Uncertainty Research of Particles Concentration Measurement in Continuous Emission Monitoring System of Thermal Power Plants

Tianqi Liang¹, Tianlin Zheng², Guangxue Zhang¹, Luyao Ma¹ and Hong Xu∗
¹College of Metrology and Measurement Engineering, China Jiliang University, Hangzhou, Zhejiang, 310018, China
²Hangzhou Zunbang Technology Co., Ltd, Hangzhou, Zhejiang, 310018, China
∗Corresponding author’s e-mail: xuhonghappy@cjlu.edu.cn

Abstract. In order to monitor the reliability of the CEMS operation data of a thermal power plant in Hangzhou, the data of its operation process were collected. The components of uncertainty influencing on the particles concentration measurement, including zero drift, range drift, relative accuracy and measuring repeatability, were analyzed in the system. The confidence interval (2.80%) and the allowable interval (8.94%) were introduced to ensure the reliability of the system data. The result of evaluation shows that the related expanded uncertainty of particles concentration measurement is 9.26% when coverage factor is k=2 and level of confidence is 95%. Measuring repeatability is the main factor affecting the uncertainty.

1. Introduction

With the continuous development of China’s economy, the national demand for energy is increasing. Energy consumption of coal-based thermal power plants is one of main causes of air pollution. Curbing pollution emissions from the source has become the focus of the environmental industry. At present, particles are one of the major pollutant emissions from thermal power plants. It has become an important task for enterprises to control the concentration of pollutants to meet environmental emission standard. Flue gas Continuous Emission Monitoring System (CEMS) is a device for continuous monitoring of stationary pollution sources. In recent years, CEMS has been widely used in thermal power plants for continuous monitoring of pollution sources. In order to ensure the implementation of ‘Hangzhou Emission Standard of Air Pollutants for Boilers’, that is, the particles concentration do not exceed 5mg/Nm³, regular calibration and testing of the power plant’s CEMS is essential. Meanwhile, it is necessary to analyze and evaluate the uncertainty to ensure the accuracy and reliability of the measuring results [1-2].

Uncertainty in measurement analyzes the dispersion of the measured values based on the information provided [3]. Each factor in the system may introduce corresponding uncertainty, which can evaluate the credibility and acceptability of results of measurement [4]. In the paper, the operation data are monitored after ultra-low emission renovation project is completed at a thermal power plant in Hangzhou, and uncertainty of the data is analyzed and evaluated according to ‘Guide to the Evaluation and Expression of Uncertainty in Measurement’ (GB/T 27418-2017).
2. Ultra-low emission renovation project in thermal power plant

There are three 130t/h high temperature and high pressure circulating fluidized bed boilers at a thermal power plant in Hangzhou. To meet the requirements of ultra-low emission, low-nitrogen combustion and wet electro-static precipitator (WESP) have been added in the plant, on the basis of retaining semi-dry absorption tower, electrostatic precipitator and fabric filter. The flue gas of the boiler is desulfurized by desulfurization tower, then is purified by WESP at the top of the tower, finally is discharge from the chimney [5]. Figure 1 shows the technological process of flue gas treatment after ultra-low emission renovation project in the power plant.

![Flue gas purification system process and sampling points](image)

Figure 1. Flue gas purification system process and sampling points

The flue gas sampling points were located at A and B. CEMS were installed at points C as shown in Figure 1, which is in the monitoring room of the chimney wall of the power plant. Flue gas is monitored online by CEMS to ensure that emissions meet national environmental standards.

2.1 Wet electro-static precipitator

The main working principles of WESP are that the water mist is sprayed to the discharge electrode and corona area. Under the action of the barbed electrode, the water mist forms a strong phenomenon of collision, interception and adsorption in the corona area. Driven by electric field force, dust particles reach the dust collecting pole and are thus captured by the water mist. The water mist forms a continuous water film on the dust collector to flush the captured dust into the ash hopper and discharge it.

The WESP not only has a good removal effect on PM2.5, but also on acid fog (SO₃), toxic heavy metals such as mercury and other pollutants removal according to domestic and foreign studies [6].

2.2 Test results and evaluation of dust removal facilities

2#boiler was selected for test to evaluate dust removal efficiency of the renovation. The inlet and outlet particles concentration of electrostatic precipitator, fabric filter and WESP were monitored separately. The concentration at the sampling point during the test is summarized in the table below. Test data came from two working conditions, high load (90%) and low load (55-65%).

As shown in Table 1, under high boiler load >90%, the dust removal efficiency of electrostatic precipitator and fabric filter is about 99.99%, while the combine removal efficiency of desulfurization tower and WESP 63.24%. Under low boiler load 55-65%, the dust removal efficiency of two combined devices mentioned above is about 99.95% and 89.57% respectively. The integration of desulfurization and WESP can control the particles emission concentration at a lower level under both boiler loads, which fully meets national environmental emission standards of thermal power plants.
| Boiler load | Dust removal facilities | Inlet particles concentration (mg/Nm³) | Outlet particles concentration (mg/Nm³) | Efficiency (%) |
|-------------|-------------------------|--------------------------------------|---------------------------------------|----------------|
| >90%        | Electrostatic precipitator and fabric filter | 1.22×10⁴                            | 1.36                                  | 99.99          |
|             | Desulfurization tower and WESP                  | 1.36                                  | 0.50                                  | 63.24          |
| 55-65%      | Electrostatic precipitator and fabric filter    | 1.01×10⁴                            | 4.70                                  | 99.95          |
|             | Desulfurization tower and WESP                  | 4.70                                  | 0.49                                  | 89.57          |

### 3. Analysis of factors affecting uncertainty of particles concentration measurement

#### 3.1 Sources of uncertainty of particles concentration measurement

Figure 2 shows the sources of uncertainty of particles concentration measurement. The uncertainty introduced by zero drift, range drift and relative accuracy is mainly determined by CEMS itself; the uncertainty introduced by measuring repeatability is affected by multiple measurements.

![Figure 2. Sources of uncertainty of particles concentration measurement](image)

The uncertainty of particulates concentration measurement includes two types, A and B. Uncertainty of type A is introduced by measurement repeatability, which can be calculated by Bessel formula [2]. Uncertainty of Type B is mainly obtained according to the instrument parameters and calibration nameplate. However, since the CEMS monitoring of flue gas is a dynamic process, different influencing factors will also change with the continuous changes in the working conditions of the measurement process. Therefore, it is necessary to collect and analyze the experimental data during operation of the system, so as to have more accurate feedback on the influencing factors of measurement uncertainty.

The technical indexes of CEMS include the requirements of the half width of the confidence interval, the half width of the allowable interval and correlation coefficient, which also reflects the uncertainty of particles concentration measurement of CEMS and ensures the data quality and credibility of flue gas monitoring process [7].

#### 3.2 Mathematical model of calculating standard uncertainty

Particles concentration can be directly obtained by CEMS. The zero drift, range drift, relative accuracy and measuring repeatability of the instruments and equipment are independent of each other and have no correlation [8], so the correlation coefficient is 0 and the sensitivity coefficient is 1 for each component. According to the calculation method of uncertainty, the combined standard uncertainty can be obtained as follows:
\[ u_c = \sqrt{\sum_{i=1}^{n} \left( \frac{\partial f}{\partial x_i} \right)^2 (u_{x_i})^2} = \sqrt{\sum_{i=1}^{n} (u_{x_i})^2} \]  

(1)

Where \( u_c \) is combined standard uncertainty; \( \frac{\partial f}{\partial x_i} \) is sensitivity coefficient; \( u_{x_i} \) is standard uncertainty of each component.

3.3 Analysis of factors affecting uncertainty of particles concentration measurement

3.3.1 Data analysis of zero drift and range drift in CEMS. After the stable operation of the analytical instrument to be tested, the zero calibration department will adjust to zero and record the stable zero reading of the instrument as \( Z_0 \); Then switch to the range calibration unit and record the reading as \( L_0 \). Repeat the above operation after 24 hours of equipment operation, record the zero reading and range reading \( Z_n \) and \( L_n \), and continue the above operation for 3 days. According to equations (2) and (3), the values of zero drift and range drift are calculated respectively.

\[ Z_d = \frac{\Delta Z}{R} \times 100\% \]  

(2)

\[ L_d = \frac{\Delta L}{R} \times 100\% \]  

(3)

Where \( Z_d \) is zero drift; \( \Delta Z \) is absolute error of zero drift; \( R \) is full range of instrument; \( L_d \) is range drift; \( \Delta L \) is absolute error of range drift. Table 2 shows the test data of zero drift and range drift.

| Test location | Monitoring room | Principle of measurement | High temperature and dilution lazer |
|---------------|-----------------|--------------------------|-----------------------------------|
| Response value of calibration | 49.3mg/Nm³ | Range | 50mg/Nm³ |
| Unit of measurement (mg/Nm³) | | | |
| \( Z_0 \) | \( Z_n \) | \( \Delta Z = Z_n - Z_0 \) | \( Z_d \) | \( L_0 \) | \( L_n \) | \( \Delta L = L_n - L_0 \) | \( L_d \) |
| 0.02 | 0.04 | 0.02 | 0.04 | 49.7 | 49.3 | -0.40 | 0.80 |
| 0.13 | 0.16 | 0.03 | 0.06 | 49.0 | 49.7 | 0.70 | 1.40 |
| 1.10 | 0.98 | -0.12 | 0.24 | 48.8 | 48.5 | -0.30 | 0.60 |
| Maximum absolute error of zero drift | -0.12 | Maximum absolute error of range drift | 0.70 | |
| Zero drift | 0.24 | Range drift | 1.40 | |

From the data of table 2, the zero drift and range drift in CEMS is 0.24% and 1.40%, better than 2%F.S. (full span) and 5%F.S. required by equipment parameters.

3.3.2 Data analysis of relative accuracy of particles concentration measurement in CEMS. The evaluation index of particles concentration measurement in CEMS introduces the half width of the confidence interval and the half width of the allowable interval, which does not directly affect the uncertainty from the data level, but also reflects the quality of the measured data of particles concentration. The CEMS data of particles were taken and compared with the concentration values measured by reference method [9] at the same time period. Manual measurement data have converted the cross-section concentration of particles under standard conditions into the cross-section concentration value of particles under actual flue gas.
Table 3. Comparison of particles concentration measured by reference method and CEMS

| Serial number | Indicating value of CEMS (X_i) | Indicating value of reference method (Y_i) | Serial number | Indicating value of CEMS (X_i) | Indicating value of reference method (Y_i) |
|---------------|-------------------------------|-----------------------------------------|---------------|-------------------------------|-----------------------------------------|
| 1             | 2.86                          | 2.85                                    | 9             | 0.96                          | 0.86                                    |
| 2             | 3.39                          | 3.19                                    | 10            | 0.13                          | 0.21                                    |
| 3             | 3.33                          | 3.22                                    | 11            | 1.14                          | 1.01                                    |
| 4             | 3.63                          | 3.53                                    | 12            | 2.03                          | 2.05                                    |
| 5             | 3.19                          | 3.23                                    | 13            | 1.96                          | 2.01                                    |
| 6             | 2.98                          | 2.88                                    | 14            | 2.1                           | 1.96                                    |
| 7             | 1.66                          | 1.56                                    | 15            | 2.48                          | 2.22                                    |
| 8             | 0.48                          | 0.28                                    |               |                               |                                         |

The linear equation is:

\[ Y = aX + b \] \hspace{1cm} (4)

Where \( Y \) is the particles concentration predicted by reference method; \( X \) is measuring concentration of particles of CEMS; \( a \) is slope of curve; \( b \) is intercept of curve.

According to relevant calculation standards [10], the slope is 0.989, the intercept is -0.060, the correlation coefficient is 0.996. The linear equation is \( Y = 0.989X - 0.060 \).

The equation for calculating the half width of the confidence interval as follows:

\[
CI = t_{df,\alpha/2} S_E \sqrt{\frac{1}{n}}
\] \hspace{1cm} (5)

\[
S_E = \sqrt{\frac{1}{n-2}\sum (Y_i - Y) \hat{Y}}^2
\] \hspace{1cm} (6)

\[
CI\% = \frac{CI}{EL} \times 100\%
\] \hspace{1cm} (7)

Where \( CI \) is the half width of the confidence interval at the average value; \( S_E \) is dispersion or deviation of the calibration curve. Refer to the relevant table, \( t_{df,\alpha/2} \) is 2.160, so \( S_E \) is 0.104, \( CI \) is 0.058. \( EL \) is the average value measured by reference method during the detection period. Therefore, \( CI\% \) is 2.80\%, which is better than 10\%, the half width of the confidence interval required by the indicator.

The equation for calculating the half width of the allowable interval as follows:

\[
TI = u'_n V_{df} S_E
\] \hspace{1cm} (8)

\[
TI\% = \frac{TI}{EL} \times 100\%
\] \hspace{1cm} (9)

Where \( TI \) is the half width of the allowable interval at the average value; refer to the relevant paper, \( u'_n \) is 1.198, \( V_{df} \) is 1.485, \( TI \) is 0.185. Then \( TI\% \) is 8.94\%, which is better than 25\%, the half width of the allowable interval required by the indicator.

The confidence interval is: \( \hat{Y} = 0.989X - 0.060 \pm 0.058 \)

The allowable interval is: \( \hat{Y} = 0.989X - 0.060 \pm 0.185 \)

Figure 3 shows the relationship between correlation calibration curve, the confidence interval and the allowable interval.
Combined with the above calculations and figures, it can be explained that the calibration curve of CEMS measured values detected by reference method is within the confidence interval and the allowable interval, and the calibration of the two indexes is far lower than the requirements of instrument performance indexes, further demonstrating that the system has higher reliability in monitoring particles concentration.

4. Evaluation results of standard uncertainty of particles concentration measurement

4.1 Uncertainty introduced by zero drift and range drift
According to the results, the zero drift and range drift are respectively 0.24% and 1.40%. The evaluation equation of uncertainty of type B as follows:

\[ u_B = \frac{\alpha}{k} \]  

(10)

Where \( \alpha \) is relative error of influencing factor, \( k \) is coverage factor. On the basis of uniform distribution, \( k = \sqrt{3} \), \( u_{B_{zero}} = \alpha / k = 0.24\% / \sqrt{3} = 0.14\% \), \( u_{B_{range}} = \alpha / k = 1.40\% / \sqrt{3} = 0.81\% \).

4.2 Uncertainty introduced by measuring repeatability
According to the real monitoring data, the hourly data of the day are summarized in the following table.

| Time   | Concentration | Time   | Concentration | Time   | Concentration |
|--------|---------------|--------|---------------|--------|---------------|
| 0~1    | 2.02          | 8~9    | 1.58          | 16~17  | 1.73          |
| 1~2    | 1.85          | 9~10   | 3.14          | 17~18  | 1.94          |
| 2~3    | 2.01          | 10~11  | 1.94          | 18~19  | 1.99          |
| 3~4    | 2.18          | 11~12  | 1.77          | 19~20  | 2.04          |
4.3 Related combined standard uncertainty of particles concentration measurement

According to the measurement and calculation above, the evaluation results of related standard uncertainty of each component are summarized in the following table.

Table 5. Summary of uncertainty of each component

| Serial number | Source of uncertainty | Component of uncertainty | Related standard uncertainty |
|---------------|-----------------------|--------------------------|------------------------------|
| 1             | Zero drift            | $u_{\text{zero}}$        | 0.14%                        |
| 2             | Range drift           | $u_{\text{range}}$       | 0.81%                        |
| 3             | Measuring repeatability | $u_A$                     | 4.56%                        |

The measuring error of particles concentration in CEMS follows the normal distribution. When coverage factor is $k=2$ and level of confidence is 95%, the related expanded uncertainty is $U = k \times u_c = 9.26\%$.

4.4 Summary

Among the factors affecting the uncertainty of particles concentration measurement in CEMS, the measuring repeatability has the greatest influence. First of all, because the particles concentration monitoring is dynamic, the monitoring value fluctuates up and down with time, and its standard deviation will be relatively high. Secondly, since the monitoring point is located behind the WESP, the velocity and moisture content of flue gas will affect the monitoring of pollutants by the probe, resulting in obvious drift of repeated measurement values of flue gas by the CEMS, and the introduced uncertainty component is large.

The measurement principle of portable flue gas analyzer used by reference method is fixed potential electrolysis method, which is different from the Fourier infrared absorption method of CEMS, resulting in deviation of monitored data. Therefore, it is necessary to introduce the confidence interval and allowable interval to evaluate the measurement results.

5. Conclusion

(1) In this paper, the uncertainty of particles concentration measurement of CEMS in a thermal power plant in Hangzhou is researched and analyzed. The results show that the related expanded uncertainty of particulates concentration measurement is 9.26%. Measurement repeatability is the main influencing factor.

(2) The uncertainty evaluation of particles concentration measurement introduces two indexes. The confidence interval half width is 0.48% and the allowable interval half width is 1.54%, which are far
Acknowledgements
This paper was supported by National Key Research and Development Program of China (2018YFC1802100).

References
[1] Zhang, X.H., Schreifels, J. (2011) Continuous emission monitoring systems at power plants in China: improving SO₂ emission measurement. Energy Policy, 39: 7432-7438.
[2] Wang, Z.Y., Liu, Z.M., Xia, X.T. (2008) Measuring Error and Uncertainty Evaluation. Science Press, Beijing.
[3] Wang, X. (2014) Interpretation of the current definition of uncertainty measurement. China Metrology, 12: 67-69.
[4] Ma, K., Li, X.J., Cui, M.M. (2015) Uncertainty evaluation for the determination of amaranthus red in wine samples by high performance liquid chromatography. Acta Metrologica Sinica, 35: 102-106.
[5] Zhang, X.F., Ruan, X. (2010) Key parameters influencing the efficiency of desulfurization in wet flue gas desulfurization systems. Energy Environmental Protection, 24: 41-44.
[6] Yang, L., Zhang, B., Wang, K.H. (2019) Conversion characteristics of combustible particles from coal-fired flue gas in WFGD and WESP. Environmental Science, 40: 121-125.
[7] Ni, Y.C. (2009) Practical Uncertainty of Measurement Evaluation. China Metrology Press, Beijing.
[8] Song, M.S., Chen, Y.H., Tao, J.S. (2005) Risk of the estimating measurement uncertainty in artificial ignored correlative case. Acta Metrologica Sinica, 26: 90-92.
[9] Ministry of Environmental Protection of the People’s Republic of China. (2017) HJ 836 Stationary source emission—Determination of mass concentration of particulate matter at low concentration—Manual gravimetric method.
[10] https://wenku.baidu.com/view/793ae37a66ec102de2bd960590c69ec3d5bbdbe7.html. Ministry of Environmental Protection of the People’s Republic of China. (2017) HJ 76 Specifications and test procedures for continuous emission monitoring systems for SO₂, NOₓ and particulate matter in flue gas emitted from stationary sources. https://www.docin.com/p-2204910993.html.
[11] Wang, H.G., Yang, J., Wang, G.P. (2007) Evaluation uncertainty of measurement for sculpture dioxide in flue gas. Instrumentation and Analysis monitoring, 4: 42-44.
[12] Dong, F., Li, X.T., Li, J.H. (2008) Evaluation and analysis of uncertainty in measurement of SO₂ automatic monitor. In: 2008 International Conference on Machine Learning and Cybernetics. Kunming. pp. 1958-1961.