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RESEARCH ARTICLE

# Fiber sensor of online biomass testing

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**Abstract** A new testing method for biomass concentration and sensor design is developed to realize online testing of biomass concentration in the microbial bacterium liquid. The sensor structure theory, optical path, theory analysis and experiment are studied in-depth. First, the optical absorption and optical scattering are related to the optical distance and incidence energy. The change in biomass concentration will cause the change in optical absorption and optical scattering, and then lead to the change in the receiving energy. Based on the physical phenomena and theory, the paper relates the receiving energy to biomass concentration testing, and a new method to measure the biomass concentration is set up. In the experiment, a lamp-house with 760 nm wavelength is chosen. Under the 20°C constant temperature, the experiment is performed on the biomass concentration test. The results indicate that the method is good for testing bacterium liquid concentration, with maximum relative error less than 0.2%. The method, which has merits such as precise online testing, high sensitivity and long life, is a practical new style biomass concentration sensor.

**Keywords** biomass concentration, online testing, sensor, absorption, scattering

## 1 Introduction

Many factors influence treatment efficiency in the biochemical treatment process for organic waste gas by trickling bio-filter due to complexities such as containing the animalcule and component of the bacterium liquid, biomass concentration, PH value, circulation speed and inner temperature. Biomass is an important technique parameter vital in online biochemical process testing. Reference [1] considers that online biomass concentration measurement is not yet mature, but has already drawn significant interest worldwide [2–5].

The traditional method can be sorted into offline testing and online testing. The first mainly covers the dry weight method, optical density method, and methylene dyeing method [2], which makes measurement and the realization of automatic control inconvenient and difficult. Online measuring technology is primarily in the theoretical and experimental stage at present and is delivered by Ref. [2] which mainly adopts the permittivity distribution measuring method. However, there always exists a certain gap between theory and practice. Meanwhile, Ref. [3] introduces another method which adopts optical reflection to measure liquid concentration and research on the change of the reflex critical angle. Although this limited research to test the common liquid has aroused more interest [6,7], there is still no high quality online testing sensor for measuring biomass concentration.

After the biological method for processing low concentration organic waste gas in engineering application, the technological key is how to test and control the process parameters, especially the biomass concentration.

Using optical scattering and absorption theory, an online testing sensor for fiber biomass concentration was designed. Based on the design theory and optical path analyses, the relation between the receiving energy and the bacterium liquid concentration was drawn out. Reference [3] focused on the change of bacterium liquid concentration under the near infrared circumstance. Experimental results and analyses show that this method is feasible for measuring microbial liquid concentration and has many merits, including precise online testing, high sensitivity and extended use. The sensor's design theory and method is meaningful for preparation, alcohol making, microanalysis, biochemistry and environmental protection. It is a practical biomass concentration sensor innovation with a bright future.

## 2 Theory of sensor structure

As Fig. 1 shows, the structure of the fiber reflecting biomass concentration sensor mainly consists of the

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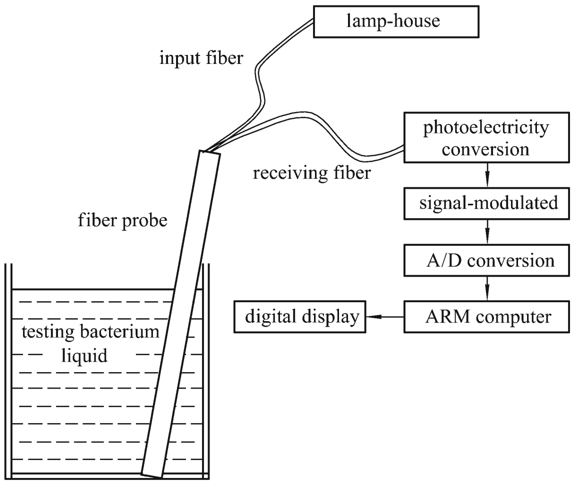


**Fig. 1** Equipment frame of fiber reflecting sensor

lamp-house, optical detector, signal processor, fiber probe and optical coupling.

The physical phenomena of the optical reflection indicate that as light transmits in the medium and is reflected, the reflecting energy is related to many factors. The paper focuses only on light transmission in the bacterium liquid with different concentrations, and the experimental results show that the output energy is gradually weakened with increasing bacterium liquid concentration.

The structure of the sensor detector is shown in Fig. 2. It consists of the input fiber, receiving fiber and reflecting faces 1 and 2. It is known that the coupling light path is $l = 2D_1 + D_2$. The fiber ports adopt different lens for focusing and making light parallel, which eases analyses of the light path and makes the test sensitive and linear.

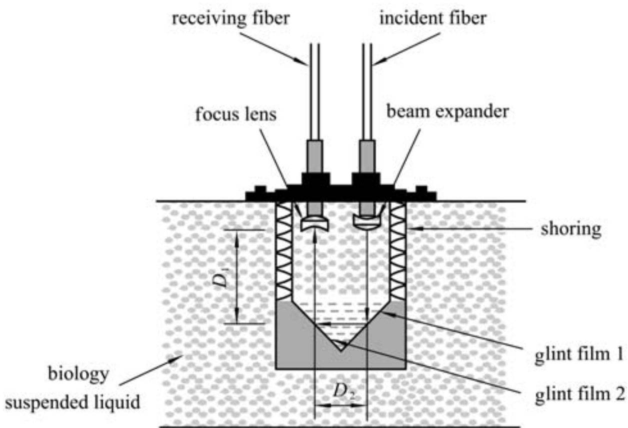


**Fig. 2** Structure principle of fiber concentration sensor's detector

Generally, the output energy becomes weakened in two cases: during absorption and scattering. The sensor adopts the optical reflectors as Fig. 2 shows: if there is no medium influences, input light energy can reach the reflecting face, and completely reflect to another reflecting face; the angle between the light and reflecting face is 45°, and the light is reflected back to the receiving fiber. In the testing process, the twice reflected light is weakened by the liquid biomass concentration. In the optics, the biomass concentration signal will be magnified by the fiber sensor.

## 3 Theory analyses of sensor principle

### 3.1 Testing theory of the sensor

Optical absorption and optical scattering are the characteristics of matters. As the liquid concentration outside the fiber changes, the optical absorption coefficient and scattering coefficient will change accordingly. When light passes through the medium, two factors weaken the receiving energy: optical absorption and optical scattering, as Fig. 3 shows. The first makes the input light energy translate into heat energy and other forms energy, while the latter changes the spatial distribution of optical energy. In terms of practical measurement, it is difficult to distinguish their influences on the receiving light. If the medium weakens the optical energy, the amplitude will decrease gradually during transmission. To reflect this fact, the medium refractive index is set as a plural [8] and expressed as

$$\tilde{n} = n + \alpha. \tag{1}$$

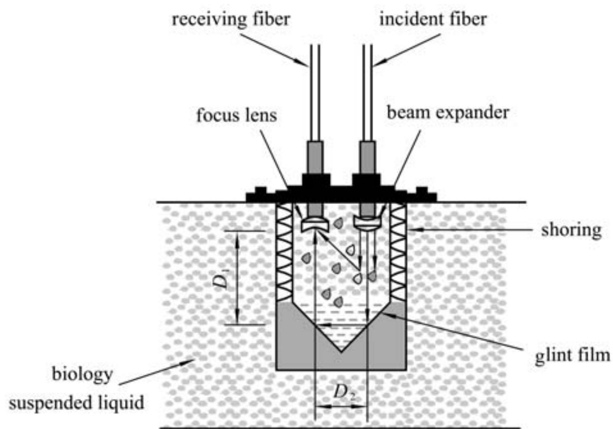


**Fig. 3** Schematic diagram of input light scattering

The real part $n$ is the refractive index which represents the light transmitting phase character and is affected by the medium. The imaginary part $\alpha$ represents the attenuation degree when light transmits in the medium and is defined as an extinction coefficient, which can describe the light absorbing character when transmitting.

$$I = I_0 \exp[-(\alpha_a + \alpha_s)l] = I_0 \exp(-\alpha l), \tag{2}$$

where $\alpha_a$ is the absorbing coefficient, $\alpha_s$ is the scattering coefficient, and $\alpha$ is the whole extinction coefficient [9]. $l$

is the efficient optical path, and $l = 2D_1 + D_2$ as Fig. 3 shows.

The relation between the absorbing coefficient and extinction coefficient is

$$\alpha_a = 2k\alpha = \frac{4\pi}{\lambda}\alpha. \quad (3)$$

Equation (3) shows that the absorbing coefficient is a function of the wavelength.

$$I = I_0 \exp\left(-\frac{4\pi}{\lambda}\alpha l\right). \quad (4)$$

For gas or insoluble matter, the absorbing coefficient $\alpha_a$ is in a direct ratio to the absorbing molecule number in unit volume, i.e., direct ratio to the concentration of the absorbing matter.

$$\alpha_a = Ac, \quad (5)$$

where $A$ is a constant regardless of the concentration and determined by molecule character of the absorbing matter.

When the concentration of matter reaches a certain degree, there will be a superposition scattering effect; scattering plays a major role. Generally, it can be classified into two kinds: one is Rayleigh-scattering, whose particle diameter is in the bound of $\lambda/5$ to $\lambda/10$; the other is Met-scattering, whose particle diameter is close to the light wavelength. In the biological bacterium liquid system, it can be classified as follows: the small-size bacterium belongs to the Rayleigh-scattering and the thalli belong to the Met-scattering.

For the complex dispersion system in biological bacteria liquid, bacteria in the testing biological bacteria liquid is often used in biochemical degradation organic waste gas (benzene, toluene, xylene, etc), and they are single cell, straight/bending bar short electrode bacteria (Pseudomonas sp), as Fig. 4 shows.

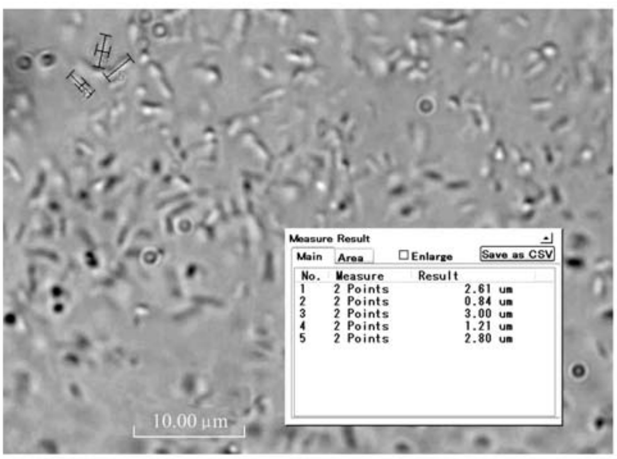


**Fig. 4** Bacterium liquid micrograph ($\times$ 2000)

This kind of short electrode bacteria is a cylindrical bar whose diameter is about 0.8 to 1.2 μm and bar length is about 2.6 to 3.0 μm based on observation by a $\times$ 2000 microscope. Because of the animalcule grain, which is far bigger than the input optical wavelength, thalli in the chosen bacteria liquid belong to the category of Met-scattering, while micro bacterium belongs to the category of Rayleigh-scattering.

The intensity of Met-scattering light is in inverse proportion to the wavelength $\lambda$ [8,10].

$$I(\theta) \propto \frac{1}{\lambda^n}, \quad (6)$$

where $n < 4$ and $n$ depend on the particulate size. The polarization degree of the scattering light decreases as $d/\lambda$ increases, where $d$ is scattering particle diameter and $\lambda$ is the input light wavelength. The angle distribution of the scattering light intensity changes with a change of $d/\lambda$. Compared to Rayleigh-scattering, its forward scattering is strengthened and back scattering weakened. The relation between Rayleigh-scattering light intensity and input light wavelength is

$$I(\theta) \propto \frac{1}{\lambda^4}, \quad (7)$$

where $I(\theta)$ is scattering light intensity corresponding to a certain direction and $\theta$ is scattering angle. Equation (7) indicates that the shorter the light wavelength, the stronger the scattering light intensity [11,12].

The light scattering coefficient $\alpha_s$ thus mainly depends on the granule diameter, refractive index, light wavelength and scattering angle. Aiming at the sizable granule, the scattering section is in a direct ratio to the granule section, and the light scattering coefficient $\alpha_s$ is close to 2 [9]. Using Moore's rule to compute the granule whose size is close to the light wavelength, according to the "abnormality diffraction" approximation method, there will be

$$\alpha_s = 2 - (4/\rho)\sin\rho + \left(4/\rho^2\right)(1 - \cos\rho), \quad (8)$$

$$\rho = 2\beta(m - 1), \quad (9)$$

$$\beta = 2\pi r/\lambda, \quad (10)$$

where $m$ is the comparatively refractive index and $m = 1.2$, $\beta$ is the granule size parameter and $r$ is the granule radius.

In this experiment, since the lamp-house with a fixed frequency wave is adopted, the change stimulated by the wave factor can be regarded as a constant. Otherwise, due to the structure of the fiber detector, the input fiber is near the receiving fiber. The scattering angle can thus be neglected, and the light distance related to the structure of the detector is also a fixed constant. According to Eqs. (9) and (10), there will be

$$\rho = \kappa \cdot r(m - 1), \quad \text{where } \kappa \text{ is a constant.} \quad (11)$$

The single bacterium species (Pseudomonas) adopted has a diameter of about 0.4 μm and a comparative refractive index related to its concentration. Thus, $\rho$ is a function related to the bacterium liquid concentration, and Eq. (9) can be described as

$$\alpha_s = 2 - \rho(c). \tag{12}$$

According to Eqs. (5), (12) and (2), the synthetical formula can be expressed as

$$\begin{aligned} I &= I_0 \exp[-(\alpha_a + \alpha_s)\cdot l] \\ &= I_0 \exp\{-Acl + [2 - \rho(c)]\cdot l\}. \end{aligned} \tag{13}$$

From Eq. (13), it is known that the receiving light is mainly related to the liquid concentration $c$ and efficient optical path $l$.

The above equations can thus be rewritten into output voltage form after photo-electricity conversion as

$$U = U_0 + I_0 \exp[-Acl + \rho(c)l], \tag{14}$$

where $U_0$ represents the initial value of the output voltage, which is tunable by adjusting the magnification of the signal-modulated circuit or by the zero-regulator, set $U_0$ to 0; $A$ is a constant which is unrelated to the concentration and just depends on the molecular characteristic of the absorbing matter; $c$ is the tested bacteria liquid concentration; $l$ is the available optical path (as Figs. 2 and 3 show) and $l = 2D_1 + D_2$; $\rho$ is a function related to the tested bacteria liquid concentration $c$, which can be described as $\alpha_s = 2 - \rho(c)$.

### 3.2 Choosing the sensor's lamp-house wave

In the scattering affection, uniformity matter can also stimulate scattering similar to asymmetry matter, i.e., molecular scattering. Reference [13] covers researches on pure water in different wave conditions. As Table 1 shows, $\lambda$ represents the wavelength, $\alpha_a$ represents the absorption coefficient, and $\alpha_s$ is the scattering coefficient.

**Table 1** Data of absorption coefficient and scattering coefficient in different wavelength conditions

| $\lambda$/nm | $\alpha_a$/m$^{-1}$ | $\alpha_s$/m$^{-1}$ |
|---|---|---|
| 400 | 0.0058 | 0.0053 |
| 450 | 0.0114 | 0.0033 |
| 500 | 0.0238 | 0.0021 |
| 550 | 0.0588 | 0.0014 |
| 600 | 0.2224 | 0.0010 |
| 650 | 0.3315 | 0.0007 |
| 700 | 0.5722 | 0.0005 |
| 750 | 2.7334 | 0.0004 |
| 800 | 2.2932 | 0.0003 |

As seen from Table 1, when the tested matter is symmetrical transparent purity water, a longer wavelength leads to less infection on the absorption by scattering. As the wavelength nears 650 nm, the scattering value is two in a thousand of the absorption value, which can be neglected. But when the wavelength is 400 nm, the scattering value is almost equal to the absorption value, so the scattering factor should be considered. To eliminate the scattering effect of water, the 800 nm wavelength light should be adopted as the lamp-house wavelength. As the bacteria in measured biological bacteria liquid is often used in biochemical degradation organic waste gas (benzene, toluene, xylene, etc), they are single cell, straight/bending bar short electrode bacteria (Pseudomonas sp.). This kind of short electrode bacteria is cylindrical whose diameter is about 0.8 to 1.2 μm and bar length is about 2.6 to 3.0 μm based on observation by a × 2000 microscope. As the animalcule grain is far bigger than the input optical wavelength [14], considering the single wavelength lamp-house circs, the lamp-house with near infrared single wavelength of 760 nm is chosen.

## 4 Experiment results and analyses

To discuss how different concentrations influence the absorbency, the concentrations are chosen as follows: 4, 8, 12, 16, 20, 24, 28, 32, 36, and 40 mL and their reflex energies (represented by OD value) are tested. Their testing result and analyses are as follows:

### 4.1 Testing results and analyses of optical density (OD value)

The experiment selects different concentrations of biological liquid (same volume): 4, 8, 12, 16, 20, 24, 28, 32, 36, and 40 mL, and the measurement is repeated. Figure 5 shows the $OD_{620\ nm}$ value measuring curve under the biomass concentration changing circumstance tested by a spectrophotometer (temperature $T$ = 20°C, lamp-house wavelength $\lambda$ = 620 nm).

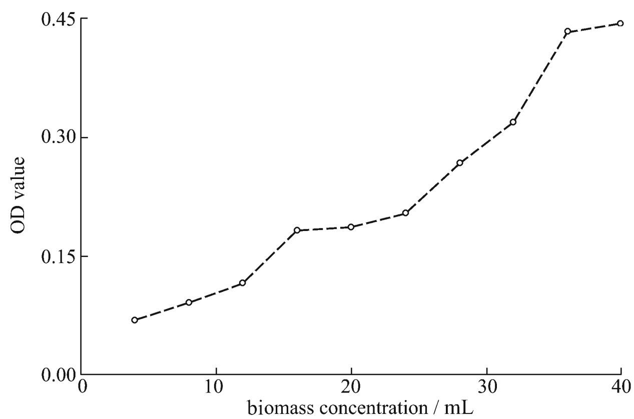


**Fig. 5** Biological liquid's OD value changes with a change in biomass concentration

The experimental curve indicates that the stronger the biomass concentration, the higher the OD value, and the stronger the absorbency; the change presents an obviously ascending trend. Meanwhile the OD value difference of the adjacent concentration increases with an increase in the concentration. This experiment indicates that biological liquid concentration could deeply influence thalli absorbency. If biological liquid concentration can be measured by testing the receiving energy, then online measurement of the biomass concentration can be realized.

### 4.2 Testing results and analyses of voltage value

Different concentrations of biological liquids are also chosen to test the voltage value. They are 4, 8, 12, 16, 20, 24, 28, 32, 36, and 40 mL, with Fig. 6 showing the attenuation voltage changing curve (temperature $T = 20°C$).

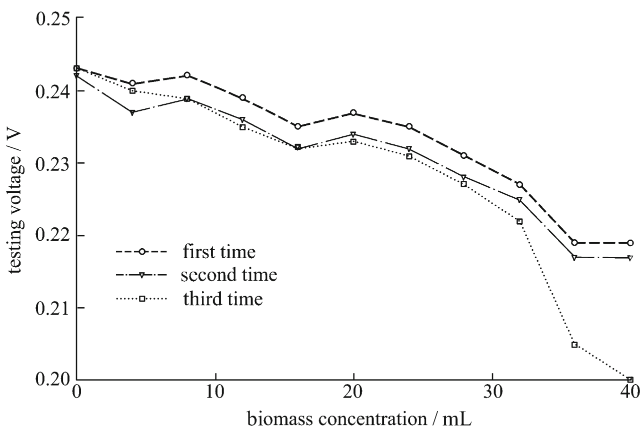


**Fig. 6** Attenuation voltage changing curve with the change of biomass concentration

The experimental curves indicate the changing attenuation voltage trend with a change in liquid concentration. Aiming at the same curve, there is good linearity in low concentration and an obvious downtrend in high concentration [15,16]. Comparing the curves with each other, the less their initialization angle difference, the more obvious the linear area, and the more sensitive the measurement. Under a high density condition, the scattering effect is obvious and a notable receiving light attenuation is shown by a rapid descent of the testing voltage value.

### 4.3 Error analyses of measuring results after compensation treatment

Four parts are adopted to constitute the measuring system in application: the fiber sensor part (including two same structure fiber probes, reflecting face, lamp-house and photo-electricity conversion part); signal modulated part; A/D conversion part; and ARM computer and digital parameter display part. Nonlinear compensation of the measuring signal is accomplished by the measuring system. Table 2 presents a comparison of the testing data after calibration with the given concentration.

**Table 2** Theoretical bacterium liquid concentration compared to testing results

| number | standard bacterium liquid concentration/mL | testing data of measurement system/mL | absolute error $\varepsilon$ |
|---|---|---|---|
| 1 | 0 | 0.019 | −0.020 |
| 2 | 4 | 4.018 | −0.020 |
| 3 | 8 | 8.025 | −0.030 |
| 4 | 12 | 12.030 | −0.030 |
| 5 | 16 | 16.030 | −0.030 |
| 6 | 20 | 20.010 | −0.010 |
| 7 | 24 | 24.000 | 0.004 |
| 8 | 28 | 27.940 | 0.061 |
| 9 | 32 | 31.950 | 0.046 |
| 10 | 36 | 35.950 | 0.048 |
| 11 | 40 | 39.970 | 0.031 |

Table 2 shows the maximum absolute error of the concentration value after neural network (NN) model treatment and the experimental measuring concentration value. The maximum absolute error is $\varepsilon \leqslant 0.06$ mL, and the most relatively error is $(0.06 \text{ mL}/28 \text{ mL})\cdot 100\% = 0.2\%$, which can meet the need for precision of on-line measurement of the biomass concentration.

### 4.4 Comparison and analyses of measuring results

As seen from the measuring theory, the different experimental methods adopted are aimed at different densities. However, these two methods have the same point: if the biological liquid density increases, its absorbency will increase and the receiving energy will decrease. According to the theory analyses, the complex-refractive index of the testing object and the light scattering effect are mainly used to achieve the measuring purpose.

1) In view of the attenuation degree of the receiving light, if just analyze and compare the low-density data, the curve is close to linearity in the density bound of 4 to 28 mL, the absorption effect dominates and voltage value could reflect the biomass density sensitively. If the density bound surpasses 28 mL, the scattering effect dominates, and the rule needs to be further improved.

2) As seen from the linear bound, the curve is linear in the density bound of 4 to 28 mL. If the bound exceeds 28 mL, there will be a distinct attenuation and the non-linear will be more obvious.

3) As seen from the linearity slope, the curve slope is less in the linear area and augments abruptly in the non-linear area. Given the experimental error, in the linear response part, the degree of the measuring value departing the curve in the low-density area is less than that in high density area.

## 5 Conclusion

According to the process of biological degradation, it is necessary to meet the online testing need, and as the biomass concentration change can stimulate absorption and scattering change and lead to light energy change, we make the receiving energy related to biomass concentration testing and set up a new measurement method. In the experiment, the lamp-house with the 760 nm wavelength was adopted. Under the 20°C constant temperature, research on the OD method and sensor output voltage measurement are performed, and the experimental results are analyzed and compared. Finally, the nonlinear and error compensation of measuring the signal are accomplished, and the results after treatment could meet required industry application precision. The experimental results indicate that the method can be used for testing bacterium liquid concentration, and the maximum relative error is less than 0.2%. Given the many merits of the approach, including precise online testing, high sensitivity and extended use, it is a practical biomass concentration sensor.

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