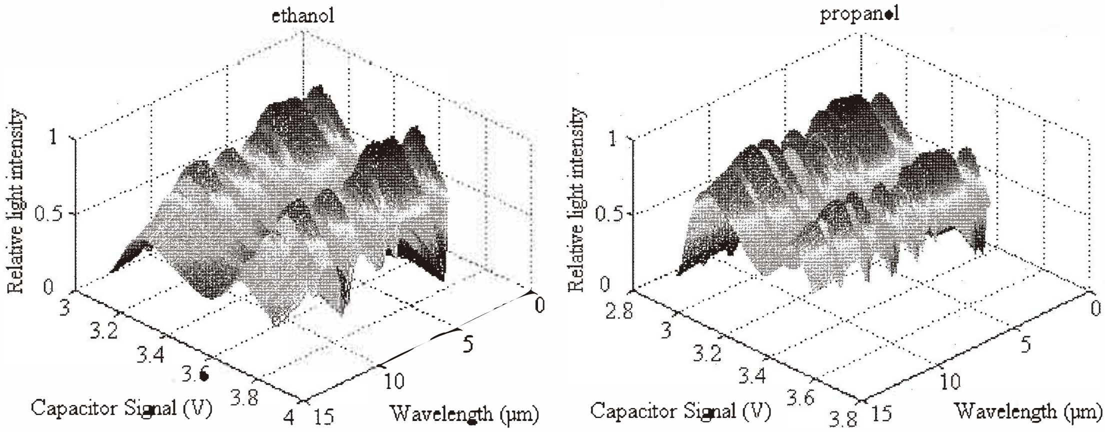

Fig. 13. The 3D LDFs of ethanol and propanol.

LDF can be obtained after integrating the spectral signal. This is a great step forward in fine discrimination among different liquids.

In a word, the first conclusion is that excellent light signals can be achieved through the designed optical liquid drop sensor. The second is that the LDF is proved to be useful for liquid identification.

Future development of the drop analysis will include calibration of instrumentation, characterization of LDFs and construction of a database for liquids, in order to quantify fine discrimination and measurement of liquid properties.

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