Research on dust concentration measurement device based on spiral flow

Liu Dandan¹, Ma Wu¹, Li Dewen ², Wang Jie ², Jing Mingming ², Tang Chunrui²

¹ College of Electrical & Control Engineering, Heilongjiang University of Science & Technology, Heilongjiang Harbin 150022, China
² China Coal Technology Engineering Group Chongqing Research Institute, Chongqing 400037, China

Email: liudandan2003@126.com

Abstract: Based on the principle of electrostatic induction, a dust detection device is designed in this paper, aiming at the problems of insensitive detection and slow movement of dust particles in the existing dust measuring devices. Its shape structure is improved on the basis of the existing straight pipe. The air inlet is arranged on the side of the cylindrical pipe wall so that the particles flow through the pipe in a double helix way and the diameter of the main pipe is changed to make the middle part of the pipe shrink. The 3D model of pipeline was established by gambit2.4 and simulated in Fluent6.3. In the improved device, the movement speed of dust particles increases. With the increase of velocity, the probability of friction and collision of dust particles in the side-entry tube is increased, and the induced charge is increased. Therefore, the improved device can effectively improve the accuracy of dust measurement under the condition of low concentration and small particle size.

1. Introduction
In recent years, the process of industrialization and urbanization has been speeding up in China. With the development of social economy, a lot of environmental problems also follow. Among them, the most concern and worry is the large-scale haze weather. The dust particles in the atmosphere have become the main pollutants in the atmosphere, so it is very important to detect and study the dust particles and to provide a true and reliable air quality data for the public[1].

So far, according to different physical principles, many measurement methods have been studied. Depending on whether it is necessary to carry out sedimentation sampling of dust particles, they are divided into two types. One is sampling method, which includes weighing method, β-ray method and piezoelectric method. The other is non-sampling method, including charge sensing method, light scattering method, light absorption method. The non-sampling method has obvious advantages and is very suitable for on-line monitoring and real-time control of dust concentration[2-3].

In this paper, the principle of electrostatic induction is used to detect dust concentration, which is a method based on the characteristics of charged dust particles. In the process of dust particles moving in the tube, the main factors affecting the size of particle charge are material, velocity and particle size. Different materials collide with each other to produce electrostatic charges, and under the same conditions, the faster the particles are subjected to the greater the collision friction, thus the greater the amount of electricity generated; The smaller the particle size, the more likely it is to collide in the pipeline, and the corresponding charge will increase [4-8]. Electrostatic induction method has the advantages of strong adaptability, durable, small maintenance, safe and reliable.
2. Analysis of the main structure and problems of the existing dust measuring devices

2.1. Ring electrostatic sensor

Professor Yan Yong of the University of England has proposed a Mathematical Model for Annular Electrostatic Sensor [9]. The induced charge of the ring electrostatic sensor is calculated as (1), (2).

\[
Q = \frac{Dq}{4\pi} \int \left( \frac{0.5D}{z} x \cos \theta \right) \left( \frac{F^2(x, \theta)}{(z + 0.5w)^2 + F^2(x, \theta)} \right)^{\frac{1}{2}} \\
\frac{z}{0.5w} \left( \frac{(z - 0.5w)^2 + F^2(x, \theta)}{(z + 0.5w)^2 + F^2(x, \theta)} \right)^{\frac{1}{2}} d\theta
\]

(1)

\[
F(x, \theta) = [(0.5D)^2 + x^2 D x \cos \theta]^2
\]

(2)

Where, \( z \) is the product of particle velocity \( v \) and time, \( w \) is the plate width, \( q \) is the point charge through the plate at a certain speed, \( D \) is the diameter of the annular plate, \( Q \) is the amount of induced charge on the plate, \( x \) is the distance between the induced charge and the central axis of the plate, \( \theta \) is the angle between the integral block and the axis. The mathematical model is shown in Figure 1.

![Mathematical Model of Annular Electrostatic Sensor](image)

Fig. 1 Mathematical Model of Annular Electrostatic Sensor

2.2. Straight tube structure analysis

The existing straight pipe equipment includes air inlet, straight pipe, inspection equipment, pumping equipment and outlet. Its structure is shown in figure 2.

Dust flow from the air inlet into the straight pipe, in the pipeline movement, particles and the wall and particles between the friction, collision, it will produce static charges, ring electrostatic sensors nested in the middle of the pipeline. The ring electrode is close to the inner wall of the pipe, and when the electrostatic charge moves through the ring electrostatic sensor, the corresponding induction signal will be generated. After amplifying the induced signal, the parameters of dust concentration can be obtained [10-11].

Although the device is simple in structure and easy to operate, it still has some shortcomings. Due to the extremely weak electric capacity of dust particles, first of all, a large amount of dust enters the straight pipeline and cannot be fully collided by friction in a limited space. The amount of electrostatic
charge generated by friction collision is also very small. Secondly, the detection device is a circular electrostatic sensor nested outside the pipe wall of the middle section of the straight pipe, but a large number of dust particles pass through the central area of the pipe, which has a great influence on the particle flow rate in the pipe wall, and can not accurately detect the particle concentration. Therefore, when the dust concentration is low, the measurement accuracy is not accurate.

3. Design of a Dust measuring device

3.1. Design principle of measuring device
The air inlet of the measuring device is arranged on one side of the pipe wall and in the middle part of the wall. Due to the different incident modes, the dust particles are forced to rotate along the pipe wall to form a double spiral flow, and the middle part of the pipe is contracted. When dust particles pass through the shrinkage section, the velocity of dust particles increases by Venturi effect, and then the electric charge of particles is measured by the measuring device, thus the dust concentration is obtained. Finally, the dust particles leave the pipeline through the outlet. The design of the dust concentration measurement device, referred to as the spiral flow tube, its structure is shown in Fig. 3, Fig. 4.

In order to ensure the intake of dust particles in the pipeline, we designed the front end of the inlet of the spiral flow pipe as a trumpet. The ring electrostatic sensor is located in the middle of the contraction section. When the incident mode of the spiral flow tube is changed, the dust particles form double helix flow in the tube, which increases the collision of the particles. With the increase of pipe length, the path of particle motion is increased, which makes the particle motion more fully. Due to the action of rotating wall attachment, the particles tend to the tube wall, avoiding the difficult to detect the middle area, and the rotating movement mode also increases the concentration of the unit cross section of the dust particles, and increases the charge of the particles. Finally, the measuring device is used to detect the charge of the particle. To dust concentration\(^{12}\).

3.2. Measurement device simulation
The 3D model of pipeline was established by gambit2.4. First, the main pipe, inlet and front extension of the model are drawn. Then, the stereoscopic model is meshed, each mesh area is 0.5mm \(^2\), and the other parameters are kept by default. The simplified meshing model is shown in figure 5. Finally, we define its boundary type and set the portion of the pipe extension as an entry, which is of type...
(VELOCITY_INLET), the right side of the pipe is an egress, and its type is (OUTFLOW), the other default is the pipe wall WALL. Output and save the structure model of this improved device.

3.3. Simulation results and analysis of measuring device

In this design, the Fluent6.3 model is used to simulate and run under the standard atmospheric pressure environment. The Eulerian model is used to simulate the dust particles numerically, and the k-epsilon model equation is used to calculate the data. The relative data of dust parameters are set, the thermal conductivity is 0.3, the density is 2600, the specific heat capacity is 1200, the viscosity is 1.8 e-05, the unit and other values are default. Physical properties define air as the main phase and dust as the second phase. The boundary conditions of the inlet are defined. The turbulent intensity of mixture is 5, the velocity of air is 4 m/s, the velocity of dust is 3 m/s, the volume fraction of particles is 0.01, the relaxation factor of 0.5. The other values are default. Convergence accuracy set to 0.001.

The dust particles will be affected by the inertia force, lift force and drag force of the gas in motion. The equations of the related forces are as follows:

\[ \frac{d\mathbf{u}_p}{dt} = F_D(u_p - u) + \frac{g(\rho_p - \rho)}{\rho_p} + F_i \]

\( \rho \) is the density of gas, kg/m\(^3\); \( u_p \) is the velocity of particles, m/s; \( g_i \) is the physical force in the \( i \) direction of the fluid element, \( N \); \( F_D \) is the drag force per unit mass of particles, \( N \); \( \rho_p \) is the bulk density of particles, kg/m\(^3\); \( F_i \) is the interphase force, \( N \); \( u \) is the velocity of the airflow, m/s.

The momentum equation for particle variation is as follows [13]:

\[ P = \sum \frac{18\mu C_D \operatorname{Re}}{24\rho_p d_p^2} (u_p - u) + \mathbf{F} \mathbf{n} \Delta t \]

In the equation, \( \mu \) is the gas dynamic viscosity, Pa\( \cdot \)s; \( \Delta t \) is the time step, s; \( \mathbf{F} \mathbf{n} \) is the particle mass flow rate, kg/s; \( d_p \) particle diameter, m; \( F \) is the interphase force other than drag force, \( N \).

The dust concentration is set to 5 mg/m\(^3\), in order to read the data easily, the XZ surface is created in the Planes in 3D to view the calculation results. The particle size of 1 \( \mu \)m is taken as an example.

Fig. 6 Velocity nephogram of straight tube

Fig. 7 Velocity nephogram of helical flow tube

Fig. 8 Motion Trajectory of Dust Particles

It can be seen from the trajectory diagram of the movement of dust particles that dust forms double spiral flow in the pipeline. The dust particles friction each other, collide with each other with the spiral flow, and the amount of induced charge increases, and mainly distributes near the pipe wall. Far away from the middle area which is difficult to detect, the precision of dust detection is greatly improved. It can be seen from the velocity cloud that after the dust enters the shrinkage section through the shrinkage port, the velocity increases and the dust particles move more intensively, so the circular electrostatic sensor is installed in the middle of the shrinkage section of the spiral flow pipe. It is beneficial to improve the precision of dust detection.
4. Experimental results and analysis
When the model is simulated in Fluent6.3, the inlet velocity air is 4 m/s, the dust is 3 m/s, the other conditions are unchanged, only the particle size of dust is changed, and the simulation and calculation are carried out many times. From the velocity cloud image, the data of the straight tube and the spiral flow tube of the existing device and the improved device are obtained as shown in Table 1.

| Grain size (μm) | 50 | 40 | 30 | 20 | 10 | 8 | 6 | 4 | 2 | 1 |
|-----------------|----|----|----|----|----|---|---|---|---|---|
| Velocity (m/s)  | 7.04 | 7.31 | 7.50 | 8.09 | 8.23 | 8.52 | 8.78 | 9.00 | 9.19 | 9.25 |
| Spiral flow tube| 3.74 | 3.82 | 3.88 | 3.93 | 3.98 | 4.04 | 4.05 | 4.08 | 4.09 | 4.14 |
| Straight tube   | 7.04 | 7.31 | 7.50 | 8.09 | 8.23 | 8.52 | 8.78 | 9.00 | 9.19 | 9.25 |
| Spiral flow tube| 3.74 | 3.82 | 3.88 | 3.93 | 3.98 | 4.04 | 4.05 | 4.08 | 4.09 | 4.14 |

According to the data of different particle sizes in Table 1, draw the velocity comparison diagram of straight tube and spiral flow tube, as shown in figure 9; The induced charge of straight tube and spiral flow tube under different particle sizes is calculated by using MATLAB tool combined with induction charge calculation formula (1), (2), and normalized, as shown in figure 10.

According to the velocity comparison chart, the improved spiral flow tube's velocity value is obviously higher than that of the straight tube. The increase of the velocity means that the particles can move more fully in the cavity, the particles move violently, they are prone to collision and extrusion, increase the collision friction between the particles, and increase the amount of induced charge. When the induced charge is normalized, when the particle size is less than 10μm, the effect of the induced charge increase is better, and the measurement precision of the dust under the condition of low concentration and small particle size is improved effectively. Through the comprehensive analysis of velocity and induction charge, it is shown that the overall effect of the spiral flow tube is better, which is beneficial to the accuracy of the measurement.

5. Conclusions
In this paper, the importance of dust detection is explained from the point of view of the harm of dust. Through the analysis and study of the existing straight pipe devices, it is found that the dust particles flow directly through the middle of the pipeline, and the measurement is not accurate. After consulting the literature, a new flow mode-spiral flow is proposed.

The testing pipe needed to generate spiral flow is plotted in gambit2.4, and the simulation analysis is carried out in the middle of Fluent6.3 software. The data of dust particle motion track and velocity in pipeline are obtained from the simulation cloud diagram, and the electrostatic induction charge is calculated. Through comparative analysis, the dust velocity and the induced charge in the side-entry pipe are higher than those in the straight tube, which means that the dust particles move more fully in the side-entry pipe, and the friction and collision between the particles are more intense, which
increases the induced charge amount of the particles. The measurement precision of dust concentration is improved.

Although the structure of the inlet on the wall of the pipe is adopted in this paper, the dust forms a spiral flow in the pipe, increases the friction and collision between the dust, and increases the electric capacity of the particles, but due to the limitation of the technology, it is impossible to make simulation analysis and quantitative calculation of its effect. Therefore, it is necessary to increase the research and analysis in this respect.

Acknowledgement
This work was supported by the National Key Research and Development Program of China(2017YFC0805208).

References
[1] Song Tsunami, Yu Liang, Zhai Fu Shun and Yu Shou Chao. Progress in monitoring and control of fine particulate matter PM_{(2.5)} in urban atmosphere [J]. Green Technology,2018 (16): 29–32.
[2] Wang Jie, Ye Changqing. Summary of dust concentration measurement methods [J]. Information on technology,2015.
[3] Cao Guang. Sampler and mechanical device for β-ray dust concentration measuring instrument [D]. Nanhua University,2012.
[4] Li Guangquan. Measurement of particle mass flow based on electrostatic sensor [D]. Baoding: North China Electric Power University,2016.
[5] Wang Xiaoyu. Measurement of translational velocity and vibration of mechanical equipment based on electrostatic induction [D]. Baoding: North China Electric Power University,2015.
[6] Zhao Enbiao, Sui Jinjun and Wang Ziliang, et al. Measurement of dust concentration based on the principle of external ring charge induction [J]. Instrumentation technology and sensors,2010,6 (02): 269–272.
[7] Hao Haitao. Study on measuring method of dust charge in mine [D]. Qingdao: Shandong University of Science and Technology, 2011.
[8] Liu Dandan, Wei Zhongyu and Li Dewen, et al. Optimization of dust mass concentration measurement device based on gas-solid two-phase flow [J]. Journal of Coal,2016,41 (07): 1866–1869.
[9] Xu Chuanlong. Study on measurement method of particle charge and flow parameters for gas-solid two-phase flow [D]. Nanjing: southeast University, 2006 :26–27.
[10] Zheng Kai, Wang Jinggang, Liu Jing and Xiong Shuangka. Dust concentration Detection Technology and Experimental study based on charge Induction [J]. Sensors and Microsystems, 2014,33 (02): 29–31.
[11] Gao Qian. Study on measurement of gas / solid two-phase flow velocity by electrostatic method [D]. Beijing Jiaotong University, 2011.
[12] Liu Dan, Jing ran and Tang Chunrui. Optimization of dust mass concentration measuring device based on charge induction principle [J]. Journal of Coal, 2018, 43 (03): 897–902.
[13] Zong Ying, Ma Deyi, Song Dan Lu and Peng Jia Qiang. Numerical Simulation and Analysis of duct flow Field of pulverized Coal Burner based on Fluent [J]. Lifting and Transportation Machinery, 2012, (03): 41–45.