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RESEARCH AND APPLICATION OF LOW PARTICULATE MATTER CONCENTRATION TESTING TECHNOLOGY IN HIGH HUMIDITY AND LOW TEMPERATURE ENVIRONMENT

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Abstract

The accuracy of the particulate matter (PM) emission measurement in coal-fired power plants has been enhanced to meet stricter environmental standards. The self-made "test and calibration device of low PM concentration" was used to simulate the complex field conditions of flue gas with high humidity, high acid and low temperature (about 50℃). The detection limits and PM trapping performances of six filtration membranes were tested. The filtration membrane with the best trapping performance was studied under different filtration wind velocities and low flow velocity condition. And the simulation test was verified by practical application. The results showed the feeding frequencies had a good linear relationship to the PM concentrations, which can be used as a standard curve to calibrate the PM concentration. The borosilicate membrane had the lowest detection limit and the best PM trapping performance in high humidity and low temperature environment. The large diameter sampling nozzle should be selected for the measurement of low PM concentration. Predicting constant current isokinetic sampling method was recommended for the measurement of low velocity PM concentration. Practical application had proved that our test method is feasible, and the borosilicate membrane is more suitable than the commonly used Swedish quartz membrane for the measurement of low PM concentration in saturated wet flue gas.

Keywords: coal-fired power plant, high humidity, low temperature, low PM concentration, testing technology

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1. Introduction

With the frequent occurrence of fog and haze, air pollution has attracted more and more attention (Zhang et al., 2005). Most of the fine particulate matter (PM) comes from pollution such as combustion and industrial production. 70% of PM emissions are caused by coal combustion, while coal combustion in power industry accounts for about 50% of total coal combustion in China (Yan, 2010). In the government work report of 2015, it clearly pointed out that "promote the reform of ultra-low emission of coal-fired power plants", and the emission requirement of low PM concentration from coal-fired power plants is not higher than 20 mg/m^3, and even less than 5 mg/m^3 in some areas (EPM, 2011; Xu et al., 2016). According to incomplete statistics, the ultra-low emission renovation of coal-fired power plants has been completed for most of the country. But there are many power plants, especially those with low smoke and dust emission concentration (e.g., less than 2.5 mg/m^3 or even less than 1 mg/m^3), the test data are questioned, and the accurate measurement of low PM concentration becomes a pivotal issue and difficult point in current research (Liu et al., 2018). In recent years, many continuous methods have been applied to

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measure the PM concentration, such as beta gauge (Courtney et al., 1982; Takahashi et al., 2008), opacity (Choi et al., 1995; Mellon et al., 2011), light scattering (Black et al., 1996; Jones, 1999; Kadota and Hiroyasu, 1984), the electrostatic method (Gajewski, 1999; Zheng et al., 2017), and microbalance (Ariessohn and Wang, 1985; Ward and Buttry, 1990). However, the main method of off-line monitoring is the weighing method. The existing weighing method in China adopts *the determination of particulates and sampling methods of gaseous pollutants emitted from exhaust gas of stationary source (GB/T 16157-1996)*. This method is only applicable to fixed pollution sources whose PM concentration is higher than 50 mg/m^3 (EPA, 1996). When the PM concentration is lower than 50 mg/m^3, the error is large. The flue gas in power plants equipped with wet flue gas desulfurization (WFGD) and wet electrostatic precipitator (WESP) (Mu et al., 2017; Wang et al., 2016) systems has high relative humidity (50~100%) and low PM concentration (even below 1 mg/m^3) at the sampling location (Sui et al., 2016). Humidity can influence PM concentration measurements (Peng et al., 2019). *GB/T 16157-1996* is unsuitable for the "two low and one high" condition in which the PM concentration in the flue is low, the temperature is low, and the humidity is high after the WFGD and the WESP. The monitoring data of the flue gas online monitoring system CEMS can only give the relative variation curve of smoke and dust concentration, and its true value needs to be calibrated by the smoke and dust measuring instrument (HJ 75-2017, HJ 76-2017) (EPM, 2017a; EPM, 2017b). In order to meet the demand for the determination of low PM concentration, Ministry of Environmental Protection issued *Stationary Source Emission-Determination of Mass Concentration of Particulate Matter at Low Concentration-Manual Gravimetric Method (HJ 836-2017)* to make up for the deficiency of *GB 16157* in monitoring PM below 20 mg/m^3. In the new method (HJ 836-2017), filtration membrane is used instead of a filtration cartridge, and the whole sampling head is used to weigh, which overcomes the error caused by the loss of glass fiber when sampling and the sediment particles in the front of the sampling device cannot be recovered (EPM, 2017c).

At present, there is no standard test-bed to calibrate the PM concentration in China, and the true value of the PM concentration in different concentration ranges cannot be determined. Therefore, the accuracy of the PM measurement can only be determined by the captured PM amount. And it is considered that the more PM is captured, the closer the result is to the true value. In addition, almost all the on-line smoke and dust concentration monitoring instruments currently in use have not been calibrated, and some relationship determined through manual comparison instruments cannot be used at all (Liang, 2013). In order to improve the accuracy of low PM concentration testing, reduce test errors and standardize test methods, a calibration device for low PM concentration testing with traceability of measurement has been developed by our research group (hereinafter referred to as calibration device) (Chen et al., 2019; Guo et al., 2017). Through the calibration device to simulate complex field conditions of flue gas with high humidity, high acid and low temperature (about 50 ℃). Under the conditions, the detection limits and PM trapping performances of six filtration membranes were tested. The filtration membrane with the best trapping performance was studied under different filtration wind velocities and low flow velocity condition. And the simulation test was verified by practical application. Thus, the optimum conditions for low PM concentration testing in high humidity, high acid and low temperature environment were selected, which can provide technical support for the revision of low PM concentration testing standards.

2. Material and methods

2.1. Experimental device

The schematic of the calibration device is shown in Fig. 1. It is mainly composed of feeding device, SO_3 generating device, air heater, electric heating steam generator, PM on-line monitoring device, thermometer, humidity meter, induced draft fan, dust and acid gas recovery device, etc. After the clean air enters the generating device, the air is heated by the air heater, the heating power of the air heater is controlled by the downstream thermometer, then the dust concentration is controlled by the feeding device with adjustable speed. After that the saturated water vapor and SO_3 are injected. The SO_3 concentration is regulated by the flowmeter of the SO_3 generating device. The dust concentration is on-line monitored by PCME 181WS. The temperature and humidity of flue gas are monitored by thermometer and hygrometer in real time. In order to reduce the residue of PM on some pipe fittings, the gas with acidic and PM is recovered by the dust recovery device after passing through the fiber-reinforced plastics (FRP) fan.

The performance evaluation test and practical application of the device were carried out by our group. The evaluation results show that the device can simulate the working conditions of high humidity, low temperature and acid gas in the field. At the same time, it can provide stable, uniform and low concentration PM output, and can provide technical support for the research of low PM concentration testing technology. Main design parameters of the calibration device are listed in Table 1.

2.2. Experimental method

2.2.1. Reliability verification of calibration device in high humidity and low temperature environment

The filtration membrane was Borosilicate membrane (BM), feeding frequencies were 13, 28, 40 and 50 Hz, respectively, fan frequency was 50 Hz, flue gas temperature was 50°C, flue gas humidity was 13.5%, SO_3 concentration was 6.08 mg/m^3, and maintained stable operation at ±2%.

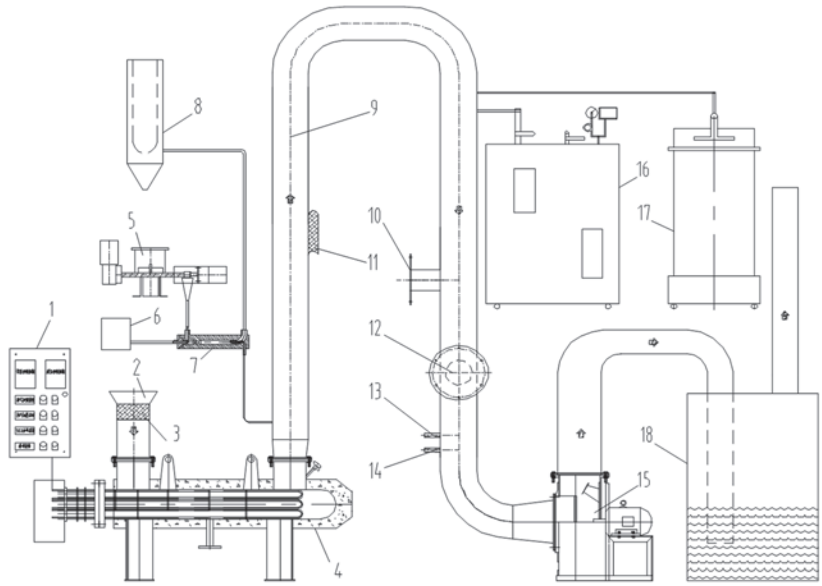


Fig. 1. Schematic of the calibration device. 1: control cabinet; 2: collector; 3: filter; 4: air heater; 5: feeder; 6: compressed air; 7: diluter; 8: small filtration bag; 9: FRP pipe; 10: online monitoring; 11: heat preservation; 12: test location; 13: hygrometer; 14: thermometer; 15: FRP fan; 16: steam generator; 17: SO_3 generating device; 18: SO_3 and dust recovery device

Table 1. Main design parameters of the calibration device

Q_f (m^3/h)	P_t (Pa)	D (μm)	v_s (m/s)	t_s (^0C)	X_{sw} (%)	C_{SO3} (mg/m^3)	C (mg/m^3)
1410～1704	3507～3253	10.505	<14	ambient temperature~100	<26%	>5	>2

Note: Q_f: Fan airflow rate (m^3/h); P_t: Total pressure (Pa); D: Medium particle diameter of the end-precipitator dust used in the test (μm); v_s: Flue gas velocity (m/s); t_s: Flue gas temperature (℃); X_{sw}: Flue gas humidity (%); C_{SO3}: SO_3 concentration (mg/m^3); C: Dust concentration (mg/m^3).

2.2.2. Detection limits of different filtration membranes

The glass fiber, quartz and polytetrafluoroethylene (PTFE) are the main materials for common filtration membranes at home and abroad now (Luo and Chen, 2018). Six different blank filtration membranes such as: Laoying glass fiber membrane (LGM), borosilicate membrane (BM), Swedish quartz membrane (SQM), Whatman quartz membrane (WQM), Pall quartz membrane (PQM) and PTFE hydrophobic membrane (PTFEM) were respectively measured 7 times in succession according to the standard specified procedure in the clean room, and the detection limits were calculated by $t_{(n-1,0.99)}$ times of the standard deviation (expressed as *S*). The verification tests were conducted at a flow rate of 10 m/s to 15 m/s, the sampling nozzles diameter of φ10, φ8, and φ6 were used for sampling. The sampling volume of each sample was 1 m^3, and the detection limits were calculated according to Eq. (1).

$$MDL = t_{(n-1,0.99)} \times S \quad (1)$$

where: *MDL*-detection limit of the method, mg/m^3; *n*-parallel measurement numbers of the sample; *t*-t distribution value when the degree of freedom is *n-1* and the reliability is 99%; *S*-standard deviation of *n* times parallel measurement.

2.2.3. Effects of different filtration membranes on the measurement of low PM concentration

Six kinds of filtration membranes were selected as the same with the method 2.2.2 for comparative experiments. Feeding frequency was 13 Hz, fan frequency was 50 Hz, flue gas temperature was 50℃, flue gas humidity was 13.5%, SO_3 concentration was 6.08 mg/m^3, and maintained stable operation at ±2%.

2.2.4. Effects of filtration wind velocity on the measurement of low PM concentration

The filtration membrane is the one with the best performance in method 2.2.2 and 2.2.3, feed frequency was 13 Hz, fan frequency was 50 Hz, flue gas temperature was 50℃, flue gas humidity was 13.5%, SO_3 concentration was 6.08 mg/m^3, and maintained stable operation at ±2%.

2.2.5. Effects of sampling method at low flow velocity on the measurement of low PM concentration

The filtration membrane is the one with the best performance in method 2.2.2 and 2.2.3, fan frequency was 30 Hz, feed frequency was 13 Hz, flue gas temperature was 50℃, flue gas humidity was 13.5%, SO_3 concentration was 6.08 mg/m^3, and maintained stable operation at ±2%.

3. Results and discussion

3.1. Reliability verification of calibration device in high humidity and low temperature environment

The experimental results of BM at different feeding frequencies in wet flue gas are listed in Table 2, the polynomial fitting curves of the feed frequencies and the PM (standard PM and measured PM) concentrations are shown in Fig. 2. It can be seen when feeding frequencies are 13, 28, 40 and 50 Hz, and flue gas flow is 450 m^3/h, the standard PM concentrations are 4.88, 5.21, 8.71 and 9.92 mg/m^3, the measured PM concentrations are 4.67, 5.01, 8.42 and 9.61 mg/m^3, respectively. The polynomial regression equation of curve 2 (the polynomial fitting curve of the feed frequency and the standard PM concentration) in Fig. 2 is $y=0.00332x^2-0.04885x+4.71123$, and the R value is 0.9795. The polynomial regression equation of curve 1 (the polynomial fitting curve of the feed frequency and the measured PM concentration) in Fig. 2 is $y=0.2125x^2+0.7605x+3.4325$, the R value is 0.9608. According to the selected significance level α and the number of observation points n minus 2 (degree of freedom), the corresponding threshold value r (α=0.05) can be found to be 0.950 in the correlation coefficient threshold table. The correlation coefficient R calculated from the test data is greater than or equal to r (≥), which proves that there is a good linear correlation between the feeding frequencies and the PM (standard PM or measured PM) concentrations, their reliabilities are as high as 95.0%. The regression curve can be used as the standard curve to calibrate the PM concentration through changing different feeding frequencies in wet flue gas. The maximum deviation between the measured PM and the standard PM concentration is 4.3%, which meets the design requirement.

The full program blank is the sample obtained when the operation is exactly the same as the actual sample, except that the sampling nozzle is back to the airflow during the sampling process, and ensure that there is at least one full program blank for each group of samples. Any sample lower than the full program blank weight gain is invalid, and the full program blank sample concentration shall not exceed 10% of the emission limit. From Table 2 can see that the percentages of full program blank concentration to measured PM concentration of BM at different feeding frequencies in wet flue gas are less than 10%, all the test results are valid.

The relationships between feeding frequencies, measured PM concentrations, and online monitoring PM concentrations are shown in Fig. 3. The online monitoring PM concentration is the average concentration monitored online during sample measured, and its calibration factor is set as y=x+0 calibrated by the factory. The measured PM concentrations are 2.2 times (the average value of the ratio of four measured and online monitoring values (2.62, 1.86, 2.24, 2.04)) that of online monitoring PM concentrations. The online monitoring PM concentrations are lower than manual measurement concentrations.

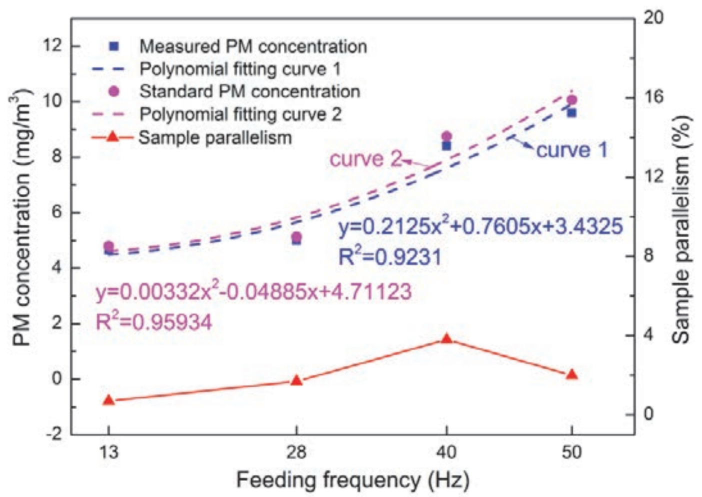


Fig. 2. PM concentration and sample parallelism distribution curves at different feeding frequencies

Table 2. Test results of BM at different feeding frequencies in wet flue gas

F_f (Hz)	t_s (^0C)	X_{sw} (%)	W (mg/min)	C_s (mg/m^3)	C_m (mg/m^3)	RSD (%)	C_f (mg/m^3)	X_c (%)	C_o (mg/m^3)
13	50	13.8	36.6	4.88	4.67	0.7	0.04	0.9	1.78
28	50	13.7	39.1	5.21	5.01	1.7	0.17	3.0	2.68
40	50	13.8	65.4	8.71	8.42	3.8	0.06	0.7	3.75
50	50	13.5	74.4	9.92	9.61	2.0	0.06	0.6	4.71

Note: F_f: Feeding frequency (Hz); t_s: Flue gas temperature (℃); X_{sw}: Flue gas humidity (%); W: Feeding weight of feeder (mg/min); C_s: Average value of standard PM concentration (mg/m^3); C_m: Average value of measured PM concentration (mg/m^3); RSD: Sample parallelism (%); C_f: Full program blank concentration (mg/m^3); X_c: Percentage of full program blank concentration to measured PM concentration (%); C_o: Online monitoring PM concentration (mg/m^3).

Table 3. Detection limits of the different filtration membranes

T_f	Testing results of parallel sample (mg/m³)								S (mg/m³)	Value t	MDL (mg/m³)
	1	2	3	4	5	6	7	C_m			
BM	0.28	0.07	0.12	0.22	0.15	0.00	0.14	0.140	0.092	3.143	0.29
SQM	0.84	0.59	0.74	0.87	0.87	0.80	0.78	0.784	0.098	3.143	0.31
WQM	0.03	-0.06	0.07	0.28	0.05	-0.06	0.08	0.056	0.114	3.143	0.36
PTFEM	-0.02	0.13	-0.21	0.03	-0.20	-0.07	-0.11	-0.064	0.123	3.143	0.39
PQM	-0.06	-0.22	0.21	-0.20	0.02	-0.15	-0.32	-0.103	0.177	3.143	0.56
LGM	-0.04	0.16	0.04	-0.34	0.07	-0.17	-0.26	-0.077	0.184	3.143	0.58

Note: T_f: Filtration membrane type; C_m: Average value of measured PM concentration (mg/m³); S: Standard deviation of 7 times parallel measurement (mg/m³); MDL: Detection limit of the method (mg/m³).

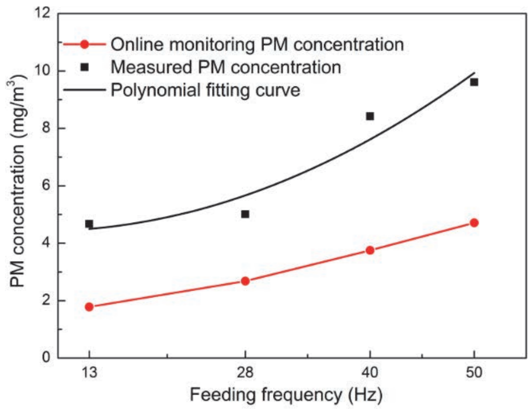


Fig. 3. Measured and online monitoring PM concentration distribution curves at different feeding frequencies

The main reason may be that the online monitoring of PM was calibrated under the condition of ambient temperature and humidity when leaving the factory, which fails to simulate the complex actual flue gas conditions. And in the process of extracting the flue sample gas from the sampling probe to the atomization chamber, there will inevitably be a loss of PM, especially for the low PM concentration, which has a greater influence on the calibration factor. Therefore, the calibration factor y=x set by the factory needs to be adjusted under different environmental conditions. According to the test results, the calibration factor should be set as y=2.2x in high humidity and low temperature environment.

3.2. Detection limits of different filtration membranes

The quality of filtration membranes is one of the key factors to ensure the accuracy of PM test results. The material selection of filtration membranes is particularly important. The material of filtration membranes should not absorb or react with gaseous compounds in exhaust gas, and avoid mass loss during the sampling process. In this paper, six kinds of common filtration were selected for comparative experiments, to optimize the filtration membranes suitable for testing low PM concentration in high humidity and low temperature environment.

The determination of detection limit is of great significance for the selection of analytical methods. In order to reflect the error of analytical methods in the whole analytical process, we tested the detection limits of six kinds of filtration membranes, and screened out the filtration membranes with the lowest detection limit. The test results of the detection limits for BM, PTFEM, LGM, SQM, PQM and WQM are listed in Table 3.

In Eq. (1) and Table 3, the value *t* is *t* distribution value when the degree of freedom is n-1 and the reliability is 99%. When testing 7 parallel samples, then n-1=6, and the corresponding reliability is 99%, then according to “Value t” distribution table, we can obtain value t is 3.143. The detection limits of the six filtration membranes are 0.29, 0.31, 0.36, 0.39, 0.56 and 0.58 mg/m³, respectively. Which all meet the requirement of the research that the detection limit should be less than 1 mg/m³. The detection limit of LGM is the highest, followed by PQM, and the lowest is BM.

3.3. Effects of different filtration membranes on the measurement of low PM concentration

The experimental results of six filtration membranes (when flue gas is 450 m³/h) in wet flue gas, are shown in Table 4 and Fig. 4. The full program blank concentrations of six filtration membranes in wet flue gas are less than 10% of the measured PM concentration, which indicates that the test results are valid.

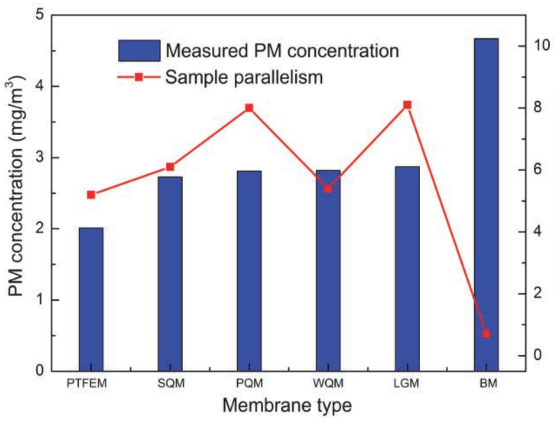


Fig. 4. Measured PM concentration and sample parallelism distribution curves of different filtration membranes

The measured PM concentrations are 2.01, 2.73, 2.81, 2.82, 2.87 and 4.67 mg/m³, respectively.

When the feeding frequency is 13 Hz, the standard PM concentration is 4.88 mg/m^3. The filtration membrane that trapped highest concentration PM is BM, the lowest one is PTFEM, the other membranes are similar. The sample parallelisms of the measured PM concentration are 0.7%, 5.2%, 5.4%, 6.1%, 8.0% and 8.1%, respectively. Which meet the requirement that the relative standard deviation should be less than 18% in the research. BM has the minimum relative standard deviation, which is only 0.7%. BM has higher trapping performance in the measurement of low PM concentration, and the test results have smaller error and higher accuracy, indicating that the BM is superior to other membranes in capturing PM under wet flue gas conditions. Scanning electron microscopy (SEM) photographs of six filtration membranes can explain the results (Fig. 5).

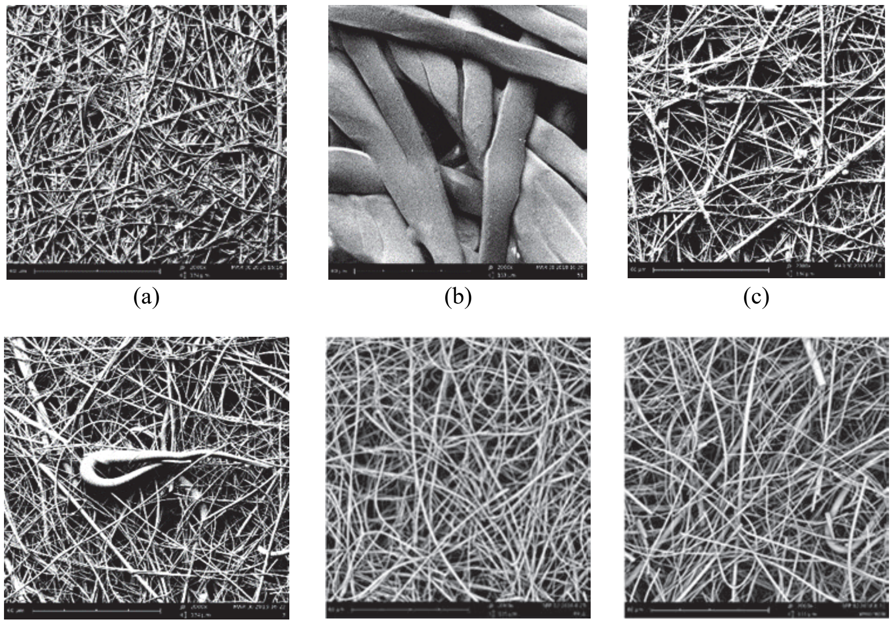
From Fig. 5, the surfaces of LGM, SQM, PQM and WQM are rough and their structures are comparatively fluffy, and their thicknesses are slightly thicker than other kinds of filtration membranes through actual comparison. The non-compactness of membrane structure and the non-uniformity of pore make their PM trapping performance poor. Fibers of PTFEM are thick and flat, and the porosity of membrane is low, high sampling resistance leads to the worst PM trapping performance.

Fibers of BM are uniform in thickness, compact in structure, flat in surface and high in porosity. Therefore, BM has better PM capture performance and smaller sampling resistance. Luo and Chen (2018) also report similar conclusions.

Table 4. Test results of six filtration membranes in wet flue gas

T_f	t_s (^0C)	X_{sw} (%)	Testing results of parallel sample (mg/m^3)				RSD (%)	C_f (mg/m^3)	X_c (%)	C_o (mg/m^3)
			1	2	3	C_m				
PTFEM	51	13.7	1.98	1.93	2.13	2.01	5.2	0.18	9.0	1.31
SQM	51	13.7	2.70	2.91	2.58	2.73	6.1	0.25	9.2	1.42
PQM	50	13.5	2.70	3.07	2.66	2.81	8.0	0.12	4.3	1.19
WQM	50	13.5	2.69	2.99	2.79	2.82	5.4	0.09	3.2	1.29
LGM	50	13.5	2.84	2.66	3.12	2.87	8.1	0.18	6.3	1.24
BM	50	13.8	4.65	4.65	4.71	4.67	0.7	0.04	0.9	1.78

Note: T_f: Filtration membrane type; t_s: Flue gas temperature (℃); X_{sw}: Flue gas humidity (%); C_m: Average value of measured PM concentration (mg/m^3); RSD: Sample parallelism (%); C_f: Full program blank concentration (mg/m^3); X_c: Percentage of full program blank concentration to measured PM concentration (%); C_o: Online monitoring PM concentration (mg/m^3).



(a) (b) (c)

(d) (e) (f)

Fig. 5. 2,000 fold magnification microscope images of filtration membranes used in the experiment: (a) represent BM, (b) represent PTFEM, (c) represent LGM, (d) represent SQM, (e) represent PQM, (f) represent WQM

Table 5. Test results of PM concentration at different filtration wind velocities

D_h (mm)	D_n (mm)	v_f (cm/min)	t_s (^0C)	X_{sw} (%)	C_m (mg/m^3)	RSD (%)	C_f (mg/m^3)	X_c (%)
47	6	2.508	50	13.8	2.77	8.0	0.26	9.8
47	8	4.805	51	13.1	3.33	11.5	0.14	4.7
47	10	6.930	50	13.8	4.67	0.7	0.04	0.9

Note: D_h: Sampling head diameter (mm); D_n: Sampling nozzle diameter (mm); v_f: Filtration wind velocity (cm/min); t_s: Flue gas temperature (℃); X_{sw}: Flue gas humidity (%); C_m: Average value of measured PM concentration (mg/m^3); RSD: Sample parallelism (%); C_f: Full program blank concentration (mg/m^3); X_c: Percentage of full program blank concentration to measured PM concentration (%).

3.4. Effects of different filtration wind velocities on measurement of low PM concentration

The experimental results of PM concentration measured by BM at different filtration wind velocities in wet flue gas are listed in Table 5, and the distribution curves are shown in Fig. 6. The full program blank concentrations at the different filtration wind velocities in the wet flue gas are less than 10% of the measured PM concentrations, and all the test results are valid.

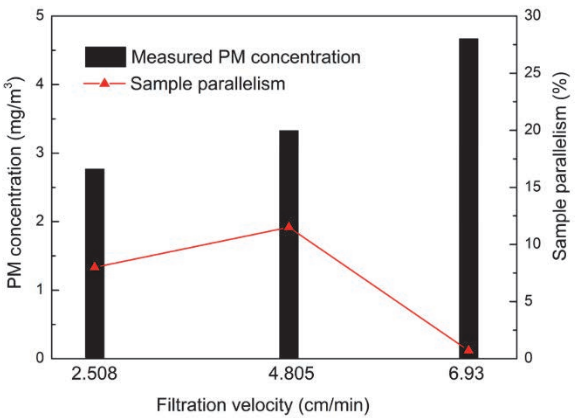


Fig. 6. Measured PM concentration and sample parallelism distribution curves at different filtration wind velocities

When the diameter of sampling head is 47 nm and the diameters of sampling nozzle are 6, 8 and 10 nm respectively, the effective filtration wind velocities are 2.508, 4.805 and 6.930 cm/min respectively. Under different filtration wind velocities, the measured PM concentrations (when flue gas flow is 450 m^3/h) are 2.77, 3.33 and 4.67 mg/m^3 respectively. When the feeding frequency is 13 Hz, the standard PM concentration is 4.88 mg/m^3. The sample parallelisms are 8.0%, 11.5% and 0.7%, respectively. Under the same conditions, the measured PM concentrations of captured by the sampling head of φ47 increase with the increase of the filtration wind velocities (i.e. the diameter increase of the sampling nozzle), which is just contrary to the fact that reducing the filtration wind velocities is beneficial to the PM capture. The reason may be that the edge of the sampling nozzle has a certain thickness (≤0.2 mm) (HJ 836-2017) (EMP, 2017), and when PM enter the sampling nozzle, they are easy to collide with the edge of the sampling nozzle. Some fine PMs are intercepted outside the sampling nozzle. When the diameter of the sampling nozzle is smaller, the probability of collision is greater than that the sampling nozzle with a larger diameter, which results in lower PM capture when the sampling nozzle has the smaller diameter.

3.5. Effect of sampling method at low flow velocity on the measurement of low PM concentration

The results of PM concentration test using predicted constant current isokinetic sampling and automatic tracking isokinetic sampling are listed in Table 6. From Table 6, the full program blank concentrations are less than 10% of the measured PM concentrations, indicating that the results are valid. When flow velocity is 2 m/s, the measured PM concentrations are 22.28, 14.94 mg/m^3, and the sample parallelisms are 14.9% and 16.0%, respectively. Under the same conditions, the measured PM concentration of the predicted constant current isokinetic sampling method is 49.1% higher than that of the automatic tracking isokinetic sampling method, and the sample parallelism is also slightly better. This is mainly because the dynamic pressure and velocity displayed by the sampler will gradually increase with the prolongation of sampling time, when the PM of low-flow saturated wet flue gas is tested by the automatic tracking isokinetic sampling method. These will result in the sampling velocity higher than the actual flow velocity of the sampling point, make the measured PM concentration lower, and the front pressure of the meter will slowly rise to the point in which the sampling is impossible. Therefore, it is recommended to adopt predictive constant current isokinetic sampling method in the measurement of low-velocity PM.

3.6. Practical application

According to HJ836 test method (EPM, 2017c), the outlet of No. 4 boiler WESP in Songyu Power Plant was tested by SQM and BM. The test results are listed in Table 7. Table 7 shows that the sampling volumes measured by SQM and BM are larger than 1 m^3, which meet the requirements of HJ836 Article 10.3.6 that the weight gain of each sample should not be less than 1 mg, or the sampling volume should not be less than 1 m^3. According to the principle of parallel double sample, the sample parallelism is not considered when the PM concentration is lower than 1 mg/m^3. However, the full program blank weight gain of SQM is 0.63 mg. The full program blank weight gain divided by the average volume of the corresponding measurement series accounts for 86.3% of the measured PM concentration, failing to meet the requirements of HJ836 Article 10.3.4 that "any below the full program blank weight gain is invalid. The full program blank weight gain divided by the average volume of the corresponding measurement series should not exceed 10% of the emission limit", and 10.3.7 "When the PM concentration is lower than the detection limit of the method, the full program blank weight gain should not be higher than 0.5 mg, and the weight loss should not be more than 0.5 mg." Therefore, the test results by using SQM are invalid. The full program blank weight gain of BM is 0.05 mg. The full program blank weight gain divided by the average volume of corresponding measurement series accounts for 8.3% of the measured PM concentration. It meets the requirements of research, and the test results are valid. It shows that BM is suitable for testing the low PM concentration in saturated wet flue gas, while SQM is unsuitable.

Table 6. Test results of PM concentration with different sampling methods at low flow rate

M_s	t_s (^0C)	X_{sw} (%)	v_s (m/s)	C_m (mg/m^3)	RSD (%)	C_f (mg/m^3)	X_c (%)
S_p	50	13.5	2	22.28	14.9	0.36	1.6
S_a	50	13.5	2	14.94	16.0	0.19	1.2

Note: M_s: Sampling method; t_s: Flue gas temperature (℃); X_{sw}: Flue gas humidity (%); v_s: Flue gas velocity (m/s); C_m: Average value of measured PM concentration (mg/m^3); RSD: Sample parallelism (%); C_f: Full program blank concentration (mg/m^3); X_c: Percentage of full program blank concentration to measured PM concentration (%); S_p: Predicting constant current isokinetic sampling; S_a: Automatic tracking isokinetic sampling.

Table 7. Test results of PM concentration using SQM and BM in Songyu Power Plant

T_f	S_p	S_n	D_n (mm)	W_i (g)	W_f (g)	W_n (mg)	V (L)	C_m (mg/m^3)		X_c (%)
SQM	1	326651	10	14.33235	14.33309	0.74	1002.2	0.74	0.73	86.3
	2	322271	10	14.27771	14.27843	0.72	1007.3	0.71		
	3	326641	10	14.24187	14.24262	0.75	1005.4	0.75		
	F_b	322281	10	14.17165	14.17228	0.63	1005.0	0.63		
BM	1	322221	10	14.19966	14.20018	0.52	1005.9	0.52	0.58	8.3
	2	326671	10	13.64836	13.64917	0.81	1003.1	0.81		
	3	326661	10	14.16982	14.17023	0.41	1002.7	0.41		
	F_b	326681	10	14.01903	14.01908	0.05	1003.9	0.05		

Note: T_f: Filtration membrane type; S_p: Parallel sample; S_n: Sample number; D_n: Sampling nozzle diameter (mm); W_i: Initial weight of sample (g); W_f: Final weight of sample (g); W_n: Net weight of sample (mg); V: Standard sample volume (L); C_m: Measured PM concentration (mg/m^3); X_c: Percentage of full program blank concentration to measured PM concentration (%); F_b: Full program blank.

4. Conclusions

At present, the ultra-low emission of flue gas from coal-fired power plants has been fully implemented. In order to improve the accuracy of the low PM concentration measurement in high humidity, low temperature after WFGD and WESP, a self-made calibration device had been used to carry out the research, and its practical application had been verified. The following conclusions were obtained. When the calibration device ran in wet flue gas, the reliability of the relationship between feeding frequencies and PM concentrations was up to 95%, and there was a good linear relationship between them. The measured PM concentrations were 2.2 times that of the online monitoring PM concentrations, the calibration factor of the online monitor should be set as y=2.2x in high humidity and low temperature environment. BM has the lowest detection limit and the best PM capture performance, was recommended for the measurement of low PM concentration in wet flue gas after WFGD and WESP. The influence of filtration wind velocity on the low PM measurement was small. If the field conditions permit, the sampling nozzle with a large inlet diameter should be selected as far as possible. At low flow velocity, the measurement of low PM concentration was recommended to adopt the predicted constant current isokinetic sampling method. Practical application results showed that our test method is feasible, and the BM is more suitable than the commonly used SQM for the measurement of low PM concentration in saturated wet flue gas.

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