The Design of Low-concentration Dust Detection System Based on Mie Scattering Theory

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Abstract: According to the requirement of low-concentration dust emission in China, this paper designed a low-cost and high-precision dust detection system based on Mie scattering. Through theoretical analysis, the relationship between the intensity of scattered light and the concentration of soot is obtained. The laser emitting unit, signal receiving unit and STM32 data processing unit are designed. The driving principle of laser modulation and the principle of selective signal amplification of weak signal are analyzed. The host computer program is written with LabVIEW software, and the test data are displayed on the front panel of the host computer. The experimental results show that this system has high sensitivity, fast response, good repeatability, and can be measured online for a long time, which means this system has good practicability.

1. Introduction
A large amount of soot particles will be produced in the power generation process of coal-fired power plants. After filtration, its concentration will become lower and its particle size will become smaller[1]. Floating in the air for a long time will enter the human body, which will cause great harm to human health and have an adverse impact on industrial production with high dust-free requirements.

Based on Mie scattering theory, it describes the law of light scattering on the surface of micro particles[2]. The detection equipment based on light scattering method has the advantages of high automation, small instrument volume and direct measurement results[3-4], it combines laser modulation, weak signal processing, and embedded technologies. This paper designs a low concentration dust detection system which can be measured online.

2. System design scheme
The system is mainly composed of four parts: laser transmitting unit, signal receiving unit, STM32 data processing unit and host computer software. The laser emits a modulated laser driven by a modulated signal, which irradiates the smoke area to be measured through the beam expander, and it scatters. The scattered light is collected by the condenser to the photodetector and converted into electrical signals, the electrical signals are amplified, filtered, and A/D converted into the STM32 processing unit for data processing, and finally sent to the upper computer through the serial port for real-time display and storage. The scheme is shown in Figure 1:
2.1. Laser emission unit

The laser emission unit mainly includes: LD laser, reference voltage source circuit, signal modulation circuit, laser current driving circuit.

The system selects an LD laser with a wavelength of 650nm as the laser light source, the laser wavelength and the soot particle size are of the same order of magnitude, and meet the theoretical requirements of Mie scattering. LM399 high precision reference voltage source is selected as the reference source and the reference voltage is 6.95v. Through the potentiometer voltage divider and low-pass filter noise elimination, the 3V DC bias voltage is obtained. The signal modulation uses the high-frequency precision function signal generator MAX038 to generate a sine signal with a frequency of 200 Hz [5], and output a 2V modulation voltage after filtering. AR1 and AR2 in the circuit are LM393 voltage followers, which are used to increase the input impedance of the circuit and prevent the interaction between the front and rear stages. The DC bias voltage $V_b$ and the signal modulation voltage $V_m$ are superimposed by the OPA188 op amp chip with low noise and zero drift to generate a 5V laser modulation voltage signal. The constant current source circuit is a negative feedback circuit composed of operational amplifiers AR4 and AR5, the circuit uses the current amplification characteristics of the NPN transistor to expand the current output, and finally obtains a 40mA laser drive current. The driving circuit is shown in Figure 2:

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**Fig 1** Block diagram of low-concentration smoke and dust detection system

**Fig 2** Laser modulation drive circuit
2.2. Signal receiving unit

The signal receiving unit mainly includes: photodetector, I-V conversion amplifier circuit, and filter circuit.

The system selects S1787-12 high-speed response silicon photodiode (PIN) as the detector, and the sensitivity can reach the highest value of 0.4A/W when the wavelength is 650nm. The electrical signal converted by the photodetector is very weak. The signal processing can not only amplify, but also have the ability to suppress noise while amplifying the useful signal. The pre-IV conversion circuit is designed to facilitate the processing of the detection signal, but a certain amount of noise and bias current will be generated during the conversion, which may cause errors in the subsequent amplifier circuit, in order to eliminate this effect, the circuit uses a T-type feedback network. The conversion chip uses high-precision OPA277 operational amplifier. In the weak signal amplification part, a secondary amplification circuit is designed, and the amplification factor can reach 1000 times. But in fact the amplifier itself also has certain noise, so the amplifying circuit can determine the most suitable amplification factor according to the actual measurement sensitivity through the adjustable resistor R21. The function of the offset adjustment is to superimpose the DC offset on the AC signal through the subtractor [6]. The circuit is shown in Figure 3:

![Fig 3 I-V conversion amplifier circuit](image)

The filter circuit plays a decisive role in improving the signal-to-noise ratio of the entire signal detection unit. Design a two-stage second-order infinite gain multiple negative feedback bandpass filter circuit, the center frequency of the first-stage circuit is 202Hz, and the second-stage circuit is adjusted to 200Hz by R29, in the phase connection method, the infinite open-loop gain of the inverting input terminal can be regarded as a virtual ground, and the output terminal consists of two feedback branches composed of resistors and capacitors. Theoretically, the quality factor Q of the circuit can reach the ideal value [7]. The circuit is shown in Figure 4:

![Fig 4 Bandpass filter circuit](image)
2.3. **STM32 data processing unit**

The STM32 data processing unit mainly includes: STM32F103, power supply circuit, JTAG program interface, A/D conversion input interface, serial port module, and data storage module.

The processor uses the STM32F103ZET6 chip, which has a high-speed embedded memory and an advanced communication interface. The power supply uses the AX1117-3.3V chip; the JTAG program download interface is used for system hardware simulation and online modulation; the serial port module uses the RS232 chip to realize the communication between the microcontroller and the host computer\(^8\); the data storage module uses the electrically erasable memory chip FM24C02, it can realize data storage and compression for subsequent analysis and processing. The structure diagram is shown in Figure 5:

![Figure 5 Block diagram of data processing unit](image)

2.4. **Host computer software design**

The upper computer of this system is developed using LabVIEW software. The upper computer interface is designed with data waveform and numerical display windows, serial port debugging windows and data storage control keys. The measuring range of the ordinate of the curve in the figure is set to be adjustable.

3. **Experimental results**

In order to verify the sensitivity and accuracy of the low concentration dust detection device, the sensitivity and curve calibration experiments were carried out. The experimental environment is a self-made cylindrical simulated flue with a volume of 0.785 m\(^3\), the dust concentration in the flue can be calculated by adding different quality dust as the standard concentration, and the standard concentration is compared with the actual measured value to calculate the error.

3.1. **Sensitivity experiment**

The experimental results are shown in Figure 6, The abscissa of the picture is time and the ordinate is voltage value.

![Figure 6 Sensitivity measurement diagram](image)
It can be seen from the figure that when the fly ash passes through the laser beam, the electrical signal received by the detector will obviously increase. With the falling of the dust, the electrical signal will gradually return to the initial value, it shows that the system is more sensitive to the backscatter signal of low-concentration dust, and can be used for low-concentration dust measurement.

3.2. Curve calibration experiment
In order to test the accuracy of the system, this paper designs two sets of measurement experiments with different increments. The increment of fly ash mass is set to 25mg in the range of 0-250mg, and the increment is set to 50mg in the range of 250-750mg. The time of each group is 200 seconds, one data is recorded per second, and the average value of 200 data is calculated. The experimental results are shown in Table 1:

| Increment 25mg group | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|----------------------|---|---|---|---|---|---|---|---|---|----|
| Mass of added fly ash (mg) | 25 | 50 | 75 | 100 | 125 | 150 | 175 | 200 | 225 | 250 |
| Fly ash concentration (mg/m³) | 31.85 | 63.69 | 95.54 | 127.39 | 159.2 | 191.08 | 222.93 | 254.78 | 286.62 | 318.47 |
| Average output voltage (mV) | 108.1 | 112.74 | 123.86 | 136.97 | 152.2 | 155.24 | 169.69 | 175.43 | 186.13 | 198.86 |

| Increment 50mg group | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|----------------------|---|---|---|---|---|---|---|---|---|---|
| Mass of added fly ash (mg) | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 | 750 |
| Fly ash concentration (mg/m³) | 382.1 | 445.86 | 509.55 | 573.25 | 636.9 | 700.64 | 764.33 | 828.03 | 897.72 | 955.41 |
| Average output voltage (mV) | 220.0 | 240.98 | 253.99 | 280.15 | 292.0 | 310.92 | 330.74 | 357.05 | 380.87 | 405.54 |

The dust concentration in Table 1 is linearly fitted to the average value of the output voltage, and the fitted calibration curve is shown in Figure 7. It can be seen from the figure that there is an obvious linear relationship between the fly ash concentration and the average value of the voltage \([9]\). The equation is 

\[ y = 3.169x - 305.3 \]  

(1)

\( y \) represents the dust concentration value (mg/m³), and \( x \) represents the output voltage value (mV).

![Fig 7 Fitting curve of soot concentration and voltage value](image-url)
The abscissa of the picture is dust concentration value (mg/m³) and the ordinate is voltage value (mV). The average error of each group of 200 measured values in the table is calculated, and the error range is 0.31% ~ 1.26%. If the variation range is small, the system repeatability is good; The error between the measured concentration and the standard concentration calculated by the calibration curve is 4.42%.

4. Conclusion
Based on the Mie scattering theory, this paper designs a system that can be used for low-concentration dust detection. Experiments have verified that this system has good sensitivity and repeatability in low concentrations. The display interface of the upper computer is designed using virtual instrument technology, which can monitor the change of smoke and dust concentration in real time. The experimental results show that there is an obvious linear relationship between the soot concentration and the output voltage, and the deviation of the measured concentration from the standard concentration is 4.42%. It can be applied to the measurement of low-concentration soot emissions from coal-fired power plants within the range of the international standard error.

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