

*Original Research*

# Validation and Accuracy Study of SO<sub>3</sub> Detection Using the Controlled Condensation Method

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## Abstract

The SO<sub>3</sub> in coal-fired flue gas is easy to condense, reduce the smoke emission transparency and cause corrosion on the surface of the equipment. With the urgency of accurate measurement and effective treatment of SO<sub>3</sub>, this article focuses on the development of the controlled condensation method (CCM) for SO<sub>3</sub> testing. An SO<sub>3</sub> test accuracy verification device is set up for evaluating the test accuracy of CCM, and the influence of factors on the accuracy of CCM is performed, such as sampling a gun's heating temperature, sampling flow rate, high SO<sub>2</sub> concentration and difference of SO<sub>3</sub> concentration during the test procedure. The CCM can effectively avoid the interference of SO<sub>2</sub> on capture efficiency. With the increase of heating temperature and flow rate, the capture efficiency first increases and then decreases. Reasonable control of the tracing temperature and sampling flow rate helps to improve the accuracy of CCM. In a certain range of SO<sub>3</sub> concentration, the capture efficiency has a linear relationship with SO<sub>3</sub> concentration. The finding of the current study shows that this is feasible and provides significant references as to how to improve SO<sub>3</sub> detection accuracy.

**Keywords:** controlled condensation method, SO<sub>3</sub> sampling system, influence factors, accuracy

## Introduction

Recently, sulfur trioxide (SO<sub>3</sub>) has captured more and more attention for its health risks and environmental harm [1-3]. The emitted SO<sub>3</sub> has become an important source of acid rain and condensable fine particulate emissions, thus causing damage to forests and buildings. Due to very active chemical nature of SO<sub>3</sub> in coal-fired flue gas, it is easy to combine with water vapor to form acid mist, which increases the dew point of flue gas [4].

When the wall plate temperature of the equipment is lower than the acid dew point, the acid mist condenses on the surface of the equipment and causes corrosion [5-7]. The research of Moretti et al. and Cao et al. [8, 9] clearly reported that when the flue gas is discharged from the stack and the level of SO<sub>3</sub> reaches 5 ppm, this will result in the blue feather phenomenon. Dunn et al. and Srivastava et al. [10, 11] investigated that the SO<sub>3</sub> easily adheres to a boiler and selective catalytic reduction (SCR) system after moisture absorption would generate ammonium bisulfate, which is difficult to remove. If the ammonium bisulfate sticks on the surface of the catalyst, it will cause clogging in the catalyst duct. According to the research of Ueda et al. and Huang et

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al. [12, 13],  $\text{SO}_3$  reacting with escaping ammonia will increase the chances of blockage in the equipment, then worsens the problems of  $\text{SO}_3$  that were neither prominent nor serious in power plants at first. Pan and Deeming et al. [14, 15] found that when the concentration of  $\text{SO}_3$  in flue gas is above 10 ppm under high humidity, blue feathers tend to appear at the outlet of the chimney, resulting in decreased transparency of smoke exhaust. Therefore, the control of  $\text{SO}_3$  emissions is urgent, and accurate measurement of  $\text{SO}_3$  concentration in flue gas is of great significance.

In order to solve the above problem, many  $\text{SO}_3$  test methods in flue gas mainly include the Fourier transform infrared analysis test method [16], isopropanol absorption method [17], dew point meter [18], salt method [19], differential optical absorption spectroscopy (DOAS) [20], controlled condensation method (CCM) [21] and so on. Fourier transform infrared method is mainly based on the Zeeman effect correction background and atomic absorption spectroscopy principle. However, since  $\text{SO}_3$ ,  $\text{SO}_2$  and  $\text{H}_2\text{O}$  in the flue gas are close in infrared band, the test process is easily affected, and test accuracy and stability cannot meet the testing requirements of low-concentration  $\text{SO}_3$  [16]. The isopropanol absorption method uses 80% isopropanol to suppress the interference of  $\text{SO}_2$  in the flue gas [22], but the isopropanol is highly volatile at the high flue gas temperature during the sampling process. The sample gas exchanges with the isopropanol absorption fluid will result in increased absorption liquid temperature, isopropanol evaporation, and  $\text{SO}_3$  entrainment, and then introduce errors into the testing result. In addition, the contact time between  $\text{SO}_3$  and absorption liquid is short and  $\text{SO}_3$  cannot be fully absorbed, which leads to test results lower than the actual value [22]. In the process of testing, the volume fraction of water in the absorption liquid increases and part of the  $\text{SO}_2$  is dissolved in the absorption liquid, which makes the test result higher than the real value. The higher the  $\text{SO}_2$  concentration, the larger the error tends to be. Experiments and research results show that the isopropanol absorption method cannot be applied to accurately test  $\text{SO}_3$  in the flue gas [23]. Among these test methods, CCM turns out to be one of the best methods for accurate measurement of  $\text{SO}_3$  because of its high reliability and adaptability, free from  $\text{SO}_2$  and PM interference, low detection limit and precise operation requirement [24]. Maddalone et al. [25] evaluated the CCM method, and acceptable results can be obtained. CCM mainly uses the principle of physical adsorption. After the flue gas temperature decreases,  $\text{SO}_3$  condenses into acid mist, which is then collected by centrifugal force [26]. The applied range of the CCM is relatively wide. But at present there is less research on the test accuracy of the CCM, so it is urgent to compare the key influential factors of this method, which can provide reference for the accurate test of  $\text{SO}_3$  and guidance for the application of new treatment technology of  $\text{SO}_3$ .

In this paper an  $\text{SO}_3$  calibration device was set up to ensure that the  $\text{SO}_3$  sample gas can be accurately, consistently and continuously generated. The factors influencing the test accuracy of the CCM during the test sampling, including the heating temperature, the sampling flow rate, the high concentration of  $\text{SO}_2$  and the difference of  $\text{SO}_3$  concentration were analyzed to demonstrate the accuracy of the control condensation method.

## Methods

### The Principle for Detecting $\text{SO}_3$ of CCM

The sampling system of CCM consists of three main components, namely sampling gun with heating and filtering unit, condenser tube and water bath unit, and flue gas sampling device [26], as shown in Fig. 1. According to GB/T 21508-2008 [27], EPA 8A [28, 29], JIS K 0103-2005 [30] and the related literature [4, 9], the CCM mainly utilizes particle centrifugal motion principle in this research.

The main principle of CCM is that the flue gas containing  $\text{SO}_3$  passes through the sampling gun with heat tracing and the quartz filter under the action of a certain flow rate. The purpose of doing this is to make  $\text{SO}_3$  exist in a gaseous state, and remove most of the dust particles in the flue gas at the same time. After that, the flue gas enters the condenser tube in the water bath. The temperature of the condenser tube is controlled between 60-85°C, which means that the temperature of the water bath unit is also 60-85°C. The temperature of the flue gas from the sampling gun is lowered, and the  $\text{SO}_3$  in the flue gas is condensed into acid mist particles at the inlet or the front end of the condenser tube. Due to the combined effect of inertia and viscous force, the acid mist is centrifuged in the condenser tube and adsorbed on the inner wall of the condenser tube. The condenser tube is cleaned with deionized water or 80% isopropanol, and the sampling volume of the flue gas is recorded. Then the concentration of  $\text{SO}_4^{2-}$  in the cleaning solution and the absorption bottle was tested, and finally the concentration of  $\text{SO}_3$  in the flue gas was calculated. The liquid absorption bottle and the dry bottle after the condenser tube are respectively used to absorb harmful substances and moisture in the flue gas. These will protect the sampling pump and prevent pollution of the environment, with normal temperature [31] of about 2-35°C.

During the experiment,  $\text{SO}_2$  or  $\text{NO}_2$ ,  $\text{CO}_2$ , etc. in flue gas, are not easy to condense and collect on the inner wall of the condenser tube, so the content of  $\text{SO}_2$  or  $\text{NO}_2$ ,  $\text{CO}_2$ , etc. in the cleaning solution is small, so the effect on the outcome is limited. And if using deionized water for cleaning, the subsequent laboratory analysis will use barium chromate spectrophotometry for testing, and the first step of the method is to add

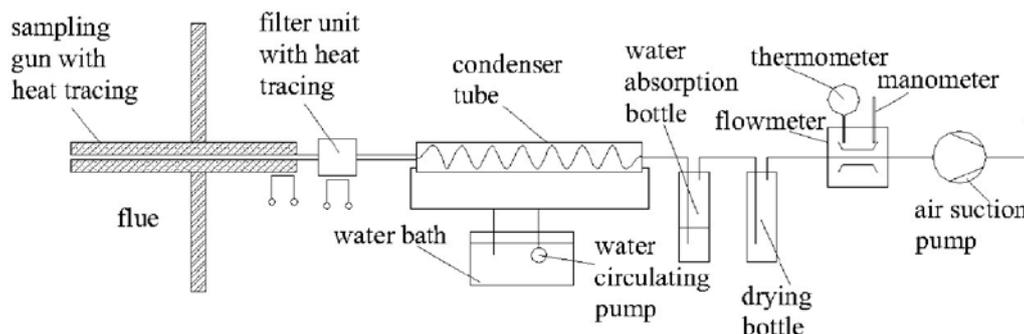


Fig. 1. SO<sub>3</sub> sampling system.

a certain amount of hydrochloric acid to remove the impact of SO<sub>2</sub>; if using 80% isopropanol for cleaning, then thorium reagent titration or thorium reagent spectrophotometry would be used for testing. In this method, 80% isopropanol can inhibit the dissolution of SO<sub>2</sub> in the cleaning solution. The main principle of laboratory analysis is that SO<sub>4</sub><sup>2-</sup> reacts with an excess of barium ions, and the remaining barium ions react with the thorium reagent to form thorium-barium complexes. Thorium-barium complexes are then determined according to the color depth of the thorium-barium complexes. The accuracy of the two laboratory analytical methods is not easily affected by several common gases found in the flue gas.

## Calibration Device

### Structure of the Calibration Device

As shown in Fig. 2, the calibration device of the SO<sub>3</sub> testing system mainly consists of SO<sub>2</sub> standard gas, mass flowmeter, SO<sub>3</sub> generator, steam generator, sampling gun, spiral condenser tube, water bath, drying bottle and flue gas sampler. The basic principle of the system is that the O<sub>2</sub> coming from the air mixes with SO<sub>2</sub> standard gas and enters into the SO<sub>3</sub> generator. Then the gas containing a concentration of SO<sub>2</sub> passes through the high-alumina catalyst to convert to SO<sub>3</sub>

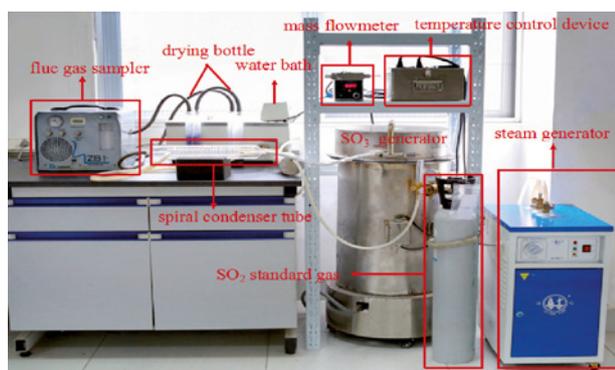


Fig. 2. Calibration device of SO<sub>3</sub> sampling system.

gas. The concentration of SO<sub>2</sub> at the inlet and outlet of the SO<sub>3</sub> generating device is measured by NGA2000 to calculate the SO<sub>3</sub> theoretical value. Then compared with the SO<sub>3</sub> value trapped in the condenser tube, and the capture efficiency is finally calculated.

The SO<sub>2</sub> standard gas is obtained through procurement, the concentration of SO<sub>2</sub> was configured before purchasing according to requirements. The catalyst used in the experiment is a catalyst for sulfuric acid production from wylton, with the main component vanadium oxide. There are two kinds of catalysts used: catalyst PH75 fitting for high temperature and PH78 fitting for low temperature. The experiment is carried out after loading 10g PH78 and 10g PH75. Although the catalyst used is selective, mainly to catalyze the SO<sub>2</sub> to SO<sub>3</sub>, it does not exclude the possibility that the main component N<sub>2</sub> in the air is catalyzed to generate NO<sub>x</sub>, and the concentration of CO changes. So the NO<sub>x</sub> and CO concentration were measured in the inlet and outlet of the generator by NGA2000. The supplementary data are shown in Table 1, and results revealed that the concentration of NO<sub>x</sub> and CO in the inlet and outlet of the generator was almost unchanged (around 0 ppm), which indicates that the transitions between CO, N<sub>2</sub> and NO<sub>2</sub> would cancel out.

For the calibration systems, the catalytic efficiency of SO<sub>2</sub> converting to SO<sub>3</sub> gas is a fixed value (about 75%). The concentration of SO<sub>3</sub> was affected by the flow rate of SO<sub>2</sub> standard gas and the SO<sub>2</sub> standard gas concentration. So, the concentration of SO<sub>3</sub> generator can meet the requirements by adjusting the flow rate of the SO<sub>2</sub> standard gas and the SO<sub>2</sub> standard gas concentration. For example, if the SO<sub>3</sub> concentration of 30 ppm is needed, when the sampling flow rate and the SO<sub>2</sub> standard gas concentration should be 7 L/min and 300 ppm, respectively, the flow rate of SO<sub>2</sub> standard is 0.7L/min. The SO<sub>2</sub> standard gas can be obtained according to requirements and analyzed by NGA2000. The flow rate of SO<sub>2</sub> standard gas is controlled by a mass flow meter, accurate to within 0.01 L/min. Furthermore, in order to ensure that the concentration of SO<sub>3</sub> is correct, the SO<sub>2</sub> concentration at the inlet and outlet of the SO<sub>3</sub> generator in each test will both be tested by NGA2000.

Table 1. Concentrations of NO<sub>x</sub> and CO at inlet and outlet of the generator.

Measuring points	Inlet of the generator	Outlet of the generator
The concentration of NO <sub>x</sub> ppm	0.1	0.1
The concentration of CO ppm	0	0

### *Sulfur Balance Determination of the Calibration Equipment*

When testing the sulfur balance in the inlet and outlet of the SO<sub>3</sub> generator, the sampling gun heating temperature was 220°C. In order to ensure the reliability of the calibration device, the flowmeters used for the measurement were separately compared and calibrated (the specific data is shown in Table 2). NGA2000 zero was adjusted and calibrated to ensure that it accurately tests the SO<sub>2</sub> concentration in inlet and outlet of the device. The analysis method of SO<sub>4</sub><sup>2-</sup> concentration in the cleaning liquid was tested and the appropriate laboratory analysis method was selected to ensure the accuracy of the amount of SO<sub>3</sub> trapped in the condenser tube. After the above steps were taken, in order to ensure that all the SO<sub>2</sub> which is missing from the generator is converted into SO<sub>3</sub>, instead of being adsorbed on the catalyst or other things in the generator, the sulfur balance of the inlet and outlet of the generator was conducted by adjusting the concentration of SO<sub>2</sub> at the inlet of the generator at about 50ppm, verified by NGA2000, and using sodium hydroxide to absorb the sulfide at the outlet of the generator including SO<sub>2</sub> and

SO<sub>3</sub>, at the same time the heating temperature of the sampling gun is 220°C, the flow rate is about 5 L/min (Table 3).

## Results and Discussion

### Model Validation

In this process, CCM were conducted to test SO<sub>3</sub>. The parameters that can be controlled include the sampling gun's heating temperature, gas flow rate and the concentration of SO<sub>3</sub>. The sampling flow rate is 4.13 m/s, the sampling gun's heating temperature is 220°C and the concentration of SO<sub>3</sub> is about 30 ppm. The simulated conditions are illustrated in Fig. 3. In order to improve the test accuracy and ensure that the method can be more adaptable, this experiment was applied to measure the influence of the sampling gun's heating temperature, sampling flow rate, SO<sub>3</sub> concentration change and high SO<sub>2</sub> concentration on capture efficiency of SO<sub>3</sub> by CCM.

### Effect of Sampling Gun's Heating Temperature on Capture Efficiency

To prevent the SO<sub>3</sub> acid mist from condensing within the sampling gun, corroding the sampling tube [32], and under-estimation of the test result, it is necessary to guarantee the SO<sub>3</sub> existing in gaseous form before the condenser tube. Namely, the heating temperature of the sampling gun must be higher than the acid dew point [33]. However, the related standards

Table 2. Calibration data for flowmeters.

Standard flowmeter L/min		0.50	1.00	2.00	3.00	5.00	7.00
Mass flow meter L/min	Flow L/min	0.50	0	2.01	2.98	4.96	6.94
	Deviation %	0.0	0.0	0.5	0.7	0.8	0.9
Sampler flow L/min	Flow L/min	---	1.01	2.02	3.02	5.04	7.03
	Deviation %	---	1.0	1.0	0.7	0.8	0.4

Note: The maximum flow deviation is 1.0%. the flowmeter using in the test can meet the requirements.

Table 3. Sulfur balance test.

SO <sub>2</sub> gas concentration ppm	Gas sampling volume DNL	Import sulfur mass theoretical value mg	Export sulfur capture value mg	Recovery %
50.0	200.3	3.58	3.56	99.5
49.8	200.5	3.57	3.52	98.7
49.6	201.6	3.57	3.59	100.6
50.2	200.8	3.60	3.65	101.4
50.0	198.5	3.54	3.48	98.2
50.3	199.7	3.59	3.56	99.3

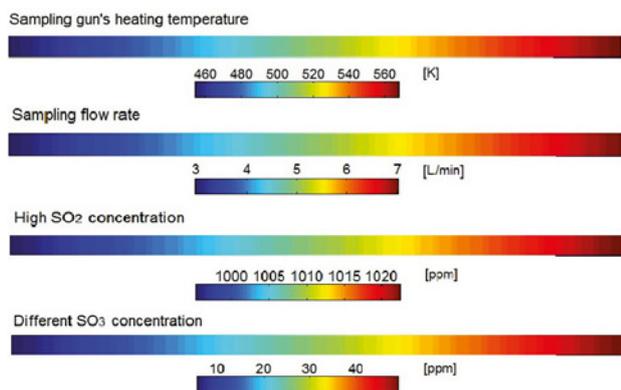


Fig. 3. Simulated conditions.

require different heating temperature, for example GB/T21508-2008 and EPA method 8A require the heating temperature above 260°C [27, 29], while DL/T 998-2016 requires a temperature above 150°C. And the standard recommendations on the heating temperature are limited in detail. On the basis of the SO<sub>3</sub> calibration system, the SO<sub>3</sub> capture efficiency was systematically tested at heating temperatures of 180°C, 220°C and 300°C respectively.

Table 4 shows the capture efficiency of the condenser tube with different sampling heating temperatures. The experimental results show that when the heating temperature was 180°C, the average capture efficiency of SO<sub>3</sub> was only 46.65%, meaning that the capture rate was very low. When the heating temperature was 220°C, the average efficiency of the condenser tube was 67.24%,

and the capture effect was significantly improved. When the tracing temperature was 300°C, the capture average efficiency of the condenser tube was 49.25%. The results come out that if the tracing temperature is too low, SO<sub>3</sub> easily reacts with ammonia, sodium oxide and other alkaline substances, or condenses in the sampling pipeline, which resulting in the loss of SO<sub>3</sub> and reduced collection efficiency. On the other hand, when the temperature is too high, the flue gas through the condenser tube cannot be quickly cooled, causing SO<sub>3</sub> to be unable to form acid mist in time and be carried out of the condenser with the flue gas, thereby reducing the collection efficiency of the condenser. Thus, the control of heating temperature is the key factor to test SO<sub>3</sub> accuracy, and from the point of the results the sampling gun of the heating temperature with 220°C is suggested.

#### Effect of Sampling Flow Rate on Capture Efficiency

The specific parameters of the condenser used in this test are shown in Table 5. The test sampling flow rates were 2.95 m/s, 4.13 m/s, 5.31 m/s and 7.08 m/s, respectively. Table 6 shows the collection efficiency of the condenser at different sample flow rates. Experimental results show that the capture efficiency increases first and then decreases, and the highest capture efficiency can be obtained when the sampling flow rate is about 4.13 m/s. The main reason probably is when the sampling velocity is relatively small, the centrifugal force generated by the condenser tube is not strong enough to drive the acid mist adhering to the

Table 4. Capture efficiency of condenser tube with different heating temperatures.

Sampling gun's heating temperature °C	Theoretical value of SO <sub>3</sub> mg	SO <sub>3</sub> amount captured in condenser tube mg	Capture efficiency %	Relative deviation %
180	32.75	15.31	46.75	0.21
	33.06	15.61	47.21	1.20
	33.11	15.23	45.99	-1.41
220	32.42	21.68	66.87	0.62
	33.15	22.72	68.54	1.93
	32.17	21.64	67.27	0.04
300	33.66	22.31	66.28	-1.43
	32.4	15.98	49.32	0.14
	33.26	16.02	48.17	-2.21
	32.92	16.55	50.27	2.07

Note: The sampling flow rate is 4.13 m/s and the concentration of SO<sub>3</sub> is about 30 ppm.

Table 5. Condenser tube size parameters.

Inner diameter mm	Screw pitch mm	Circle diameter mm	Number of turns
6	11	35	28

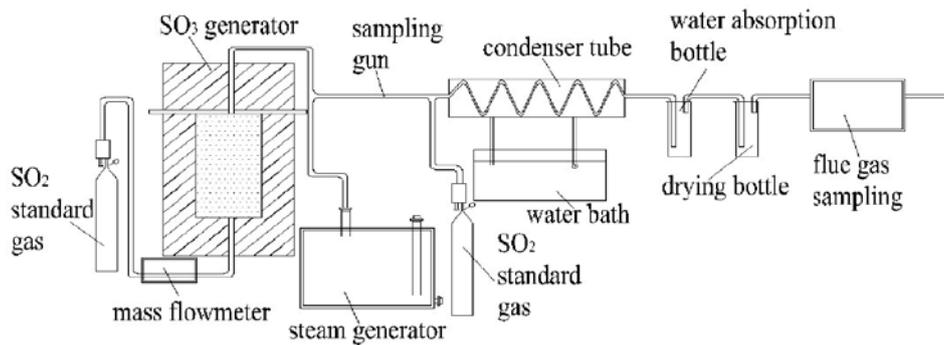


Fig. 4. Devices of the effect test with high SO<sub>2</sub> concentration.

inner wall, causing the SO<sub>3</sub> to be carried out by gas; as the flow rate increases, the centrifugal force generated becomes larger, benefiting the acid mist attached to the inner wall of the condenser tube, then the collection efficiency improves. However, if the flow rate is further increased, it means the time of acid mist particles in the condenser tube is shorter, and the acid mist is more susceptible to secondary impact and crushing, and then the probability of being carried becomes larger. Thus,

according to the analysis of the test results, the sampling flow rate with 4.13 m/s is a good choice.

#### Effect of High SO<sub>2</sub> Concentration on Capture Efficiency

In order to study the effect of high SO<sub>2</sub> concentration on capture efficiency of SO<sub>3</sub> by CCM, the high concentration of SO<sub>2</sub> gas was injected before

Table 6. Capture efficiency of condenser tube with different sampling flows.

Sampling flow rate m/s	Theoretical value of SO mg	SO <sub>3</sub> amount captured in condenser pipe mg	Capture efficiency %	Relative deviation %
2.95	35.47	13.75	38.77	-4.65
	31.98	13.4	41.90	3.07
	32.45	13.4	41.29	1.58
4.13	32.42	21.68	66.87	0.09
	32.17	21.64	67.27	0.69
	33.66	22.31	66.28	-0.79
5.31	32.93	17	51.62	-2.97
	33.42	17.68	52.90	-0.57
	35.22	19.4	55.08	3.53
7.08	33.39	14.65	43.88	1.18
	34.9	15.4	44.13	1.76
	40.87	17.2	42.08	-2.95

Note: The sampling gun's heating temperature is 220°C and the concentration of SO<sub>3</sub> is about 30 ppm.

Table 7. Data of effect test at high SO<sub>2</sub> concentrations.

The SO <sub>2</sub> concentration at reactor outlet ppm	Theoretical value of SO <sub>3</sub> mg	Test value of SO <sub>3</sub> mg	Capture efficiency %	Relative deviation %
995	31.34	20.78	66.31	-2.04
995	32.17	21.98	68.32	0.95
1023	32.65	22.34	68.42	1.09

Note: The sampling gun's heating temperature is 220°C, the sampling flow is 4.13 m/s, the concentration of SO<sub>3</sub> is about 30 ppm.

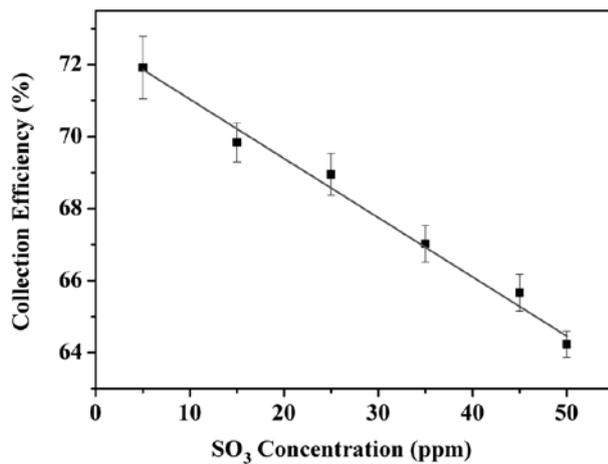


Fig. 5. Capture efficiency of condenser tube at different SO<sub>3</sub> concentrations.

the condenser tube. The schematic diagram of the experimental apparatus is shown in Fig. 4. The SO<sub>2</sub> can be slightly soluble in water and then oxidize to sulfuric acid after being sulfurous acid. If the concentration of SO<sub>3</sub> is low, the relative error of the test increases and the accuracy is affected. Therefore, the higher the SO<sub>2</sub> concentration, the more likely it is to influence SO<sub>3</sub> test

accuracy. The SO<sub>2</sub> in the flue gas of coal-fired power plants is below 1000 ppm. Thus, the SO<sub>2</sub> concentration for this experiment is controlled at about 1000 ppm.

Table 7 shows the results of effect test in high SO<sub>2</sub> concentrations. As can be seen from the comparison of Table 6, there is no obvious change in the capture efficiency of SO<sub>3</sub> when a certain amount of SO<sub>2</sub> passes through before the condensing tube. This phenomenon illustrates that a high concentration of SO<sub>2</sub> for the SO<sub>3</sub> test does not produce significant interference. To further research, since the temperature of the condenser tube is lower than the acid dew point, SO<sub>3</sub> in the flue gas begins to condense to form acid mist. However, the temperature of the condenser tube is much higher than the dew point of SO<sub>2</sub>, so SO<sub>2</sub> cannot condense and attach to the inner wall, so SO<sub>2</sub> has no effect on the collection efficiency of the SO<sub>3</sub>. Therefore, the CCM is suitable for the test of high SO<sub>2</sub> concentration section in coal-fired power plants, even if the SO<sub>2</sub> concentration is as high as 1000 ppm.

#### Effect of Different SO<sub>3</sub> Concentrations on Capture Efficiency

To further research the SO<sub>3</sub> emissions from coal-fired power plants, the range of 5 ppm - 50 ppm

Table 8. Capture efficiency of condenser tube with different SO<sub>3</sub> concentrations.

The SO <sub>3</sub> concentration ppm	Theoretical value of SO <sub>3</sub> mg	SO <sub>3</sub> value captured in condenser tube mg	Capture efficiency %	Relative deviation %	Average collection efficiency %
5	23.25	16.89	72.65	1.02	71.91
	23.47	16.93	72.13	0.31	
	25.62	18.18	70.96	-1.33	
15	27.65	19.46	70.38	0.77	69.84
	28.30	19.77	69.86	0.02	
	28.17	19.52	69.29	-0.79	
25	29.11	20.16	69.25	0.44	68.95
	29.54	20.17	68.28	-0.98	
	30.32	21.02	69.33	0.54	
35	31.70	21.31	67.22	0.30	67.02
	32.12	21.65	67.40	0.57	
	33.40	22.19	66.44	-0.87	
45	34.36	22.67	65.98	0.49	65.66
	33.87	22.04	65.07	-0.89	
	33.28	21.94	65.93	0.41	
50	35.26	22.63	64.18	-0.07	64.23
	36.44	23.28	63.89	-0.53	
	34.59	22.35	64.61	0.60	

Note: The sampling gun's heating temperature is 220°C and the sampling flow is 4.13 m/s.

Table 9. Comparison test between CCM and isopropanol absorption methods.

Test condition	The time from sampling to analysis is 24h		The time from sampling to analysis is 24h	
	Recovery of CCM %	Recovery of isopropanol absorption method %	Recovery of CCM %	Recovery of isopropanol absorption method %
10 ppm SO <sub>3</sub>	70.51	63.75	70.39	68.02
10 ppm SO <sub>3</sub> + 1000 ppm SO <sub>2</sub>	70.32	85.34	70.17	92.55
20 ppm SO <sub>3</sub>	69.23	65.62	69.46	66.78
20 ppm SO <sub>3</sub> + 1000 ppm SO <sub>2</sub>	69.83	83.58	69.32	113.60

Note: 10 ppm SO<sub>3</sub> means the concentration of SO<sub>3</sub> is 10 ppm at the outlet of the generator, 10 ppm SO<sub>3</sub> + 1000 ppm SO<sub>2</sub> means the concentration of SO<sub>3</sub> is 10 ppm, and extras adds SO<sub>3</sub> with 1000 ppm concentration.

of SO<sub>3</sub> concentration was set by adjusting the SO<sub>3</sub> concentration generated by the calibration device in this study. The effects of capture efficiency with different SO<sub>3</sub> concentrations were studied in this test.

The experimental results of the collection efficiency with different SO<sub>3</sub> concentrations are shown in Table 8, and the relationship between the collection efficiency and SO<sub>3</sub> concentration is shown in Fig. 5. Test results show that with the increase of SO<sub>3</sub> concentration, the capture efficiency of the condenser tube is reduced. In a certain concentration range, the capture efficiency shows a linear relationship with the SO<sub>3</sub> concentration. As shown in Fig. 5, the SO<sub>3</sub> concentration and capture efficiency are regressed by the formula  $y = -0.1644x + 72.678$ , and correlation index is  $R^2 = 0.9826$ , the reliability is greater than 99%. Investigating the reason of test, when the SO<sub>3</sub> concentration is changing, the formation of the SO<sub>3</sub> acid mist particle size is different, and the different concentrations of acid mist have different requirements for the attachment area of the inner wall. When the area of the condenser tube wall is constant, the SO<sub>3</sub> condensing area decreases, varying with the increase of SO<sub>3</sub> concentration, which results in a lower SO<sub>3</sub> capture efficiency. From the result, the SO<sub>3</sub> test data can be corrected by the formula between SO<sub>3</sub> concentration and capture efficiency, then the test result can close to the true SO<sub>3</sub> concentration.

#### Comparison Test between EPA Method 8 and CCM

At present, the widely used SO<sub>3</sub> test methods include CCM and isopropanol absorption. According to the above test, the best heating temperature of the sampling gun is 220°C and the suitable sampling flow rate of CCM is 4.13 m/s; referring to relevant literature [28, 29], the sampling velocity of the isopropanol absorption method was set to 1L/min, then the SO<sub>2</sub> concentration at the inlet of the generator was adjusted to make the concentration of SO<sub>3</sub> at the outlet with 10 ppm and 20 ppm respectively, and after that the test was conducted. The comparison test results are shown in Table 9.

Table 9 shows that the recovery rate of CCM and the isopropanol absorption method is reduced with the increasing of the SO<sub>3</sub> concentration. But facing the high concentration of SO<sub>2</sub>, the isopropanol absorption method is obviously vulnerable, while the CCM is not affected. Meanwhile, when the time from sampling to laboratory analysis is different, the recoveries of two methods differ significantly, and the isopropanol absorption method is significantly disturbed. With the extension of the time from sampling to analysis, the recovery of isopropanol absorption method increases, even exceeding 100%, while the recovery of CCM is not obviously changed. The main reason for the instability of the results is that although 80% isopropanol can inhibit the solubility of part SO<sub>2</sub>, there is still some interference of SO<sub>2</sub>, especially with the high concentration of SO<sub>2</sub> and the extension of the time from sampling to analysis. The amount of SO<sub>2</sub> oxidized increases, bringing about serious interference. Comparing the two methods, although the recovery of CCM is only about 70%, it is affected by SO<sub>2</sub> and the interval between sampling and analysis lesser, and the recovery rate is stable. Correcting the test data according to the above regression equation, the result can be relatively accurate and reliable.

#### Conclusions

This paper analyzes the advantages and disadvantages of Fourier transform infrared spectroscopy, isopropanol absorption method and CCM to test SO<sub>3</sub> concentration in flue gas. Then the CCM is adopted to test the SO<sub>3</sub> concentration, an SO<sub>3</sub> test accuracy verification device is set up to carry out comparative experiments that influence the test accuracy of CCM. The factors considered include the sampling gun's heating temperature, sampling flow rate, high SO<sub>2</sub> concentration and SO<sub>3</sub> concentration difference. The results show that the heat tracing temperature has an important influence on the condensation and acid fog formation of SO<sub>3</sub> in the sampling line, which affects the capture efficiency of the condenser tube. Reasonable control of the tracing temperature helps to improve the accuracy of CCM. Acid mist particles

adhered and broken in the serpentine tube were related to the flow rate in the tube, which affected the capture efficiency of the condenser tube. The specific trend was to increase first and then decrease with the increase of the flow rate, which means the reasonable sampling flow rate plays an important role to the accurate testing of SO<sub>3</sub>. The capture efficiency increases with the increase of flow rate and then decreases with the increase of flow rate. Appropriate sampling flow rate plays an important role in the measurement accuracy of SO<sub>3</sub>. The high concentration of SO<sub>2</sub> has little effect on capture efficiency, and the CCM can effectively avoid the interference of SO<sub>2</sub> on capture efficiency, suitable for the SO<sub>3</sub> testing of a coal-fired power plant. With the increase of SO<sub>3</sub> concentration, the collection efficiency of the condenser tube is reduced. In a certain range of SO<sub>3</sub> concentration, the collection efficiency showed a linear relationship with SO<sub>3</sub> concentration. The conclusion of the experiment has important reference significance for how to improve the accuracy of SO<sub>3</sub> detection.

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### Conflict of Interest

The authors declare no conflict of interest.

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