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Research of Intelligent Turbidity Sensor

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Abstract: Turbidity is an important index to evaluate the water quality. Turbidity can reflect the effects of insoluble substances that contain bait and seston on water. Traditional methods of turbidity detection are complicated, they have low efficiency and poor reliability. To solve the turbidity detection problem in aquaculture, an intelligent optical turbidity sensor which is based on scattering theory has been proposed in this paper. After analyzing the quality characteristics of aquaculture water, the light with 880nm wavelength has been selected as the light source, it can effectively overcome the effect of bait and other organic matter in aquaculture water on turbidity detection. According to the characteristics of turbidity detection, the signal transmitting circuit has been designed to eliminate the effects of noise. So, the accuracy of the sensor is improved. Based on the test experiment on performance of the turbidity sensor, an intelligent correction and compensation model has been designed, which overcomes the influence of temperature fluctuation on the measurement results, improving stability of the turbidity detection. Results of the test have shown that the intelligent turbidity sensor has good stability and reliability, which is suitable for turbidity detection of aquaculture water. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Intelligent sensor, Turbidity, Scattering.

1 Introduction

Turbidity is an important parameter of water quality. Detection of the water turbidity is an important means of controlling water quality, which can measure all kinds of insoluble substance in water. The higher turbidity value, the more turbid water is [1]. However, the traditional measurements are difficult to achieve rapid monitoring on water quality, it not only affects the accuracy of measurement, but is also unable to cope with sudden changes in water quality. Therefore, it is difficult to meet the requirements of Aquaculture Informatization [2].

Many people have developed a lot of turbidity sensors, such as Canada's John F. Orwin [3]. He has developed a set of cheap turbidity meters for detecting suspended solids in water. Japan's Kunio Ebie [4] developed a turbidity meter with high sensitivity, which is designed by using double optical paths. Garcia A. et al [5] has developed a sensor for detecting water turbidity by using fiber. Sun Lixiang of the Jiangsu University [6], has developed a turbidity meter based on a single chip microcomputer (C8051F020). Ren Yongqin of the Tianjin University [7], has developed a seawater turbidity sensor and so on. However, these turbidity sensors are often used in industrial fields. They accuracy is very high, but with a high price, large volume, and poor anti-interference ability. Furthermore, in terms of the wavelength, the matching between the light source and the receiving device is inappropriate. Consequently, it can not meet the actual requirement of sensors in the field of aquaculture water quality monitoring.

Traditional sensors cannot implement remote data transmission, and instruments are needed to carry. If necessary, the machine needs field calibration, and it has low efficiency, and high volume. High performance is also not stable. Intelligent sensors, with zero adjustment, self-calibration, data transmission, effectively solve the problems of water quality sensors encountered in practical application. It is the development direction of water quality sensors [8-10].

The author has carried out relevant research, and successfully developed intelligent turbidity sensors. Using near infrared light (880 nm) as the excitation light source, a silicon photocell is used as receiver. So the sensor repeatability is better. The right angle scattering method, can lower the impact of the outside light. In addition, the requirements of the instrument and equipment are low. The storage and processing of the data can be completed by PC. Moreover, the small size makes it easy to carry around, and its own high accuracy, low-cost and so on.

2. Turbidity Measurement Principle

According to the IS07027 standard, the measuring method includes light transmission method, light scattering method, surface scattering method and the transmission of light - scattering light comparison method [11]. Transmission method can get greater turbidity measurement range, but, when there are light-absorbing substances in water, the high test results will make the measurement accuracy low [12]. When using surface scattering turbidity measurements, because the insoluble organic matter easily floats on the water surface, so that the light scattering is enhanced. As a result, the accuracy of the measurements is not very good. In addition, the requirements of the measuring device are high [13]. The transmission of light - scattering light comparison method, when there are bubbles existing in the optical path, it makes the scattering intensity increase. At the same time, the transmission of light intensity is weakened. Thus it makes the measured turbidity value high, and the stability poor [14].

Using the scattering measurement, stability requirements of the light source and the circuit is relatively low. The stability of the instrument is easy to realize, and it can realize low turbidity measurement. According to the law of Rayleigh scattering, scattering intensity and the turbidity value are proportional. Furthermore, the calibration curve is a straight line. When using the right-angle scatter-turbidity measurement methods, the color of water and light of the sun and other effects can be avoided or reduced. Turbidity measurement usually uses the optical measurement method of scattering. It can obtain liquid turbidity value, by measuring the intensity of scattered light in the liquid. It can be shown in Fig. 1.

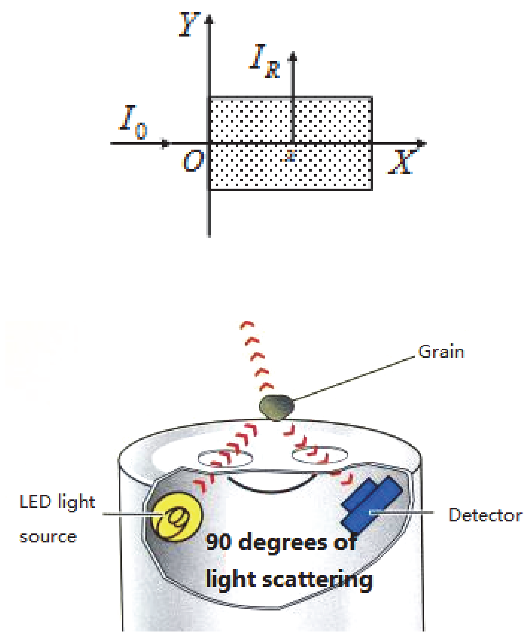

Fig. 1. Schematic diagram of vertical scattering. (a) Diagram of vertical scatter, (b) Structure diagram of vertical scattering.

When a beam with a certain wavelength rips into the water, turbidity in water scatter incident light. Intensity of scattering light and water turbidity is proportional. Consequently, water turbidity is obtained by means of measuring the intensity of scattering light in the perpendicular direction to the incident light. The principle of scattering measurement method is, when a beam of light through the measured water, It can be represented by the formula 1 [15]:

$$I_R = \frac{KNV^2}{\lambda^4} I_0, \tag{1}$$

where I_0 is the intensity of incident light; N is the number of particles in per unit volume; V is the volume of particle; λ is the wavelength of the incident light; K is the coefficient. Assuming λ and V is constant. $\frac{KNV^2}{\lambda^4}$ and the turbidity is proportional. Therefore, in the case that I_0 is a constant, the intensity of scattered light I_R and the turbidity is proportional [16]. It can be represented by the formula 2.

$$I_R = K' T I_0, \tag{2}$$

where T is the water turbidity; K' is another factor. So, in the case that I_0 is a constant, the intensity of scattered light I_R and the turbidity is proportional. The intensity of scattered light values can be used to express the turbidity value.

3. Hardware Design of the Sensor

3.1. Structure Chart of the Sensor

This turbidity sensor comprises an optical measurement module, signal conditioning module, microcontroller MSP43, bus interface module and power management module. Optical measurement module is used to collect turbidity signals in water. Connecting to the optical measurement module, the microprocessor module is used for dealing with turbidity signals. According to the calibration parameters, it converts the processing turbidity signal into turbidity value. Bus interface module, which outputs the turbidity value after processing, is connected with the microprocessor. The power management module, which is connected with the constant current source providing a constant current power with the optical measurement module, offers the signal conditioning module and microprocessor a stable power. Fig. 2 shows the structure diagram.

3.2. Power Supply

1) Power module.

As shown in Fig. 3, the power supply module can convert the 7. 2 V voltage into 3. 3 V. It provides constant current source for the optical measurement module and the microprocessor with a stable power voltage. Pin 3 is the logic high input. Capacitance C11 is a bypass capacitor, it can make the output of the regulator uniform, and reduce the demand of the load. Capacitors C4, C5, C1 are decoupling capacitors. Function is filtering the interference of output signal, in order to prevent interference in the signal from returning to power. At the same time, storage is a function of the decoupling capacitor. Moreover, shunt capacitance C4, C5, C1 makes the low frequency, high frequency signal pass easily.

2) Constant current source.

Infrared emitting diode is a drive device that is the current mode. Its brightness and current are approximate linear relation. In order to improve stability and longevity of the system, the constant current source is used to supply power. In this design, constant current source of the integrated operational amplifier, as one of constant current sources, can expand the range of output current and provide light emitting diode with continuous power. The circuit output voltage does not change along with the change of load and environmental temperature. And the resistance is infinite, as shown in Fig. 4.

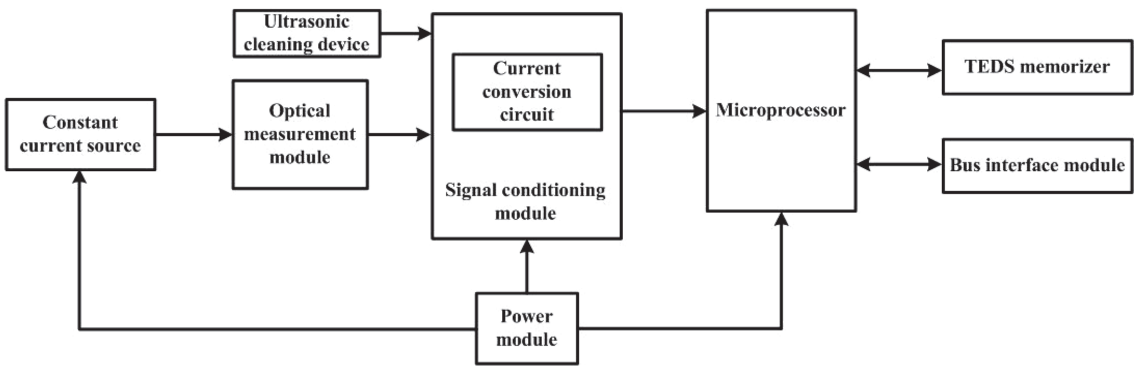

Fig. 2. Architecture diagram of turbidity sensor hardware.

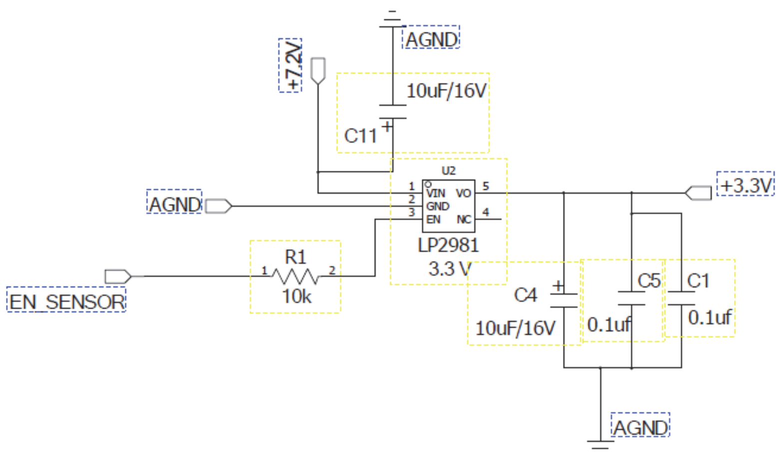

Fig. 3. Power module circuit.

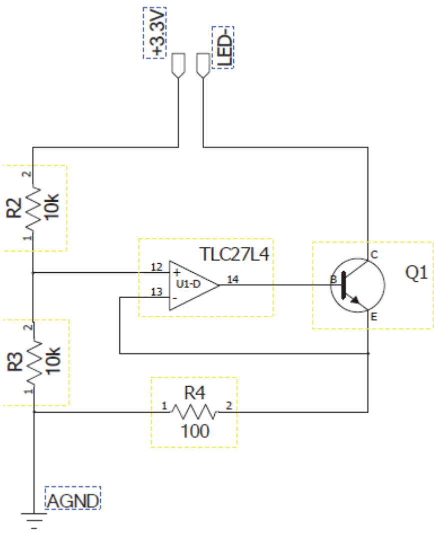

Fig. 4. Constant current source.

3.3. Optical Measurement Module

1) Optical transmitter.

In this paper, LED light with wavelength of 880 nm was selected as the light emitter. Compared with the incident light of shorter wavelengths, the measurement result is low by using near infrared (880nm) as the incident light. But there are two reasons to explain why the 880 nm infrared emitting diode can be chosen [17]:

Organic matter in water interferes with turbidity measurements. Its apparent light absorption (wavelength is less than 500 nm). Generally speaking, the absorption peak is at 260-300 nm. The color of water absorbs light of specific wavelengths, thus affecting the turbidity measurement. Therefore we use near-infrared light to measure the turbidity, so that the influence can be reduced to a minimum. In this spectral region, blue was found to have the least influence on turbidity measurement in the definite water sample.

2) Photoelectric receiver.

We choose HAMAMATSU Hamamatsu silicon PIN tube S1223-01 as photoelectric receiver. When exposed to light, silicon photovoltaic cells produce large electromotive force and current. Therefore, in the design of the turbidity sensor, silicon light battery was chosen instead of the [18] photodiode. It has a wide range of spectral response, linear response, long service life, no noise, no pollution, it is stable reliable and has other advantages [19]. Spectral response curve is shown in Fig. 5.

3.4. Design of Signal Transmission Circuit

Because the current output signal of the silicon photocell is very weak, the current transmission circuit is needed to put the current signal into voltage signal. And then, the filter amplifier circuit converts the signal collection into voltage signal which is suitable for the microprocessor to process. Operational amplifier (TLC27L4) is the main part of the transmission circuit. The amplifier has many advantages, including a wide range of input offset, high input impedance, low power consumption, high gain, and the gain of it can be adjusted according to the actual requirement. Offset voltage of high stability is the biggest advantage of it.

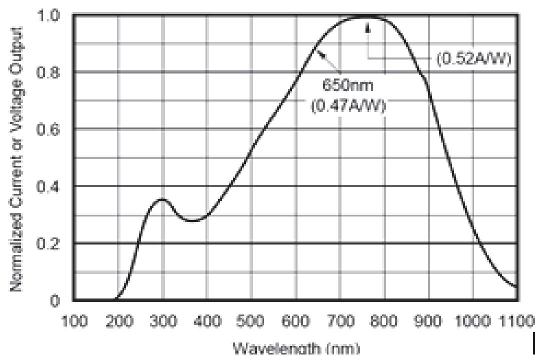

Fig. 5. Spectral response curve of silicon photocell.

1) Current transmission circuit (As shown in Fig. 6).

The current transmission circuit can amplify the weak current signal, and convert it into the voltage signal. Current input amplifiers reduce the input impedance by using negative feedback, in order to realize preamplifier of pure current input. Using this method, even though the value of resistor R6 is increased, we can also reduce the value of input impedance through the effect of negative feedback. For this preamplifier, the ratio of signal average power and noise average power (S/N) is influenced by the feedback resistor. The higher value feedback resistor is, the more advantageous S/N. So, the resistance of 2 MΩ has been chosen.

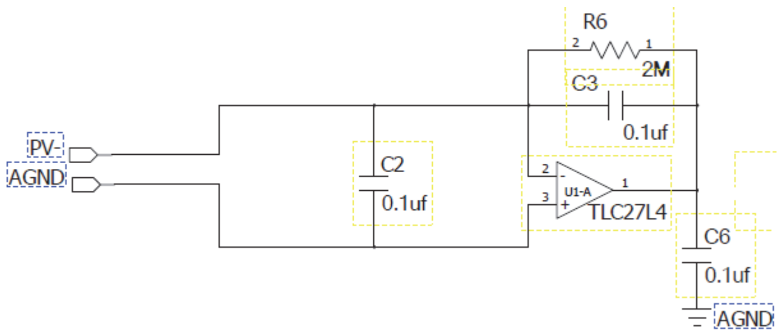

Fig. 6. Current transmission circuit based on the inverse feedback.

Capacitor C3 which is paralleled at the two ends of the resistor is designed to compensate the phase. The input capacitor C2 can filter signals that frequency is greater than 100 KHz. Bypass capacitor C6 is used to filter the AC and high frequency signal of DC signal. Finally, we can gain a relatively stable voltage signal of DC.

2) RC low pass filter (As shown in Fig. 7).

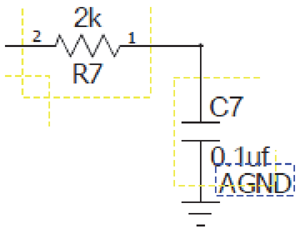

Fig. 7. Low-pass filter.

Because output signal of the current transmission amplifier circuit contains high-frequency noise, it will result in signal distortion, so low pass filtering is needed to improve the signal-to-noise ratio. RC filter can block the high-frequency noise which is harmful, so that useful signals can be properly enlarged. TLC27L4 amplifier has good performance and frequency characteristics, but the high frequency noise generated by the amplifier often lowers the S/N. RC filter cut off high frequency gain which is not needed, so it improves the S/N.

3) 50 Hz notch filter(As shown in Fig. 8).

The weak current signal outputted by the silicon photocell, is enlarged by the current transmission circuit. And then a low pass filter can be used to filter the high frequency signal. Finally, a shock voltage signal is obtained. After passing through a 50 HZ notch filter, the signal is removed. Then we can get a turbidity voltage signal which is an approximate DC signal. Fig. 8 is a 50 Hz notch filter with positive feedback. It is also designated as the double T notch filter. This filter can remove the fundamental component, and the amplitude of it is large. When small signal without fundamental components is added to the amplifier, the distortion which occurred in the amplifier will be smaller.

Trailing arm of double T network is connected to the output of voltage follower U1-B. Amplifier U1-B sends a part of the output signal to the trailing arm of double T network, forming a positive feedback. The value of Q increases with feedback quantity, so that stop band of the notch filter becomes narrow and the value of Q increase. This circuit has good notch depth and high value of Q [20].

3.5. Design of the System Master Control Program

The traditional measurements are difficult to achieve rapid monitoring on water quality. It not only affects the accuracy of measurement, but also unable to cope with sudden changes in water quality. Intelligent sensor comprises a microcontroller. The microcontroller reads the software and sends the resulting signal via USB [21] or RS-232 [22] to the data recording device to display or store the results. The transducers capable of measuring a wide range of turbidity, have good sensitivity, high accuracy and precision. Moreover, embedded with a microcontroller unit or microprocessor, the transducers can perform more powerful functions such as self-calibration [23].

Flow diagram of the system program is shown in Fig. 9. Firstly, in the initialization of hardware, TEDS parameters which are stored in a FM24CL16 ferroelectric memory are taken out. According to the Meta-TEDS in TEDS parameter, type of probe, manufacturer, serial number, number of channels, physical type and data structure can be identified. Secondly, it can measure the voltage of power, signal from probe interface by using self-diagnostic program. So that fault of sensor can be determined. Finally, in order to reduce the power consumption, the microprocessor controls the external device to enter sleep mode (also known as a low power mode), waiting for triggers of task. It can wake up the system in two ways: One, when the acquisition request is timing triggered, is A/D data acquisition and data processing including turbidity calibration; Another is the operation of the service program belongs to interface module of smart transducer.

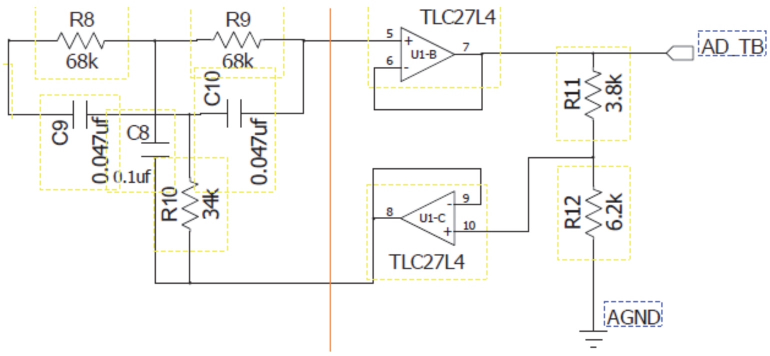

Fig. 8. 50 Hz notch filter with positive feedback.

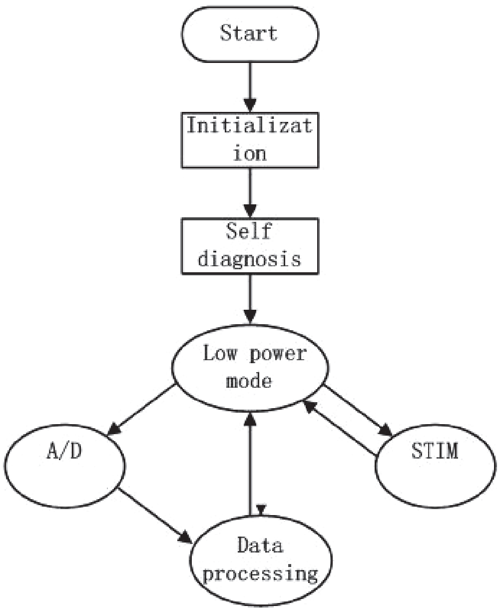

Fig. 9. Main program flow chart of system.

3.6. Design of Anti-interference

Design of the housing.

In the process of measurement, a bubble can enter the probe, scattering the incident light. It has an effect on the results of measurement, leading to the large results. The effect is shown in Fig. 10.

The profile and bottom of the housing are equipped with water pore. It can make water get in and out. It is also used to shield external light sources, reducing interference of external light sources on the module of the optical Measurement. Meanwhile, effects of air bubbles on the results of measurement can be excluded. In order to get a good effect of measurement, the position of hole is higher than that of window glass in front of the photoelectric receiver. We can see it in Fig. 11.

Cleaning device.

Because the sensor is placed in the water for a long time, the optical window will be covered in dirt, and the dirt can affect the transparency effect of the optical window. The value of scattering light received by silicon photocell is smaller than the actual value. Therefore, using the ultrasonic cleaning device, dirt on optical window is cleaned off and then outflow from the detector by ultrasonic oscillations. Ultrasonic cleaning module, which is connected with the microprocessor, comprises ultrasonic generator, vibrating membrane and gland. Controlled by the microprocessor, this module cleans the dirt on optical window. Function of self cleaning can be realized [24]. It can be seen in Fig. 12.

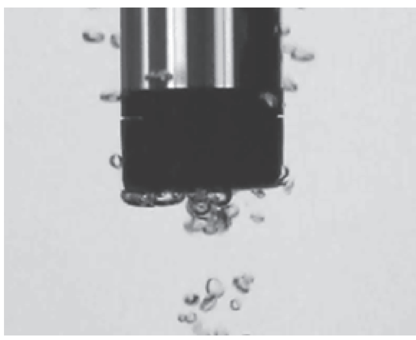

Fig. 10. Effect of bubbles on the measurement results.

Fig. 11. Housing of probe

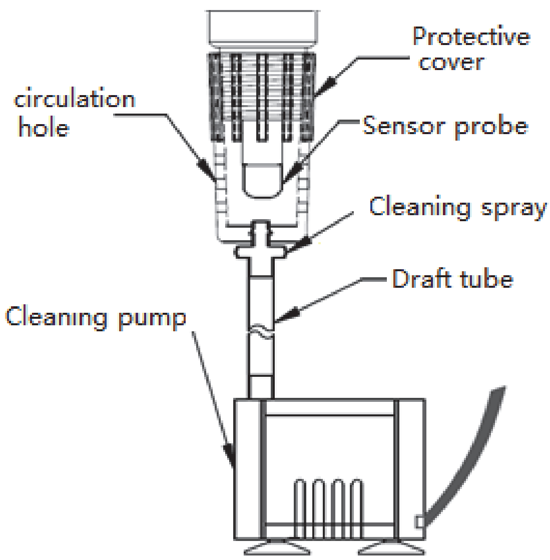

Fig. 12. Self-cleaning structure of sensor.

4. The Experimental Results and Analysis of Data

4.1. The Experiment of Calibration

At room temperature, we did the linearity measurement of turbidity sensor. Using pure water, turbidity standard solutions of Formazin were adjusted with filtered water into water samples of 0–100 NTU. The suspension was mixed for 1 min, so as to create an intensive mixing. Ten sample solutions were measured 20 times. Interval of the measurement was 5 s. The measurement results are shown in Table 1. Calibration curve of the probe was fitted according to the principle of least square which is y=0.1939x-38.384, and the correlation coefficient is R2=0.9998. Results show all the solutions measured gave nearly linear relations between the concentration of the standard solutions and the measured turbidity. Fig. 13 shows the results.

4.2. Accuracy Analysis

Experiments were carried out at room temperature. Five sample solutions (7.40 NTU, 9.80 NTU, 20.40 NTU, 56.60 NTU and 102.40 NTU) were measured 8 times. Table 2 shows the results of continuous monitoring of Formazin standard solutions with the transducer which was completely submerged under the solution. As the figure shows, the measurement accuracy is very high and the relative measurement error is within ± 2 % for all these samples.

Table 1. Measurement results of turbidity standard solutions of Formazin.

Sample /NTU	Measurement results /NTU	Sample /NTU	Measurement results /NTU
0. 3	201	45	427. 788
9. 8	249	56. 6	489. 0628
11. 7	259. 93	74. 3	586. 975
20. 4	302. 838	90. 3	661. 192
31. 5	356	102. 4	726

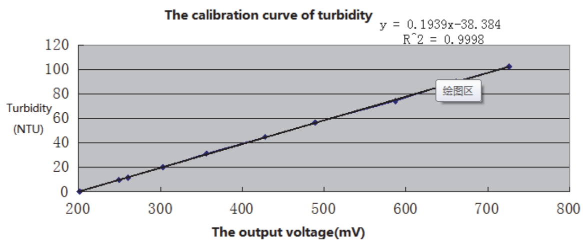

Fig. 13. Calibration curve of turbidity sensor.

4.3. Precision Analysis

Precision refers to the discrete degree of the values measured by the same method in the same experimental condition for the same sample repeatedly, generally with the relative standard deviation (RSD) to represent. The calculation formula of precision is can be represented by the formula 3:

$$RSD = \frac{\sqrt{\frac{\sum_{i=1}^{n}\left(X_i + \bar{X}\right)^2}{n-1}}}{\bar{X}}, \quad (3)$$

where X is the single sample measurement, $\bar{X}$ is the average value of n parallel sample survey data, n-1 is the degree of freedom. The smaller the relative standard deviation (RSD) is means the results are more concentrated and the precision is better.

Turbidity standard solutions of Formazin were adjusted with pure water into sample of 196. 4 NTU. Measuring this water sample 10 times, we show the measurement results in Table 3. The results show that: the sensor has high accuracy.

4.4. Effect of Temperature

Using pure water, standard solution of Formazine was diluted into 10NTU, 20NTU and 80NTU. The sample solution was placed in the refrigerator. When it was refrigerated to 0 °C, we put the sensor into the sample solution. Then the sensor and sample solution were immersed in tank with water of constant temperature. Adjusting temperature of water in bath to 40 °C slowly, we recorded sensor data at set intervals. At the same time, agitating the sample solution with a glass rod slowly, we removed air bubbles caused by heating, so as not to affect the measurement results. The measurement results are shown in Fig. 14.

As Fig. 14 shows, when the temperature was in the range of 1~40 °C, the relationship between the outputs signals of sensor [25]. It can be represented by the formula 4.

$$y = mx^2 + nx + p, \tag{4}$$

where y is the output signal of turbidimeter, x is the temperature, m , n and p are the coefficients.

Reading three sets of voltage signal ($B(x_1, y_1)$ and $C(x_2, y_2)$) about same sample in different temperatures, it can substitute the quantitative data of A, Band C into equation (4). So the three coefficients (m, n and p) can be obtained. Then according to this equation, the turbidity value of voltage corresponding to 25 °C can be calculated.

The above-mentioned method is designed to program, and be carried by MCU which is used to compensate the measurement errors by soft programming.

Table 2. Accuracy result.

Sample/ NTU	Measurement results/NTU								Avera-ge/NTU	Absolute deviation	Relative deviation
	1	2	3	4	5	6	7	8			
7.40	7.30	7.41	7.43	7.23	7.45	7.47	7.27	7.38	7.37	0.075	1.02 %
9.80	10.05	9.80	9.77	9.85	10.1	9.75	9.81	9.88	9.87	0.086	0.88 %
20.40	19.96	20.01	20.48	20.1	20.6	19.90	20.30	20.40	20.2	0.158	0.77 %
56.60	56.41	56.61	56.0	57.0	56.1	56.63	56.81	56.43	56.49	0.26	0.47 %
102.40	100.58	102.30	101.9	102.8	101.8	102.28	102.09	102.24	102.01	0.56	0.54 %

Table 3. Measurement results of precision.

Number of measure-ments	1	2	3	4	5	6	7	8	9	10	Average	RSD
Measured value NTU	196.0	196.4	196.39	196.3	196.7	196.45	196.2	195.9	196.8	195.8	196.3	0.17 %

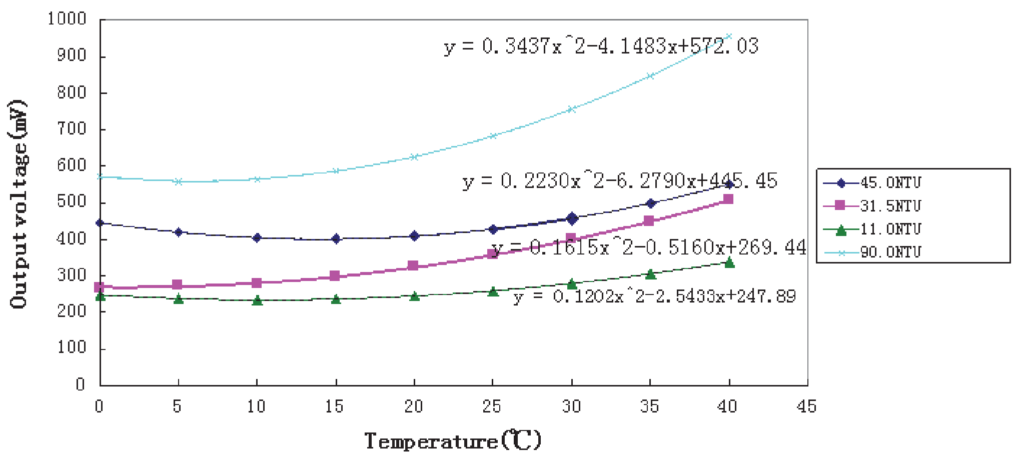

Fig. 14. Relationship of temperature and output signal of sensor.

5. Conclusion

1) To solve the problem of turbidity monitoring, this paper adopts method of 90 degree scattering. Through a comparative analysis of a variety of photoelectric detection devices and light-emitting diode, this paper use infrared light emitting diodes and silicon photocell as excitation light source and photoelectric receiving device, and then the constant current source is used to supply power for light source. It greatly reduces the influence from the water color and other factors on measurement results, improving the stability and service life of the system.

2) According to the intelligent demand for water quality sensors, we combine SCM technology with photoelectric detection technology. Based on the standard protocol of IEEE1451, the design of sensor with interface module, Transducer Electronic Data Sheet (TEDS) and bus interface (RS-485) are achieved, in order to solve the problem that measurement results of sensor are wireless transmitted.

3) To solve the problem that sensor works under water, the sensor housing which is hermetic is designed, solving the waterproof problem of the sensor. In view of the influence of bubbles on the sensors accuracy, water hole are designed in the probe shell, effectively reducing the effect of external light source on the measurement results, and solving the problem of reliability.

4) According to the actual requirements for water quality sensors, linearity, accuracy, precision, repeatability and stability of the turbidity sensor are verified through experiment. It is confirmed that the main performance index of the sensors meet the practical requirements.

Acknowledgements

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