Study on Interference Factors of Light Scattering PM2.5 Dust Test Instrument

Yiming Fang 1, Qi Li*, Zhemin Chen 2 and Yanbo Tu 1

1 Institute of mechanical and electrical engineering, China Jiliang University, Hangzhou, Zhejiang, 310018, China
2 Institute of Optics and Metrology, Zhejiang Province Institute of Metrology, Hangzhou, Zhejiang, 310018, China
*Corresponding author’s e-mail: lq13306532957@163.com

Abstract. Light scattering PM2.5 dust test instrument is widely used, but it is susceptible to many kinds of interference, and will produce large deviation in some industrial sites. The influence of particle size, relative humidity and other parameters on the measurement results of light scattering dust meter is studied and corrected. The experimental results show that the relative error of detecting single particle size dust is smaller than that of detecting multi-particle size dust. Relative humidity has no effect on non-hygroscopic dust detection, but has obvious influence on hygroscopic dust detection, and the relative error after correction is significantly reduced.

1. Introduction
With the hazards of PM2.5 dust, it gradually coming into public view. The detection methods of PM2.5 dust concentration are more and more diverse. At present, the methods used to detect PM2.5 dust concentration include light scattering method, filter weighing method, beta-ray method, oscillating balance method, piezoelectric crystal induction method, capacitance method, light absorption method and electrostatic induction method. Among them, the light scattering method is the most widely used. The light scattering dust test instrument is compact, portable, can be real-time online detection, and has a wide range of measurement. However, the measurement results of light scattering method are disturbed by many factors. In some complex industrial sites (such as mines, quarries, etc.), the deviation will be larger. Therefore, how to use light scattering PM2.5 dust test instrument to obtain more accurate measurement results is extremely important.

The main factors affecting the measurement results of light scattering dust test instrument are particle size, shape, composition, scattering angle, environmental relative humidity, water mist and so on. Particle size, shape and composition all belong to the property of the dust under test, because the common instrument calibration use standard dust whose property is fixed (i.e. the particle size is fixed, the shape is approximate to regular sphere, and the composition is uniform). While the actual industrial field dust particle size distribution is complex, the shape is irregular, and the composition is diverse. The scattering angle refers to the angle between the incident light emitted by the light source and the photodetector used to collect the scattering light intensity. Relative humidity is an interference factor in the environment, and water mist also causes serious deviations occurred.
2. Analysis and experiments

In order to correct the interference factors, the detection data of each interference factor acting alone must be obtained first. Therefore, a series of experiments are designed by using the control variable method, that is, to control other interference variables unchanged to study the influence of single interference on the detection of light scattering dust test instrument.

2.1. Defects of dust generator

Due to the limitation of existing dust generating devices, the shape and composition of dust cannot be tested by controlling variable method. The former is due to the fact that the existing dust generating devices used to produce micron-sized particles, but cannot control the shape of particles; The latter is due to the fact that dry powder such as pulverized coal, talcum powder, etc., is usually ground and extruded from the nozzle by compressed air in the dry powder aerosol generator, and the agglomerated powder particles are separated by the shear force of the nozzle mouth. Dispersion cannot ensure the formation of uniform particle size and cannot control the particle size and mass concentration. Generally, the method of forming uniform particle size usually requires that the particle can dissolve in water (e.g. sodium chloride). After the formation of solvent, the particle size and shape are basically the same through atomization, air drying and other steps. However, the dust composition used in this method has great limitations. So, the research on the influence of dust properties on scattered light intensity is still in the theoretical stage at present.

2.2. Study on the disturbance of shape and composition.

In the study of light scattering characteristics, the research methods for non-spherical particles are T-matrix method, finite-time-domain difference method, discrete dipole approximation method, etc. The degree of dust shape deviating from spherical particles is usually measured by the shape ratio of dust (such as aspect ratio). Experiments show that the more the dust shape deviates from the spherical shape, the greater the deviation of the results.

The influence of dust composition on scattered light is mainly due to the different dust density, refractive index and absorption properties of different test instruments, and the difference is significant. At present, it is impossible to use a strict functional relationship or mathematical model to express the relationship between dust composition and the measured results of light scattering dust test instrument. Usually, the light scattering dust test instrument will give a comparison table of K-value (mass concentration conversion coefficient) of different dust test instruments, but the actual dust system in the field is generally composed of a mixture of various test instruments, so the actual measurement needs to adjust K-value according to the actual site, but the big error remains when the dust composition is relatively unstable.
2.3. Particle size interference experiments

According to Mie scattering theory, the scattering intensity is related to particle size, refractive index, scattering angle, azimuth angle and the properties of incident light:

\[
I_{\text{sca}} = I_0 \frac{\lambda^2}{4\pi^2 r^2} [i_0(\theta)\sin^2 \phi + i_2(\theta)\cos^2 \phi]
\]

In formula (1): \(I_{\text{sca}}\) is scattered light intensity; \(I_0\) is incident light intensity; \(\lambda\) is incident light wavelength; \(r\) is the distance between scattering point and observation point; \(\theta\) is scattering angle; \(\phi\) is azimuth; \(i_0(\theta)\) or \(i_2(\theta)\) is intensity function of scattered light, which is a function related to particle size, scattering angle and refractive index. The refractive index is a test instrument-related quantity, and the scattering angle is usually fixed. The light scattering dust test instrument usually only measures the scattering light intensity at a fixed angle.

Dust with single particle size distribution is rare in nature, and it is usually multi-particle size distribution. Regarding particle size, it has been shown that the larger the median diameter of particle size, the smaller the average scattered light intensity and the smaller the concentration value obtained. The dust particles in this experiment are divided into two groups: the first group has a single particle size of 2.5μm (the geometric standard deviation is less than 1.15); the second group has a multi-particle size distribution of 0.5-2.5μm, and the distribution is more uniform. The particle sizes of the two groups were measured by weighing method and light scattering method respectively, and the data obtained by weighing method were used as standard values. The experiment was carried out under the condition of 50% humidity. The average dust concentration measured by light scattering dust test instrument and weighing method for 6 hours. The results are shown in Table 1.

The instruments and materials used in the experiment include: light scattering dust test instrument, PM2.5 high performance filter, analytical balance, vibration hole monodisperse aerosol generator (NaCl), particle size spectrometer, vacuum air pump and gas flow controller.

Table 1. Relative errors of light scattering method with different particle sizes.

| Group | Particle size | Light scattering method | Weighing method | Absolute value of relative error(%) |
|-------|---------------|-------------------------|-----------------|-----------------------------------|
| 1     | 2.5μm         | 2.86                    | 3.28            | 12.8                              |
| 2     | 0.5-2.5μm     | 2.90                    | 3.58            | 19.3                              |

In table 1, the data units of the row of particle size are micron, and the data units measured by light scattering method and weighing method are mg/m³. The flow rate of NaCl solution can be controlled by setting the flow rate of the micro-injection pump to further control the aerosol mass concentration produced by the generator. The same experiment as Table 1 was carried out six times. The statistical data of absolute relative error between the two methods in each experiment are shown in Figure 2.

Figure 2. Relative errors of two groups of particle size measurements

From the above data, it can be seen that the relative error between the results measured by light scattering method and those measured by weighing method at single particle size is small, averaging
12.84%. At multi-particle distribution is larger, averaging 17.11%. That is to say, the change of particle size will increase the measurement error of light scattering dust test instrument. But it is not that the bigger or smaller the particle size, the bigger the relative error. There is no necessary connection between the two. The above data also show that when the dust concentration is high, the overall measurement results of the light scattering dust test instrument are small, which may be due to the fact that the probability of overlapping particles is higher when the concentration is higher, and the scattered light cannot distinguish the overlapping particles, so the measurement results are smaller.

2.4. Relative humidity interference experiments
Relative humidity influence experiment should ensure the consistency of particle size, shape and composition, only change the humidity. The purpose of this experiment is to analyze the measurement deviation of light scattering dust test instrument under different humidity. The experiment is divided into seven humidity gradients. Light scattering method and weighing method are used to measure each humidity gradient in parallel. The median value of each humidity gradient is taken as the average value of the humidity in this group, and the data is in Table 2.

The instruments used in the experiment include light scattering dust test instrument, vibration hole aerosol generator (NaCl), vacuum air pump, PM2.5 high performance filter, analytical balance and humidifying device.

Table 2. Measurement of relative errors of NaCl dust under different relative humidity

| Relative humidity (%) | Light scattering method (ug/m³) | Weighing method (ug/m³) | Relative error(%) |
|----------------------|--------------------------------|-------------------------|-------------------|
| 15                   | 217.2                          | 209.8                   | 3.53              |
| 25                   | 208.2                          | 200.1                   | 4.05              |
| 35                   | 208.7                          | 230.1                   | -9.30             |
| 45                   | 251.2                          | 259.3                   | -3.12             |
| 55                   | 203.8                          | 183.7                   | 10.94             |
| 65                   | 266.6                          | 248.3                   | 7.37              |
| 75                   | 205.4                          | 186.4                   | 10.19             |

Before analyzing the correlation between relative error and relative humidity, we first need to test the normality of the two sets of data. Because there are fewer sample data, using K-S normality test, we can get that the P value of the two sets of data is much larger than the significance level of 0.05. Pearson correlation analysis can be used to get the correlation coefficient of relative error and humidity, it is 0.493, which proves that the correlation between them is very weak, and there is no obvious correlation. The relative error between the light scattering dust test instrument of each humidity gradient and the measured value of weighing method is relatively stable, indicating that relative humidity does not affect light scattering. It shows that relative humidity has no effect on the results of detection of pure sodium chloride particles by light scattering method.

Originally, the pure NaCl particles in this experiment are not hygroscopic. The sodium chloride on the market is often a mixture, which mostly contains magnesium chloride (MgCl₂), while magnesium chloride is hygroscopic. People mistakenly think that sodium chloride has hygroscopicity. Therefore, when the relative humidity is not saturated to form condensate droplets and the dust material has no hygroscopicity, the humidity has little effect on the measurement results of the light scattering dust test instrument.

The atmospheric particulate matter is generally hygroscopic. Relative humidity of atmospheric and particulate matter concentration measured by weighing method and light scattering dust test instrument at the same place, at the same altitude for several days are recorded. The relationship between relative error and relative humidity is shown in Table 3.

Table 3. Relative errors of atmospheric dust under different humidity by light scattering method

| Relative humidity (%) | 30 | 35 | 44 | 55 | 66 | 78 | 79 |
|----------------------|----|----|----|----|----|----|----|
| Absolute value of relative error(%) | 8.3 | 7.9 | 9.0 | 10.1 | 15.6 | 19.8 | 19.5 |
It can be seen that when the humidity is lower than 55%, the absolute value of relative error is less than 10%, and when the humidity is higher than 66%, the relative error shows an increasing trend.

2.5. Water mist interference experiments
The above relative humidity interference experiments were carried out without condensation, but when the relative humidity was over-saturated, there would be condensation or water mist, which would make the light scattering dust test instrument unable to work. In the laboratory cabin, the water mist mixed dust generated by the humidifier simulation was detected. The results are as follows:

| Weighing method (mg/m³) | 81.6 | 98.6 | 151.5 |
|-------------------------|------|------|-------|
| Light scattering method (mg/m³) | 20.5 | 25.6 | 38.0 |
| Relative error(%) | -60.27 | -71.11 | -74.92 |

From the data in Table 4, it can be seen that the absolute relative error between the standard value obtained by weighing method and the measured value of light scattering dust test instrument is generally greater than 60% in the presence of water mist, which is seriously beyond the stipulation in JJF 1659-2017-Calibration Specification for PM2.5 Mass Concentration Measurement Instruments, which stipulated the relative error is less than 20%. This shows that the light scattering dust test instrument cannot identify the small particles formed by water in the gas well, and mistakenly treat the water droplets as the dust to be measured, which increases the measured value. Therefore, in the case of water mist, we must use heating and protective cover to prohibit water mist from entering the scattering cavity of light scattering dust test instrument, otherwise it will not work properly.

3. Correction scheme

3.1. K-value
Due to the complexity of dust properties, and considering the possible absorption of dust to light and the complex reflection between dust particles and particles, it is difficult to establish a strict functional relationship with the measurement results of light scattering dust test instrument. Therefore, K-value can only be adjusted according to the particle size distribution in the field. K-value is related to the particle size, composition, shape, absorption characteristics and reflection characteristics of dust. In different scenarios, it needs to be adjusted according to different situations, which also causes the shortcoming of frequent adjustment of light scattering dust test instrument. The method cannot trace the origin of dust concentration detection, which is also the limitation of light scattering method.

3.2. Humidity correction factor
Two methods are usually used for humidity correction: one is drying method, i.e. drying the sampling gas before entering the scattering chamber of the light scattering dust test instrument. The commonly used method is heating the sampling pipeline, but this method is difficult to operate and costly; the other is adding humidity correction factor to calibrate the measurement results. The commonly used humidity correction factor f is shown in Formula (2).

\[ f = 1 + 0.2 \times RH^2 / (1 - RH) \]  

Under the premise of known relative humidity, the measurement result of light scattering dust test instrument divided by the correction factor is the result after correction.

In Table 3, a humidity correction factor is added to the measured data of atmospheric particulate matter mass concentration by light scattering dust test instrument at different humidity. When the relative humidity is above 66%, the relative error after correction decreases by 5.9% on average.

4. Conclusions
In this paper, the interference factors of light scattering dust test instrument which is most commonly used in industrial field are studied. It is pointed out that the current dust generating device cannot
control the composition and shape of particles while ensuring the consistency of particle size. The experiment proves that the relative error of single particle size dust detection is smaller than that of multi-particle size dust detection; the relative humidity only interferes with the detection of hygroscopic dust, but does not interfere with the measurement of non-hygroscopic dust, and the humidity correction factor can effectively reduce the error; water mist will make the light scattering dust test instrument unable to work properly, so it is necessary to effectively avoid water mist entering the scattering chamber.

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