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Development of a Coal Dust Concentration Sensor Based on the Electrostatic Induction Method

Jiange Chen, Dewen Li,* Guoqing Liu, Yanzhu Li, Anran Zhang, Siyuan Lu, and Mi Zhou

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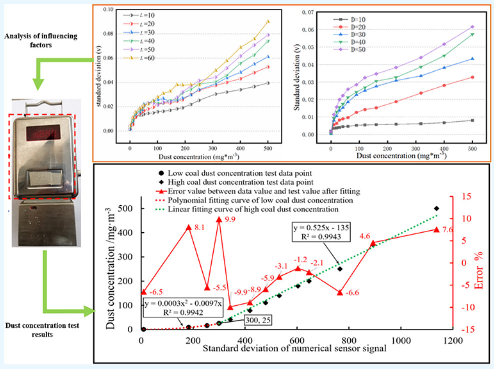
ABSTRACT: In order to solve the problems of easy blockage and difficult maintenance of the current coal dust concentration sensor, a coal dust concentration sensor based on the electrostatic induction method was designed. Based on the analysis of the principle of electrostatic induction dust concentration detection, an electrostatic induction dust concentration sensor composed of a electrostatic detection electrode, a dust extraction fan, an induction signal processing circuit, an insulator, a shield, and other parts was designed. The influence of the length and width of the electrostatic detection electrode and the particle flow rate on the standard deviation of the induction signal was analyzed through experiments to optimize them. The induction signals on the electrostatic detection electrode at different dust concentrations were determined in tests, and the mathematical relationship between the standard deviation of the induction signal and the dust concentration was obtained. According to segment multiple-curve height fitting, the maximum deviation between the detected value and actual dust concentration does not exceed 10%.



1. INTRODUCTION

Coal is one of the main energy sources for the development of the human economy. In the production process of coal mines, a large amount of coal dust is inevitably generated due to coal cutting and transfer.[1,2] A large amount of coal dust is can easily cause major disasters and accidents such as coal dust explosions.[3,4] In 2021, due to a large coal dust explosion accident, seven people died in one Coal Mine in Shandong Province, China. Workers who are frequently exposed to coal dust are also prone to incurable pneumoconiosis, which may lead to loss of labor force or life.[5,6] Therefore, the harm of coal dust in coal mines cannot be ignored, and it is necessary to accurately detect the concentration of coal dust in coal mine operation sites. If the dust concentration exceeds a specific threshold, a warning message is sent to the coal miners. In this case, they must evacuate the dust-laden environment or take dust prevention measures to prevent dust explosions and injuries.

At present, the main test methods of coal dust concentration in coal mines are the sampling and weighing method, the β-ray method, and the light scattering method.[7,8] The sampling and weighing method is the direct method for dust concentration detection, and the test result is the reference standard value of other indirect dust concentration detection methods. The process of the sampling and weighing method is to collect a gas–solid mixture in the air through the sampler and then weigh the mass of the dust filtered on the filter membrane. The dust concentration is obtained by dividing the dust mass by the volume of the sample.[9,10] The operation is cumbersome, and the data of dust concentration cannot be obtained in time. It is mainly used to calibrate other types of dust concentration detection devices in the laboratory. The basic principle of the β-ray method is to characterize the dust concentration by measuring the attenuation value of the dust on the surface of the filter membrane against the radiation intensity.[11,12] The β-ray method dust concentration detection equipment needs frequent replacement of the filter membrane, with which it is difficult to achieve online detection. The light-scattering method's dust concentration detection technology is used to characterize the dust concentration value by detecting the scattered light intensity of the dust particles.[13,14] At present, the coal dust concentration sensor in coal mines mainly adopts the technology.[15,16] The dust concentrations produced in coal mines can reach up to 500 mg/m^3. Hence, the dust can easily block the pipeline and pollute the photodiode of the light-scattering dust concentration sensor. To ensure detection accuracy, the optical sensor must be frequently maintained, which poses a great challenge.

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In this study, the electrostatic induction method, which requires less maintenance and is suitable for harsh environments, will be used to develop a new type of dust concentration sensors. Electrostatic induction can be performed with a simple device structure. In addition, the costs are low, and the devices are highly sensitive.[17−19] Over the past few years, the particle concentration detection technology based on the electrostatic induction method has developed rapidly and has been studied by a large number of scholars at home and abroad. Yan et al. built an electrostatic dust concentration sensor with a ring electrode and a rod electrode to detect the flow rates and concentrations of particles in pipes and fluidized beds.[20,21] Based on electrostatic induction, an array-type electrostatic detection electrode was used to detect the local particle concentrations and flow rates in pipelines by Wang et al. and Zhong et al.[22,23] Wang and Qian used the cross-correlation algorithm to analyze the electrostatic induction signal of the static detection electrode installed at the upstream and downstream of the pipeline to detect the particle flow rate in the pipeline.[24,25] According to the published research results, the electrostatic induction method is widely applied in fluidized beds and dust pipelines. The main detection electrodes are the rod electrodes and ring electrodes. There is relatively little research on the detection of coal dust concentration in the environment by the electrostatic induction method. Because the movement direction of coal dust in the coal mine environment is inconsistent and the concentration fluctuation range is large, it is difficult to accurately detect the concentration of coal dust in the environment by the electrostatic induction method, which is also a research focus of scholars at present. Liu changed the straight pipe into a spiral pipe and reduced the diameter of the pipe, increased the chance of contact between dust particles and the pipe wall, improved the intensity of the dust particle induction signal, and improved the detection accuracy and stability of the dust concentration.[26] The pipe for detecting dust is changed to a spiral shape and its diameter is reduced, which can cause the pipe to be blocked by dust and requires frequent maintenance. The advantage of the maintenance-free electrostatic induction dust concentration sensor is no longer available. FLUENT software was used to optimize the electrostatic detection electrode to improve the induction signal strength of the dust particles and ensure the detection accuracy and stability of dust particles.[27,28] However, there is no analysis of the influence of the geometric parameters of the electrostatic detection electrode on the induction signal, and the geometric dimensions of the electrostatic detection electrode are not optimized by experimental means. Therefore, this paper analyzed the influence of the geometric size of the electrostatic detection electrode and the particle flow velocity on the induction signal by means of experiments, optimized its parameters, and made the electrostatic induction dust concentration sensor achieve accurate detection of coal dust concentration.

In this study, an electrostatic induction dust concentration sensor consisting of an exhaust fan, an electrostatic detection electrode, an insulator, and a signal processing circuit was developed for diffused dust in external environments. By using an experimental device in a uniform dust distribution with an adjustable dust concentration, the influence of the length and diameter of the electrostatic detection electrodes and wind speed on the induction signal was experimentally analyzed at different dust concentrations. The optimum geometrical size of the electrostatic detection electrodes and dust extraction speed were determined, and an optimized dust concentration sensor was designed based on the electrostatic induction method. Finally, the mathematical relationship between the standard deviation of the induction signal and the dust concentration was determined through experiments, and the detection accuracy of the dust concentration sensor based on electrostatic induction was determined.

2. PRINCIPLE OF MEASUREMENT

2.1. Electrostatic Induction Method. The dust concentration sensor mainly includes an electrostatic detection electrode, an IV conversion circuit, and auxiliary parts. Its working principle is shown in Figure 1.[29,30] When dust is close

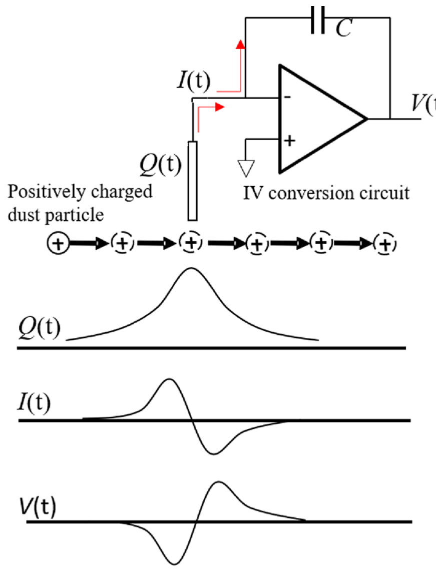

Figure 1. Schematic of the electrostatic induction method.

to and far from the surface of the electrostatic detection electrode, a certain charge is induced on its surface owing to electrostatic induction. The change in the current signal caused by the changing charge can be converted into a voltage signal with an IV conversion circuit. If the dust particles are positively charged, the current signal caused by the induced charges on the surface of the detection electrode owing to the moving dust particles flowing first from the detection electrode to the IV conversion circuit and then back to the detection electrode. If the dust particles are negatively charged, the induced current flows in the opposite direction. When the dynamic dust particles pass through the electrostatic detection electrode, the alternating voltage signal of the IV conversion circuit is the superposition of the alternating signals generated by each dust particle. Thus, the dust concentration can be represented by counting the fluctuations of the alternating signals of the dust.[31,32] In order to realize the detection of coal dust concentration in the environment, it is necessary to rely on the fan to pass the freely floating coal dust in the environment through the detection area of the electrostatic detection electrode at a certain speed. Through the electrostatic detection electrode and the IV conversion circuit connected with it, the induction signal generated by the dynamic dust can be obtained, and the fluctuating induction charge signal on the surface of the electrostatic detection electrode can be converted into the fluctuating voltage signal. The dust

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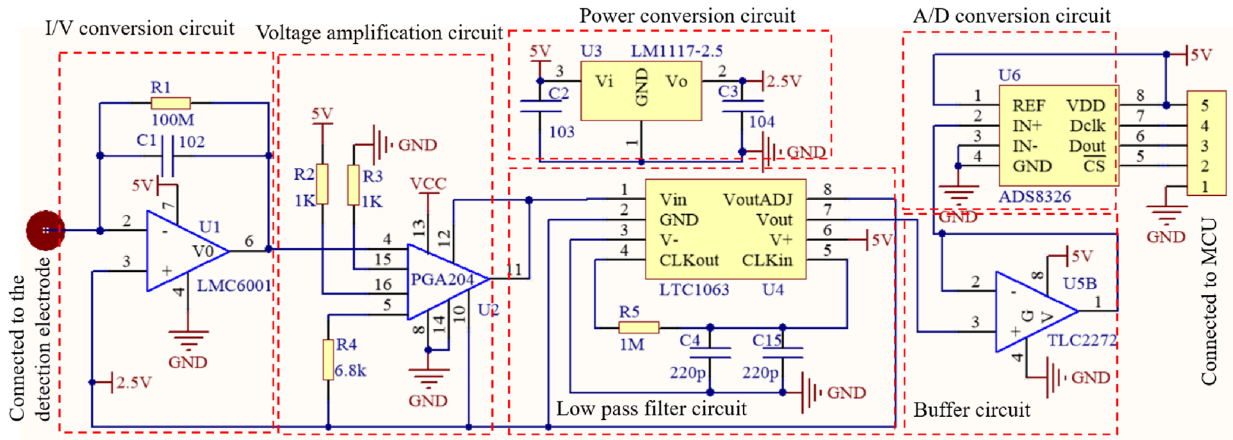

Figure 2. Diagram of the signal processing circuit.

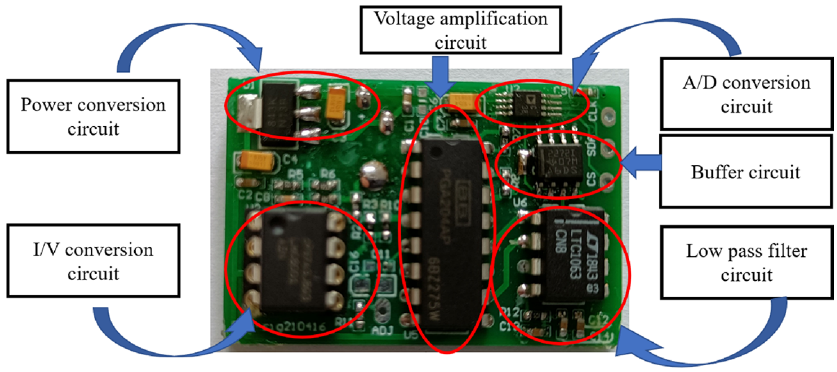

Figure 3. Photograph of the signal processing circuit board.

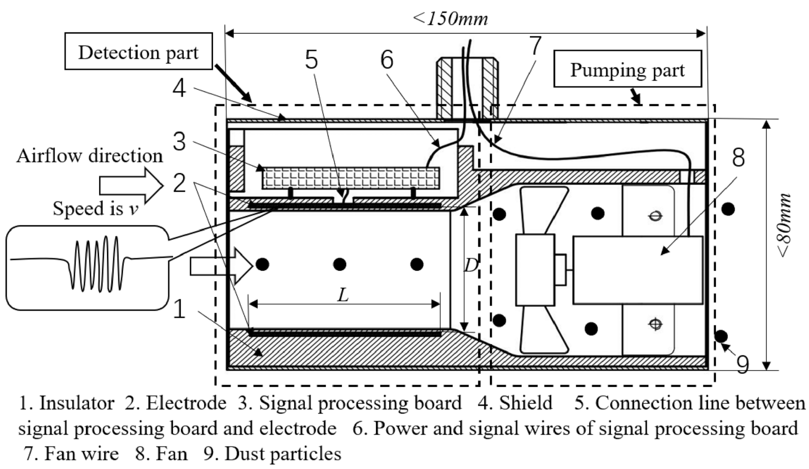

Figure 4. Schematic of the electrostatic induction dust concentration sensor.

concentration value is obtained by further analyzing the fluctuating voltage signal.

2.2. Processing of the Electrostatic Induction Signal. The electrostatic induction signal processing circuit is an important part of the sensor. The circuit includes an IV conversion circuit, a voltage amplification circuit, a low-pass filter circuit, a buffer circuit, an AD conversion circuit, and a power conversion circuit. The circuit diagram is shown in Figure 2. The signal processing circuit board, which is based on an analog signal processing circuit, is shown in Figure 3. The charge induced by the dust particles on the surface of the detection electrode is converted into a voltage signal through the IV conversion circuit LMC6001. The LM6001 operational amplifier has a low input bias current, high input impedance, high common mode rejection ratio, wide bandwidth gain product, large input impedance, and less noise, which render it suitable for the processing of electrostatic induction signals. The PGA204 operational amplifier circuit is integrated into the voltage amplifier circuit to amplify the small voltage signal by the IV conversion circuit by 100 times. Subsequently, high-frequency clutter is removed by the LTC1063 chip, which is a five-order Butterworth low-pass filter. The 16-bit AD7683 analog–digital conversion circuit converts the analog signal into a digital signal. Finally, the test data are transmitted to the

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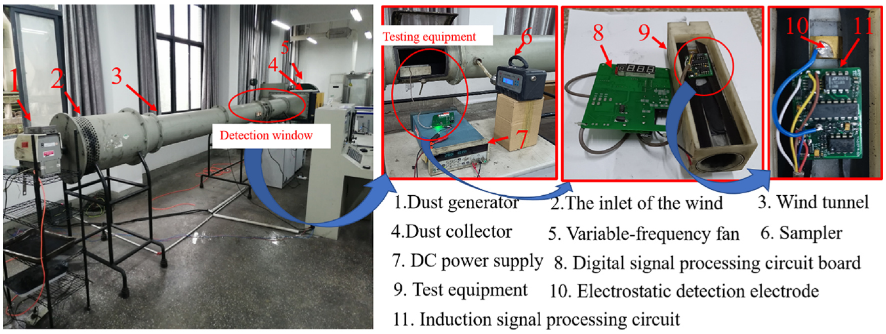

Figure 5. Photographs of the test devices.

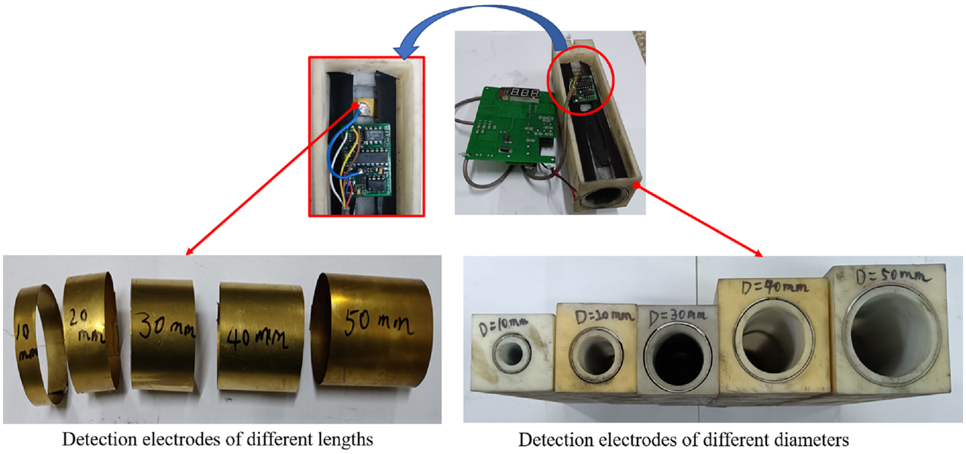

Figure 6. Detection electrodes for the electrostatic induction dust concentration sensor.

microcontroller through the SPI communication mode for further processing, and the standard deviation of the induction signal is calculated to characterize the dust concentration in the environment.

2.3. Sensor Design and Installation. The designed electrostatic induction dust sensor is shown in Figure 4. In order to facilitate the installation and use of the electrostatic induction dust concentration sensor, the external length of the electrostatic induction dust concentration sensor shall not exceed 150 mm and the outer diameter shall not exceed 80 mm. It includes an insulator, an electrostatic detection electrode, a DC fan, a metal shield, and a signal processing circuit. The copper strip with a detection electrode length L and diameter D is installed inside the insulating body (polytetrafluoroethylene) with an annular groove inside. Under the action of the fan installed at the end of the electrostatic induction dust concentration sensor, the dust particles in the air pass through the detection area at a certain speed v and are then discharged into the air through the fan. The fluctuations of the alternating signal induced by moving dust on the surface of the electrostatic detection electrode represent the dust concentration. This paper focuses on the influence of the size of the electrostatic detection electrode and dust particle velocity on the fluctuations of the electrostatic induction signal. To improve the signal-to-noise ratio and reduce external electromagnetic interference, a grounded metal shield is installed at the outer end of the insulator and the signal processing circuit is as close as possible to the detection electrode.

3. EXPERIMENTAL SETUP

3.1. Experimental Device. The wind tunnel of the State Key Laboratory of the China Coal Science and Engineering Group Chongqing Research Institute Co., Ltd., shown in Figure 5, was used for the tests. The air tunnel consists of a dust generator, an air tunnel, a test window, a dust remover, a variable-frequency fan, a control center, and other main parts. The variable-frequency fan at the end of the air tunnel creates a stable flow velocity in the air tunnel. The airflow speed (0.5−6 m/s) can be adjusted by changing the fan speed. The dust generator sprays a certain amount of dust into the air tunnel, which results in a stable and evenly distributed dust flow inside the air tunnel under the action of the airflow. The dust concentration in the airflow can be changed by adjusting the amount of dust generated by the dust generator (0−1000 mg/m^3). The dust collector at the end of the air tunnel collects the dust in the airflow such that it is not discharged into the environment. The electrostatic induction dust concentration sensor is inserted into the air tunnel through the test window, and the digital signal processing circuit is installed outside the detection window to display the processing results of the induction signal. The electrostatic induction dust concentration sensor is powered by a DC 24 V power supply. To determine the dust concentration in the air tunnel, the dust−gas mixture in the air tunnel is collected and weighed. The sampling port of the sampler is parallel to the electrostatic induction dust concentration sensor.

To analyze the influence of the diameter and length of the electrostatic detection electrode and dust velocity on the electrostatic induction signal, an electrostatic induction dust concentration measuring device was manufactured. The device

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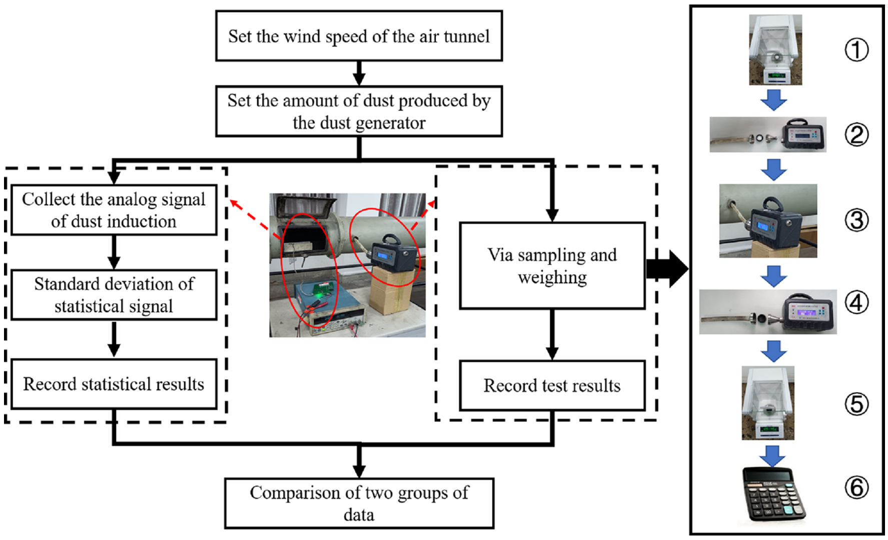

Figure 7. Test flow chart.

includes electrostatic detection electrodes of different widths and lengths, insulating support seats, and signal processing circuits; there are no fans with impellers. The velocity of the particles in the detection electrodes can be changed by changing the wind speed in the air tunnel. The digital signal processing board for determining the collected concentrations is connected to the signal processing board of the electrostatic detection electrode. Furthermore, the electrostatic induction dust concentration sensor is shown in Figure 5. It should be small and lightweight. Therefore, electrostatic detection electrodes with 10, 20, 30, 40, and 50 mm diameters and 10, 20, 30, 40, and 50 mm lengths were used in the tests. They are shown in Figure 6.

3.2. Test Procedure. To reduce the influence of the equipment on the particle logistics field, the electrostatic induction dust concentration sensor was inserted into the air tunnel, and the digital signal processing circuit was installed outside the air tunnel. The test flow chart is shown in Figure 7. The standard deviation of the signals collected for 5 s was counted, displayed, and recorded. The sampler working in parallel with the electrostatic dust concentration sensor determined the real dust concentration in the air tunnel by sampling and weighing. The specific process is as follows[33,34] (Figure 7):

(1) A clean filter membrane was weighed (m_1).

(2) The clean filter membrane was inserted into the sampling head of the sampler.

(3) The sampling tube of the sampler was pushed deep into the air tunnel to collect a certain amount of the gas−solid particle mixture. The collected gas volume was measured (v). As the filter paper lets gas pass through, all dust particles in the gas−solid particle mixture remained on the surface of the filter paper.

(4) The filter membrane with the dust layer was removed from the sampling head of the sampler.

(5) The dust-covered filter membrane was weighed (m_2).

(6) The actual dust concentration in the air tunnel was calculated with the equation $(m_2 - m_1)/v$ (mg/m^3). The output data of the electrostatic induction dust concentration sensor and the real dust concentration in the air tunnel were recorded and compared.

4. RESULTS AND DISCUSSION

4.1. Analysis of Influence of Length of Electrostatic Detection Electrode. To analyze the influence of the length of the electrode on the induction signal, its diameter was fixed to 40 mm; its lengths were 10, 20, 30, 40, and 50 mm; and the flow velocity through the electrostatic detection electrode was 2 m/s, while the dust concentration was changed. As shown in Figure 8, the standard deviation of the output induction signal at different dust concentrations was recorded.

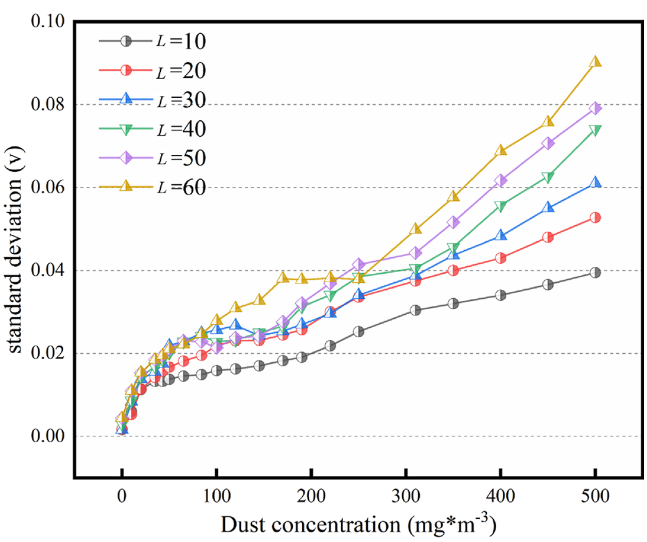

Figure 8. Influence of the length of the electrostatic detection electrode on the electrostatic induction signal.

According to the results in Figure 8, the standard deviation of the output induction signal of the electrostatic induction dust concentration sensor increases with the length of the electrostatic detection electrode. The longer the electrode is, the more charged dust particles can be detected in the sensing area, which leads to a stronger electrostatic signal on the surface of the electrode. With increasing dust concentration, the charge rate of the standard deviation of the induction signal of the electrostatic detection electrode with different lengths

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becomes higher. Thus, the sensitivity of the electrostatic detection electrode to low dust concentrations is higher.

In addition, with the increasing length of the electrode, the linearity between the standard deviation of the induction signal and the dust concentration becomes worse. The length of the electrostatic detection electrode has a great influence on the positive relationship between the standard deviation of the induction signal and the dust concentration. When the length of the electrode exceeds 20 mm, the standard deviation of the induction signal by the electrostatic induction dust concentration sensor first increases and then decreases. It is difficult to measure the dust concentration between 0 and 500 mg/m^3.

To detect the dust concentration within the range of 0−500 mg/m^3, we chose a detection electrode with a good positive correlation between the standard deviation of the electrostatic induction signal and the dust concentration. Therefore, the length of the electrostatic detection electrode was 10 mm.

4.2. Analysis of the Influence of the Diameter of the Electrostatic Detection Electrode. To analyze the influence of the diameter on the standard deviation of the induction signal, the chosen length of the electrostatic detection electrodes was 10 mm, and the flow velocity through the electrostatic detection electrode was 2 m/s. Furthermore, the diameters of the electrostatic detection electrodes were 10, 20, 30, 40, and 50 mm. The standard deviation of the induction signal was recorded at different dust concentrations, as shown in Figure 9.

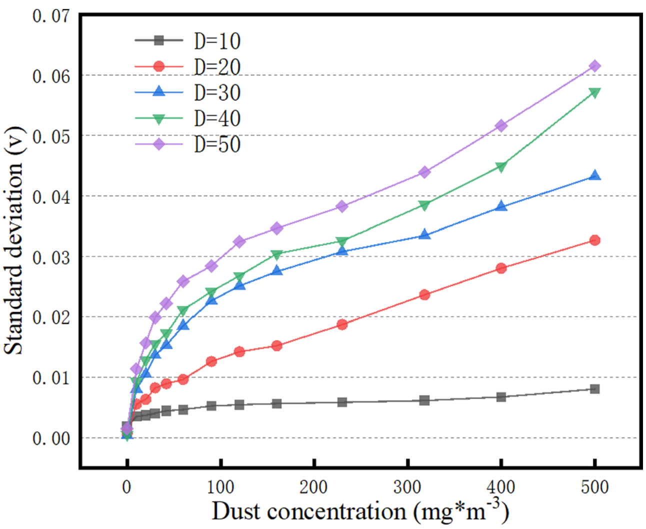

Figure 9. Influence of the diameter of the detection electrode on the induction signal.

According to the data analysis results in Figure 9, the diameter of the electrostatic detection electrode has a significant influence on the standard deviation of the induction signal. By contrast, it has no influence on the positive correlation between the standard deviation of the induction signal and the dust concentration. As the diameter of the electrostatic detection electrode increases, the standard deviation of the induction signal increases. The results show that the larger the diameter of the electrostatic detection electrode is, the better the detection of the dust concentration is. This is because as the diameter of the electrostatic detection electrode increases, the electrode encounters more dust. Thus, the standard deviation of the output induction signal is relatively large. In engineering applications, the diameter of the electrostatic detection electrode should be as large as possible.

4.3. Analysis of the Influence of the Gas Flow Velocity. To analyze the influence of wind speed on the output induction signal of the electrostatic detection electrode, the studied electrode length was 10 mm, the diameter was 40 mm, and the wind speeds of the wind tunnel were 1, 2, 3, 4, 5, and 6 m/s. The dust concentration in the wind tunnel was adjusted to 15, 100, 300, and 500 mg/m^3 (Figure 10).

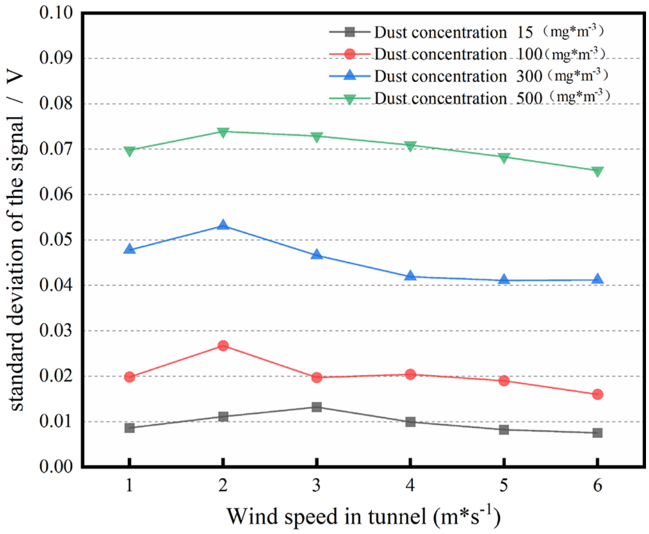

Figure 10. Influence of wind speed on the induction signal.

According to the data analysis results in Figure 10, the wind speed has a certain influence on the standard deviation of the induction signal. At different dust concentrations, with increasing gas flow velocity, the standard deviation of the induction signal first increases and then decreases. When the dust concentration is 15 mg/m^3 and the wind speed is 3 m/s, the standard deviation of the induction signal is maximum. When the wind speed is 2 m/s, the standard deviation is maximum at the other dust concentrations. Furthermore, when the dust concentration is 15 mg/m^3, the influence of wind speed on the standard deviation of the induction signal is relatively small. Compared with the other dust concentrations, when the wind speed increases from 2 to 3 m/s, the increase in the standard deviation of the induction signal is relatively small. For the other dust concentrations, when the wind speed is 2 m/s, the standard deviation of the induction signal is maximum. Evidently, a wind speed of 2 m/s is better for the electrostatic detection electrode.

By analyzing the influence of the length and diameter of the electrostatic detection electrode and wind speed on the standard deviation of the induction signal, we discovered that the length of the electrostatic detection electrode has a significant influence on the positive correlation of the curve of the standard deviation of the induction signal and dust concentration and sensitivity of the induction signal. However, at 0−500 mg/m^3 concentration, the positive correlation of the curve of the standard deviation of the induction signal and dust concentration is more dominant. To obtain a better positive correlation of the curve of the standard deviation and dust concentration, the sensitivity is sacrificed. Thus, an electrostatic detection electrode with 10 mm length was selected. The diameter of the electrostatic detection electrode has a

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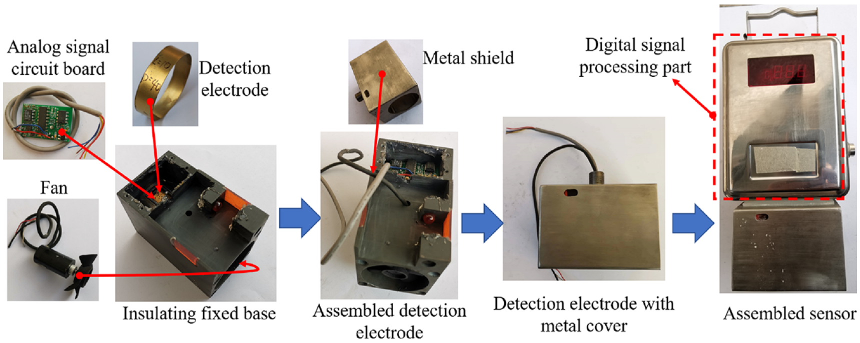

Figure 11. Assembly of the electrostatic induction dust concentration sensor.

significant influence on the slope of the curve of the standard deviation of the induction signal and dust concentration. The greater the slope is, the higher the sensitivity is. For a convenient installation, the diameter of the electrostatic detection electrode was 40 mm. The influence of the wind speed on the relationship between the standard deviation of the induction signal and dust concentration is relatively small. To obtain a higher standard deviation of the induction signal, the wind speed was set to 2 m/s.

5. TEST AND ANALYSIS OF THE SENSOR

Based on the previously presented analysis results, an electrostatic detection electrode with 10 mm length and 40 mm diameter was made. The selected fan and impeller can create approximately 2 m/s wind speed in the ring electrode. The fan, electrode, and analog signal processing circuit were assembled on the insulator, and the metal shield and digital signal processing circuit were mounted outside to build the electrostatic induction dust concentration sensor. The assembly of the electrostatic induction dust concentration sensor is shown in Figure 11.

The electrostatic induction dust concentration sensor was inserted into the test device presented in Figure 5, and the wind speed in the wind tunnel was adjusted to 0.5 m/s. At a low wind speed, the dust drifted from the dust generator to the detection port. The influence of the low dust flow rate on the test results was negligible. Based on the test operation flow in Figure 7, the 16 bit AD conversion value of the sensor's analog electrostatic induction signal and the real dust concentration in the air tunnel were recorded. The curve of the standard deviation of the conversion value and the real dust concentration in the air tunnel is shown in Figure 11. Thirteen groups of test points were recorded within the range of 0−500 mg/m^3.

Due to the aging of the electronic devices and other factors during the long-term use of the sensor, it is necessary to calibrate the sensor in order to ensure the detection accuracy. Therefore, the fitting curve should be as simple as possible. According to the distribution of the test points, the standard deviation value of the electrostatic sensor induction signal was positively correlated with the dust concentration value, laying a foundation for the electrostatic induction method to detect dust with a concentration of 0−500 mg/m^3. When the dust concentration exceeds 25 mg/m^3, the dust concentration value has a high linear relationship with the standard deviation of the induction signal. When the dust concentration is lower than 25 mg/m^3, the dust concentration value has a weak linear relationship with the standard deviation of the induction signal. Therefore, when the dust concentration exceeded 25 mg/m^3, linear fitting was used, and when the dust concentration was lower than 25 mg/m^3, polynomial fitting was used. The fitting formula was as follows:

$$y = \begin{cases} 0.0003x^2 - 0.0097x & x \leq 300 \\ 0.525x - 150 & x > 300 \end{cases} \tag{1}$$

where y was calculated with the fitting equation of the standard deviation of the sensor's detected value, that is, the representative value of the dust concentration by the sensor, and x is the standard deviation of the sensing signal of the sensor.

The error between the fitted value of the standard deviation of the induced signal and the actual dust concentration can be calculated as follows:

$$e = \frac{y - y_0}{y_0} \times 100\% \tag{2}$$

where e is the error of the dust concentration detected by the sensor, and y_0 is the real dust concentration in the air tunnel.

The fitting curve of the test data points and calculated errors are shown in Figure 12.

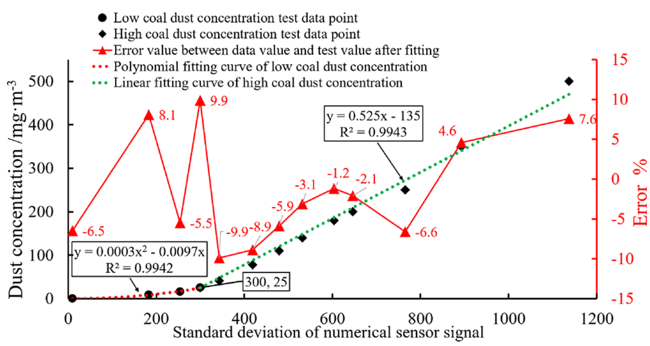

Figure 12. Fitting curve and error calculation of the test points.

According to Figure 12, the mathematical relationship between the dust concentration and the standard deviation of the inductive signal is determined by fitting the standard deviation of the sensor's inductive signal into multiple curves. Linear fitting is adopted for high dust concentrations, and quadratic curve fitting is adopted for low dust concentrations. The fitting R coefficient reaches 0.994 with a high fitting degree. According to the calculation of the deviation between the detected results of the electrostatic induction dust concentration sensor and real dust concentration, the detection

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error of the sensor does not exceed 10%. Due to the large concentration and uneven spatial distribution of coal dust in coal mines, it is difficult to detect the concentration of coal dust. The standard of "MT/T1102-2009 Dust Mass Concentration Sensor for Coal Mines" stipulates that the detection error of the dust concentration sensor shall not exceed 15%. Therefore, the detection error shall not exceed 15% as an important indicator of the current coal dust concentration detection sensor. Compared with the 15% detection error of currently used dust concentration sensors, the presented electrostatic induction dust concentration sensor is more accurate.

6. CONCLUSIONS

(1) Based on the detection of dust concentrations with the electrostatic induction method, an electrostatic induction dust concentration sensor composed of electrostatic detection electrodes, an induction signal-processing circuit, a dust exhaust fan, a shielding cover, a digital signal processing part, and other components was designed to realize real-time online detection of dust concentrations in the environment.

(2) The influences of the length and diameter of the electrostatic detection electrode and dust velocity on the standard deviation of the induction signal were analyzed. The length of the electrostatic detection electrode has a great influence on the positive correlation between the induction signal and dust concentration. The positive correlation between the induction signal and the dust concentration decreases with the increase of the length of the electrostatic detection electrode. The diameter of electrostatic detection has a great influence on the slope of the curve between the standard deviation of the induction signal and the dust concentration. The greater the slope, the higher the sensitivity. The influence of the wind speed on the standard deviation of the induction signal is relatively small. Through the analysis of the test results, the basis for the design of the electrostatic detection electrode was provided.

(3) The mathematical model for characterizing the dust concentration of the designed electrostatic induction dust concentration sensor was determined through experiments. The calculation of the errors between the detection results of the electrostatic induction dust concentration sensor and actual dust concentration showed that the errors do not exceed 10%. The designed electrostatic induction dust concentration sensor has a high detection accuracy for coal dust in mines. Therefore, the application field of dust concentration detection technology based on the electrostatic induction method can be expanded.

■ AUTHOR INFORMATION

Corresponding Author

Dewen Li − *State Key Laboratory of the Gas Disaster Detecting, Preventing and Emergency Controlling, Chongqing 400037, China; China Coal Technology and Engineering Group, Chongqing Research Institute, Chongqing 400037, China;* orcid.org/0000-0001-5049-4940; Phone: 023-65239372; Email: cqmkyldw@126.com

Authors

Jiange Chen − *School of Resources and Safety Engineering, Chongqing University, Chongqing 400044, China; State Key Laboratory of the Gas Disaster Detecting, Preventing and Emergency Controlling, Chongqing 400037, China; China Coal Technology and Engineering Group, Chongqing Research Institute, Chongqing 400037, China*

Guoqing Liu − *China Coal Technology and Engineering Group, Chongqing Research Institute, Chongqing 400037, China*

Yanzhu Li − *China Coal Technology and Engineering Group, Chongqing Research Institute, Chongqing 400037, China*

Anran Zhang − *China Coal Technology and Engineering Group, Chongqing Research Institute, Chongqing 400037, China*

Siyuan Lu − *Huaibei Mining (Group) Co., Ltd., Anhui 235000, China*

Mi Zhou − *China Coal Technology and Engineering Group, Chongqing Research Institute, Chongqing 400037, China*

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.3c00319

Author Contributions

J.C. designed the structure of electrostatic sensing electrode. G.L. designed the signal processing circuit of the electrostatic sensor. Y.L. welded and debugged the processing circuit according to the design circuit. A.Z., M.Z., and S.L. completed the test content in the paper. D.L. designed the paper test process content, analyzed the test data, and reviewed/edited the manuscript. All authors have read and agreed to the published version of the manuscript.

Notes

The authors declare no competing financial interest.

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