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Distribution and emission characteristics of filterable and condensable particulate matter in the flue gas emitted from an ultra-low emission coal-fired power plant

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ABSTRACT

Total particulate matter emitted from coal-fired power plants can be classified into filterable particulate matter (FPM) and condensable particulate matter (CPM). In this study, the FPM and CPM in the flue gas were sampled from a 300 MW ultra-low emission coal-fired power plant by the simultaneous sampling system, which was conducted according to ISO 23210-2009 and U.S. EPA method 202. The results show that the emission concentration of CPM rose from 5.15 mg/Nm^3 to 7.19 mg/Nm^3 at the stack when coal mixed with sludge. Almost all of the air pollutant control devices have a positive effect on the removal of CPM and FPM in the flue gas, except the influence of the selective catalytic reduction (SCR) denitration device on CPM. And the SCR denitration equipment increased the concentration of inorganic components of CPM in flue gas. The low-low temperature electrostatic precipitator had the most obvious removal effect on CPM and FPM, and the removal efficiency for FPM and CPM was more than 90% and 75% respectively. The organic fraction in CPM was mainly composed of hydrocarbons, esters, organosilicon, and other organics. In particular, the proportion of hydrocarbons and organosilicon was relatively high. In the case of co-combustion of sludge and coal, the concentration of CPM and FPM in flue gas increased as a whole, but the distribution trend of CPM and FPM was consistent with that of the non-combustion sludge and the distribution of organic components in CPM was almost the same.

1. Introduction

According to the Statistical Review of World Energy 2021 [1], coal production and consumption in China showed an upward trend in 2020, rising by 1.15 and 0.48 EJ (100 billion joules) respectively. Meanwhile, the proportion of coal-fired power generation in the power structure was 63.22%, which demonstrates that coal is still the largest single energy source for power generation in China. A large number of air pollutants are emitted from coal-fired power plants, including sulfur dioxide (SO_2), nitrogen oxide (NO_X), particulate matter (PM), and others [2]. Because these pollutants are extremely detrimental to the ecological environment and human health [3], the Chinese government published a strict emission standard for air pollutants from thermal power plants (GB 13223-2011) [4]. Some regions have also issued more stringent policies on these pollutants, which promotes the ultra-low emission transformation of coal-fired power plants [5,6]. In recent years, a lot of coal-fired power plants have reached the ultra-low emission limits of conventional air pollutants in China, i.e., PM < 5 mg/m^3, $SO_2 < 35$ mg/m^3, and NOx < 50 mg/m^3, under dry standard 6% O_2 conditions [4]. At present, scholars have gradually shifted their attention to unconventional pollutants recently, such as condensable particulate matter (CPM).

CPM, which together with filterable particulate matter (FPM) constitutes total particulate matter (TPM). CPM is a material that exists in the form of gas or vapor phase at flue gas temperature before discharge but turns into a particulate substance after dilution and cooling in the plume [7–9]. For this reason, the traditional filtration membrane can capture FPM, but not CPM directly. This has attracted the attention of the majority of scholars [10–12]. Moreover, CPM has been proven to easily absorb harmful elements and compounds due to its large specific surface area [9], making CPM one of the important components of pollutants produced in the process of coal combustion [13,14]. A great quantity of CPM is discharged into the atmosphere, which will greatly reduce the visibility of the atmosphere and increase the possibility of haze weather [9,14]. Furthermore, CPM can stay in the atmosphere for a long time, also can enter the human body through the respiratory

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system, posing a threat to human health [9,11,14,15].

One of the most widely considered issues in CPM from flue gas is its emission characteristics. The emission characteristics of CPM from different stationary sources including coal-fired power plants were studied [12,16–19]. The results demonstrated that CPM accounted for 44.2~99.6% of the $PM_{2.5}$, which was an important part of TPM. Different fuels also affected the emission characteristics of CPM [20,21]. In addition to the emission characteristics, the removal of CPM by different air pollutant control devices (APCDs) is also significant. Existing data showed that current APCDs had a different effect on removing CPM in the flue gas. The low-low temperature electrostatic precipitator (LLT-ESP) had a remarkable removal efficiency for CPM, with a CPM removal efficiency of more than 60% [22,23]. The results of different studies showed that the wet flue gas desulphurization (WFGD) system and wet electrostatic precipitator (WESP) had different removal efficiency for CPM, ranging from 20% to 65% [2,12,16,24]. In addition, some scholars illustrated that the two devices had contrary effects on CPM removal [13]. However, there is no research on the effect of selective catalytic reduction (SCR) denitration devices on CPM in flue gas, only the removal effect of SCR denitration devices on FPM. As the first step of flue gas treatment in conventional power plants, it is necessary to study the impact of SCR denitration devices on CPM. Furthermore, it was also found that CPM was composed of organic and inorganic components [12,13,16], and the components were analyzed respectively.

With the continuous growth of the social economy and the rapid growth of population, the annual organic solid waste is also growing at full speed [25,26]. Among various treatment methods of organic solid waste, incineration, as a relatively mature technology, is becoming one of the most commonly used methods to treat organic solid waste in China. However, the traditional waste incinerator faces a series of problems, such as low thermal efficiency, large emission of air pollutants, and high risk of fly ash products [19,25]. In contrast, coal-fired power plants have efficient power generation systems and centralized APCDs [27,28]. Therefore, there are increasing attempts to use co-combustion technology of organic solid waste and coal in coal-fired power plants [27,29]. As an important part of organic solid waste [30], the co-combustion technology of organic sludge and coal has been widely used in many existing coal-fired power plants in China [25,27]. However, the current research on pollutants produced by co-combustion of sludge and coal is mainly about some conventional pollutants, heavy metals, and organic toxic pollutants [25], and there is no research on the comparison of CPM produced by mixed coal combustion and pure coal combustion.

In this work, CPM and FPM samples were collected from a domestic ultra-low emission coal-fired power plant to study their emission characteristics. The removal of PM by APCDs, including the effect of the SCR denitration device, was analyzed. This study improved the emission characteristics of CPM in the flue gas process of a coal-fired power plant and obtained more complete emission data of CPM of the whole flue gas process of a coal-fired power plant. In addition, the effect of sludge co-combustion on CPM in the flue gas of a coal-fired power plant was studied and compared. The work of this paper provides some guidance for the understanding and control of CPM.

2. Materials and methods

2.1. Facility and sampling sites

In this study, all the samples of PM were collected from a 300 MW coal-fired unit, which was reformed with ultra-low emission. The main flue gas purification devices consist of an SCR denitration device, an LLT-ESP (which combined with a traditional temperature electrostatic precipitator (ESP) and a non-leakage media gas-gas exchanger (MGGH)), a WFGD system, and a WESP. The overall purification process of the flue gas and sampling sites are shown in Fig. 1. And the sampling sites were selected on the basis of China GB/T 16157-1996 [31], which

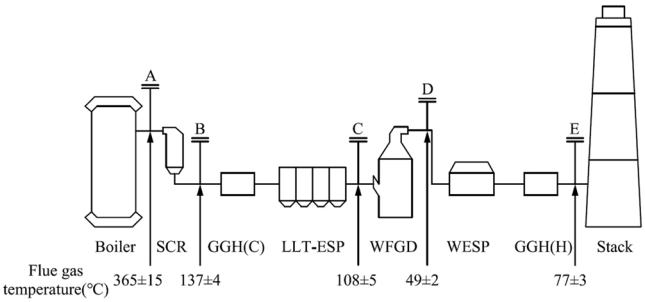

Fig. 1. Schematic showing the sampling sites and their flue gas temperature.

were arranged at the SCR denitration device inlet (site A), the LLT-ESP inlet (site B), the WFGD system inlet (site C), the WESP inlet (site D) and the Stack (site E). In addition, during sample collection, the load of coal-fired unit was maintained at about 280 MW. In this study, the PM samples of two kinds of fuels were collected, in which the data of the whole flue gas process was collected for bituminous coal combustion (site A, B, C, D and E), and only the emission data of the chimney was collected for coal mixed with sludge combustion (site E). The results of proximate and ultimate analyses of the bituminous coal and blended coal are listed in Table 1.

2.2. Sampling equipment and methods

Fig. 2 shows the simultaneous sampling system for collecting FPM and CPM from flue gas, which was conducted according to ISO 23210-2009 [32] and U.S. EPA method 202 [33]. The system consists of two parts, one is used to collect FPM in flue gas, and the other is to collect CPM from remaining flue gas. First, the flue gas entered the stainless-steel sampling tube through the isokinetic nozzles. Second, a dekati PM_{10} impactor was used to collect FPM in the flue gas flow, and FPM could be divided into four categories: ≥ 10 μm, 10–2.5 μm, 2.5–1 μm, < 1 μm. Before the remaining flue gas entered the CPM collection system, heat tracing should be carried out in the whole process, and the temperature of the whole process should be maintained at 120–130 ℃. Then the flue gas passed through the Dimroth condenser, the short stem impactor, the long stem impactor and the CPM filter in turn. The two stem impactors were placed in an ice water bath. A stack dust automatic detector was connected at the end of the system, and the built-in air pump could provide draft force for the whole system. Leak detection was performed before each sample collection. And the sampling flow rate was set to 10 L/min. In order to ensure the reliability of data, 2–3 samples were collected at each sampling site, and the collection time of each sample is 90 min but the sample collection time of Site A and Site B was 15 min. Due to the high concentration FPM in the flue gas at these two sites, the sampling time was too long, which is easy to lead to inaccurate measurement. And the sample collection also included a group of blank samples.

2.3. Analytical procedure for samples

There are two kinds of films used to collect FPM in the dekati PM_{10} impactor: 47 mm polyester filter is used to collect particles less than 1 μm, and particles of other sizes are collected with a special 25 mm tin foil film. The 25 mm tin foil films need to be coated with a layer of turpentine solution (dissolving CCl_4, m/m, 1:20). And all films need to be dried in an oven at 130 ℃ for 2 h, and then put into a drying dish containing discolored silica gel at room temperature for 2 h. Weigh and record after the mass of the films is stable. After sampling, all films also need to be conditioned and weighed by the same balance.

The analytical procedure of CPM is based on U.S. EPA Method 202 [33]. After sampling, purged the sampling devices with N_2 immediately. Then, the CPM collecting devices were washed three times each with

Table 1
Details of the Coal's parameters.

Sample	Proximate analyses (%)				Ultimate analyses (%)					Q_{net}
	M_{ad}	A_{ad}	V_{ad}	FC_{ad}	C_{ad}	H_{ad}	N_{ad}	$S_{t,ad}$	O_{ad}	(MJ/kg)
Bituminous Coal	2.05	8.02	29.91	60.02	74.50	3.04	1.01	0.52	10.86	27.71
Blended Coal	2.11	15.19	28.01	54.69	68.18	2.80	0.96	0.60	10.16	25.33

[a]Note: ad = air dry basis, M = moisture content, A = ash content, V = volatile content, FC = fixed carbon, S_t = total sulfur, and Q_{net} = net calorific value.

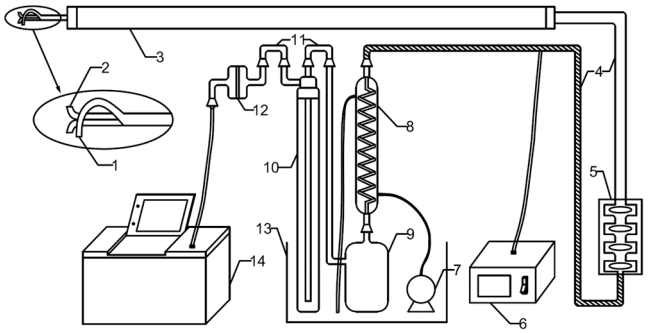

Fig. 2. Schematic of the simultaneous sampling system of FPM and CPM in flue gas. 1, isokinetic nozzles; 2, pitot tube; 3, stainless steel sampling tube; 4, polytetrafluoroethylene tube (with impactor heater and heater controller); 5, Dekati PM_{10} impactor (with impactor heater and heater controller); 6, temperature controller (with temperature sensor and heating function); 7, recirculation pump; 8, Dimroth condenser; 9, short stem impactor; 10, long stem impactor; 11, connector; 12, CPM filter; 13, water bath; 14, ZR-7100 portable dust direct reading instrument.

deionized water, acetone and n-hexane in turn. Collect deionized water rinses, organic solvent rinses and CPM filter in separate clean containers. After returning to the laboratory, the CPM filter was extracted in an ultrasound with deionized water, acetone and n-hexane three times each. Put the aqueous extracts and organic solvent extracts into corresponding rinses respectively. Then the water rinses were extracted three times with 50 ml n-hexane in a separating funnel, and the organic phase was added into the organic solvent rinses. The inorganic (water rinses) and organic (organic solvent rinses) fractions were evaporated to about 10 ml, dried at room temperature (20–25 °C), and then put into a drying dish containing discolored silica gel until the mass no longer changed, then weighed and recorded. Field blanks were also measured using Method 202 [33].

After the mass analysis, the organic extract of CPM samples was ultrasonically dissolved in n-hexane to 10 ml and then stored for later use. When gas chromatograph/ mass spectrometer (GC/MS) was used to measure the organic fractions of CPM, 1 ml of n-hexane solution was taken for measurement. The specific setting parameters of GC/MS referred to our lab's previous paper [2,16].

3. Results and discussion

3.1. Distribution characteristic of PM

The concentrations of FPM and CPM were based on the average value of continuous samples, and have been converted into standard concentrations at 6% oxygen, dry standard conditions, according to GB/T 16157-1996 [31] and GB 13223-2011 [4] before further analysis. The mass concentrations of PM at the sampling sites were listed in Table 2. Fig. 3 better shows the specific concentration distribution of FPM and CPM, and it also directly shows that APCDs had a positive effect on the reduction of PM, but SCR denitration device had the opposite effect on the removal of CPM. The reason will be analyzed in the next section. The emission concentration of TPM in flue gas at different sites ranged from 6.97 mg/Nm^3 from 381.15 mg/Nm^3. Before the LLT-ESP, the concentrations of TPM exceeded 350 mg/Nm^3, and the concentrations of FPM were much higher than those of CPM. After this device, the concentrations of TPM dropped sharply to below 20 mg/Nm^3. The proportion of CPM and FPM had also changed, but CPM still occupied a dominant position. This result is also consistent with previous studies [13,18,20].

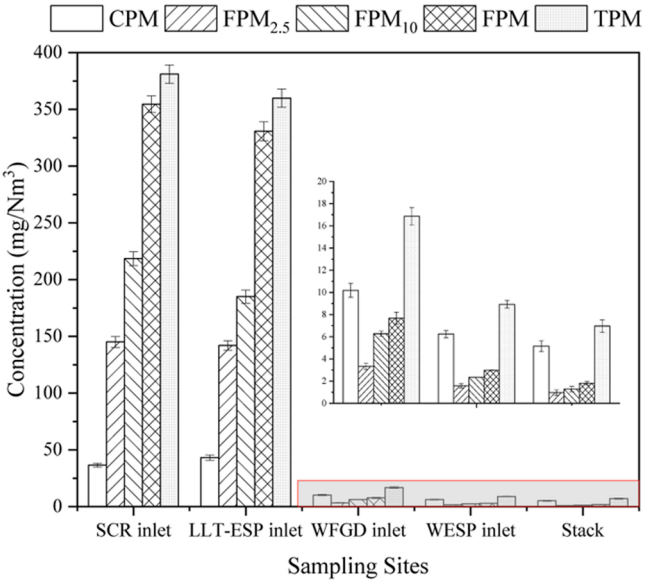

Fig. 3. The average mass concentrations of PM at the sampling sites.

Table 2
The average concentrations of PM at the sampling sites(mg/Nm^3).

Sampling sites	CPM			FPM			TPM
	Organic fraction	Inorganic fraction	CPM	$FPM_{2.5}$	FPM_{10}	FPM[a]	
SCR inlet	21.53	15.02	36.55	145.09	218.54	354.60	391.15
LLT-ESP inlet	19.77	23.41	43.18	142.02	185.03	330.77	373.96
WFGD inlet	6.40	3.79	10.19	3.33	6.27	7.67	17.86
WESP inlet	3.97	2.28	6.24	1.58	2.35	2.98	9.23
Stack	3.49	1.66	5.15	0.96	1.28	1.82	6.97
Stack-mix	4.57	2.62	7.19	1.07	1.45	1.94	9.14

[a] FPM: Filterable particles of all particle sizes, contains $FPM_{2.5}$ and FPM_{10}, but not the sum of the two.

This is because LLT-ESP has a very significant removal effect on FPM, but its removal effect on CPM is not so obvious [22,23]. On the one hand, with the decrease of flue gas temperature, CPM will be adsorbed on fly ash and removed by electrostatic precipitator. On the other hand, some organic parts of CPM might be destroyed by the high voltage of electrostatic precipitator. Therefore, the removal efficiency of CPM components with low boiling point or difficult ionization is quite low [22].

$PM_{2.5}$ is ultra-fine particle matter with aerodynamic diameter less than 2.5 μm, which consists of all CPM and part of FPM. Fig. 4 illustrated the distribution of $FPM_{2.5}$ and CPM in $PM_{2.5}$. The general downward trend in Fig. 4(a) shows that APCDs had positive removal effect on $PM_{2.5}$. From the Fig. 4(b), we can see that before the flue gas passed through LLT-ESP, $FPM_{2.5}$ was the main component in $PM_{2.5}$ of flue gas, accounting for more than 75%. After LLT-ESP, the concentration of $FPM_{2.5}$ dropped sharply, with the result that CPM accounted for more than 70% in $PM_{2.5}$ of flue gas. This result is also consistent with the different particles removal effect of LLT-ESP mentioned above.

The removal efficiencies of several PM by different devices were calculated by Formula 1, in which $\eta_{equipment\ PM}$ is removal efficiency of CPM and FPM by different equipment, $C_{inletPM}$ and $C_{outletPM}$ are the concentrations of PM in the flue gas upstream and downstream of different devices, respectively [22]. The removal efficiencies for CPM, $FPM_{2.5}$, FPM_{10}, TFPM and TPM of different devices are shown in Fig. 5.

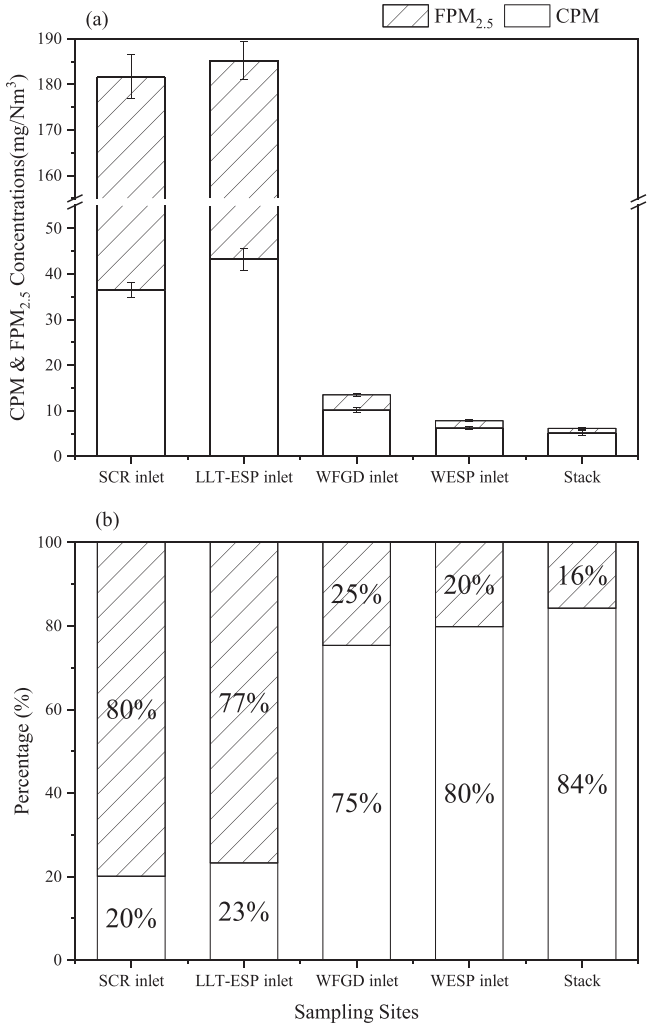

Fig. 4. Distribution of $FPM_{2.5}$ and CPM in $PM_{2.5}$. (a) Mass concentration distribution of $FPM_{2.5}$ and CPM in $PM_{2.5}$. (b) Mass percentage distribution of $FPM_{2.5}$ and CPM in $PM_{2.5}$.

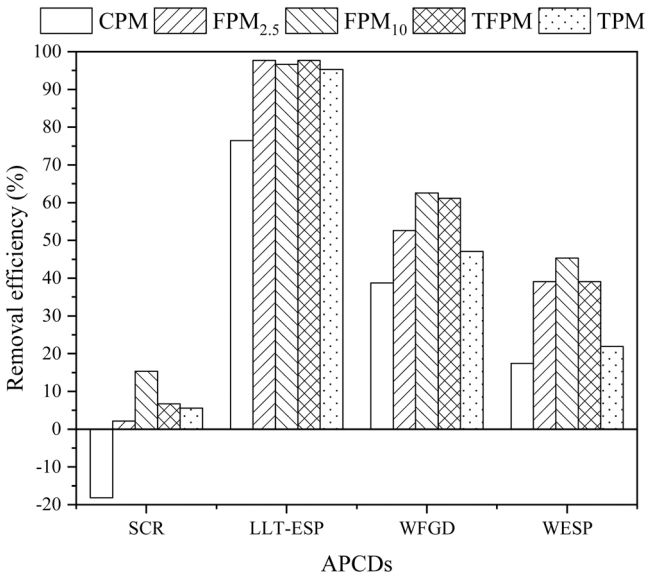

Fig. 5. The removal efficiency of APCDs for FPM and CPM.

It can be seen directly from the Fig. 5 that most APCDs were effective in removing PM, and the removal efficiency generally decreased with the flue gas flow, except that the flue gas passes through the SCR denitration device. And it can be concluded that SCR denitration device had a negative effect on the removal of CPM. The removal effect of LLT-ESP was the most significant among several devices, and the removal efficiency for $FPM_{2.5}$ and CPM was more than 90% and 75% respectively. After that device, the downward trend might be due to the fact that the original content in the flue gas was not very high. Besides, WFGD system was more effective than WESP in the removal of CPM. The reason of such result is that, WFGD system can effectively remove part of the inorganic components of CPM in flue gas, such as SO_3 and HCl [13]. Another reason could be that the temperature of flue gas would drop by about 60 °C from the inlet of WFGD system to the inlet of WESP. However, the temperature of flue gas would rise from the inlet of WESP to the stack.

$$\eta_{equipment\text{-}PM} = \frac{C_{inlet\text{-}PM} - C_{outlet\text{-}PM}}{C_{inlet\text{-}PM}} \times 100\% \quad (1)$$

3.2. Distribution of organic compounds of CPM

In general, CPM is composed of organic and inorganic components, and Fig. 6 displayed the distribution of organic and inorganic fractions of CPM at different sampling sites, including mass concentration distribution (Fig. 6(a)) and percentage distribution (Fig. 6(b)). Along the flue gas flow, the concentrations of organic fraction at different sampling sites were 21.53, 19.77, 6.40, 3.97 and 3.49 mg/Nm^3, which accounted for 59%, 46%, 63%, 64% and 68% of the total CPM, respectively. In this study, the organic component in CPM accounted for more than 50% at most sampling sites, which was higher than inorganic component in CPM. However, the opposite situation existed. For example, the proportion of inorganic components at the inlet of LLT-ESP was higher than that of organic components in CPM. This phenomenon is consistent with the many research results in recent years [13,16,22,23]. Nevertheless, some researchers' conclusions were not completely consistent with the above results [20,34]. In addition to the difference of emission sources, the influence of coal types, combustion and operating conditions, and the application of different APCDs all would cause the change of component proportion in CPM. Furthermore, Fig. 6 displayed that SCR denitration device significantly increased the content of inorganic components in CPM, resulting in the proportion of inorganic components also increased and exceeded that of organic components. According to the previous research results [35], in order to improve NO_x

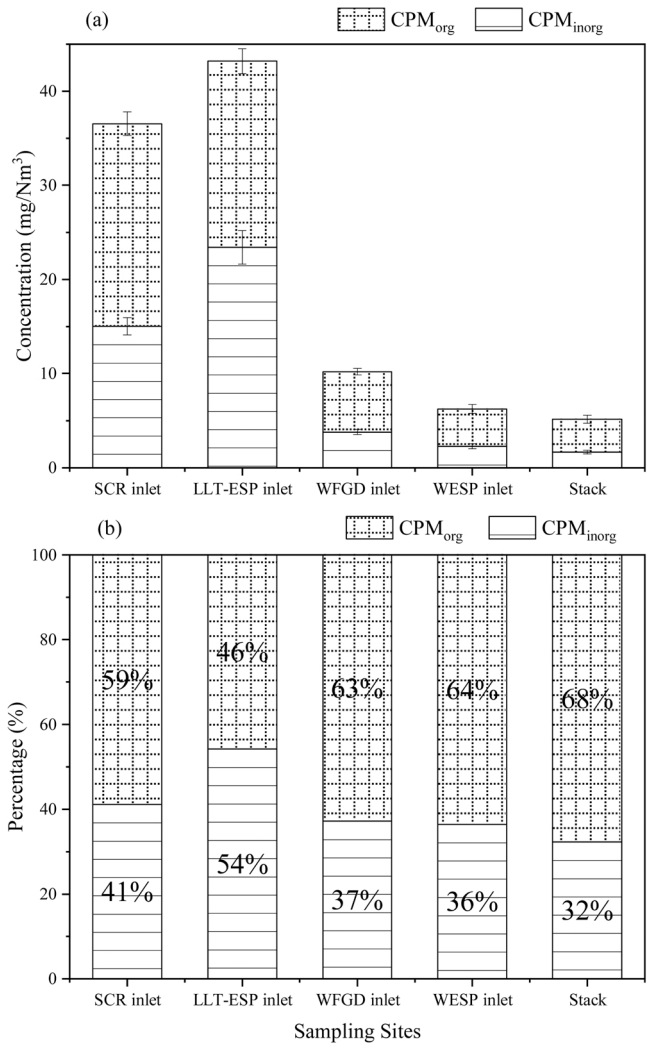

Fig. 6. Distribution of organic and inorganic fraction in CPM. (a) Mass concentration distribution of organic and inorganic fraction in CPM. (b) Mass percentage distribution of organic and inorganic fraction in CPM.

removal rate, excessive ammonia would be injected. Part of SO_2 could be oxidized to SO_3 by SCR catalyst and further reacted with excessive ammonia to produce $(NH_4)_2SO_4$ or $(NH_4)HSO_4$, which would lead to a significant increase in $PM_{2.5}$ concentration. In addition, it was reported that the mass concentration of PM_1 increased by 52.11% after SCR denitration device, and they then proved that the concentrations of Na^+, NH_4^+, Cl^-, and SO_4^{2-} in PM_1 significantly increased after SCR denitration device [3]. Although previous research results were about FPM, it was also applicable to apply this conclusion to CPM.

It was concluded from the previous section that organic compounds account for a large proportion of CPM. The organic compounds in the CPM could be detected by GC/MS. However, it's very hard to quantify the concentrations of all organic components in CPM by GC/MS. The main reason was that the number of organic compounds in CPM was very large, and the composition of organic compounds was not very clear. Besides, it was time-consuming, laborious and impractical to quantify a single organic matter in CPM. In recent years, GC/MS has also been used to detect some typical organic compounds in CPM, such as n-alkanes, phthalates and polycyclic aromatic hydrocarbons [2,7,36]. In this study, GC/MS was only used to do a semi-quantitative analysis of organic components in CPM.

The test reports not only listed the name of hundreds of detected organic substances, but also included the retention time, CAS Number, molecular formula, and area proportion of each substance. There were many types of organic substances in CPM, which could be roughly divided into the following four categories: hydrocarbons, esters, organosilicon and other organics. Other organics mainly included heteroatoms (contained heteroatoms except C, H, O, Si), aldehydes, ketones, ethers, alcohols and other complex macromolecular organic compounds. In order to visually displayed the differences of the proportions of various organic compounds, the peak areas of the same type of organic substances were combined to obtain data and plotted the proportion results as shown in Fig. 7. The data in Fig. 7 vividly illustrated that hydrocarbons, esters and organosilicon accounted for more than 90%. In the whole flue gas process, the proportion of esters showed a downward trend, but the proportion of hydrocarbons showed an upward trend in the flue gas process after SCR denitration device. Recently, some scholars had studied the organic compounds in CPM in coal-fired power plants, their results indicated that alkanes were the main organic compounds in CPM [16,23]. It is worth mentioning that the average proportion of organosilicon in the CPM accounting for a large proportion at different sites. The existence of organosilicon in flue gas was also found in previous research results [13,37], and it was proved that the main component was siloxane. Studies have shown that siloxane can damage the liver and fertility, and it has even been proved to have potential carcinogenic effects [38,39]. Therefore, the organosilicon in the CPM emitted from coal-fired flue gas deserves attention. What we can know is that the different types of coal, power plant conditions and the differences in sampling and analysis methods will lead to different results. It can be known from the existing research results that the accurate qualitative and quantitative analysis of the characteristic organic matter with high content and high toxicity in CPM is a great challenge to the deep purification of CPM.

3.3. *Effect of the coal-fired coupled sludge power generation technology on PM emission characteristics*

Recently, more and more attention has been paid to the coal-fired coupled sludge power generation technology, which is conducive to the reduction, stabilization, harmless and resource utilization of municipal sludge [40,41]. This study also carried out experimental research on the PM emission characteristics of coal-fired coupled with sludge power generation. The moisture content in sludge is 56%, and the sludge blending ratio is 10%.

The concentrations of various PM in stack of two different fuels were

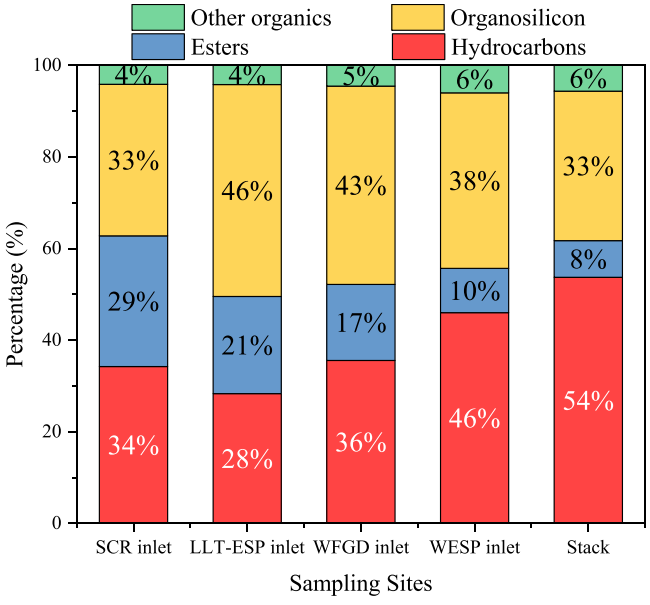

Fig. 7. Distribution of organic fraction in CPM.

listed in the Table 2 and the Fig. 8 showed the difference more intuitively. It could be found from Fig. 8 that the sludge mixed with coal combustion would not affect the overall distribution of particles, but it would lead to an increase in the overall emission level. The concentration of CPM increased by 39.56%, but the increase of FPM concentration was not so obvious, only 6.59%. The proximate analysis results of bituminous coal and blended coal during the test were shown in Table 1, from which it could be seen that the proportion of ash in the blended coal would increase and the proportion of fixed carbon would decrease when the sludge was mixed, resulting in the decrease of calorific value. This result was in line with the previous research [42,43], but the calorific value of oily sludge mixed with coal would be increased [44,45]. In this study, oily sludge was not used, so the calorific value of fuel decreased. Besides, the high ash content of blended coal was easy to cause ash deposition and coking, which had a really negative impact on the combustion condition and heat transfer of boiler. Thus, the decrease of fuel calorific value and the increase of ash content would lead to insufficient combustion and more particles were produced.

The distribution in $PM_{2.5}$ and CPM of two different fuels was shown in Fig. 9. The distribution of CPM and $FPM_{2.5}$ in $PM_{2.5}$ of the two fuels are similar, but the proportion of CPM was larger when sludge was mixed with coal. As mentioned above, the combustion temperature would decrease when the sludge was mixed and the flue gas temperature would decrease when the combustion temperature decreased. The decrease of flue gas temperature would also lead to the formation of CPM [22,23], so the concentration of CPM would increase obviously when the sludge was mixed with combustion. This was why the proportion of CPM in $PM_{2.5}$ increased. Another information could be drawn from the Fig. 9 was that the distribution of organic and inorganic components in CPM of the two fuels was similar, too. However, the proportion of inorganic components in CPM increased slightly when coal was mixed with sludge. This might be attributed to the high ash content of the blended coal. Some experiments have been carried out to study the formation and distribution characteristics of CPM produced by three kinds of coal combustion in one-dimensional furnace in the laboratory [21]. It is found that the CPM of flue gas emitted from coal-fired power plant, and the coal with high ash content would make the proportion of inorganic components higher. This phenomenon is consistent with the results of this paper.

Fig. 10 showed that the semi-quantitative analysis results of the organic fraction of CPM from two different fuels. There was no significant difference in the overall distribution of organic components

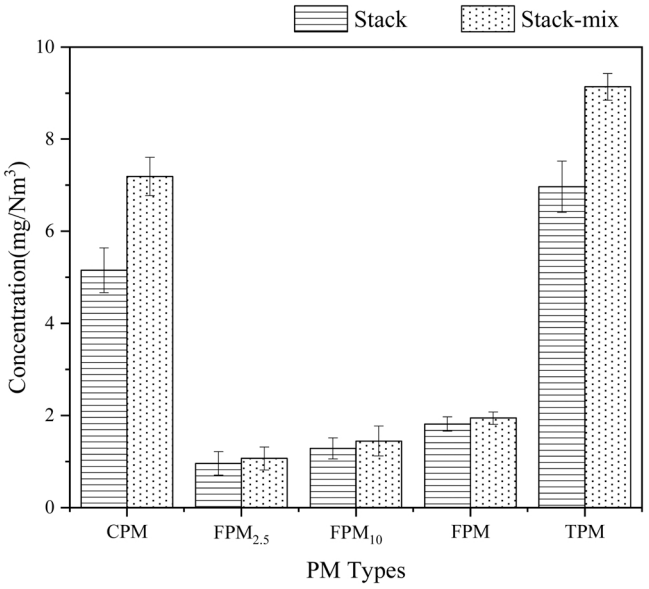

Fig. 8. The average mass concentrations of PM of different fuels.

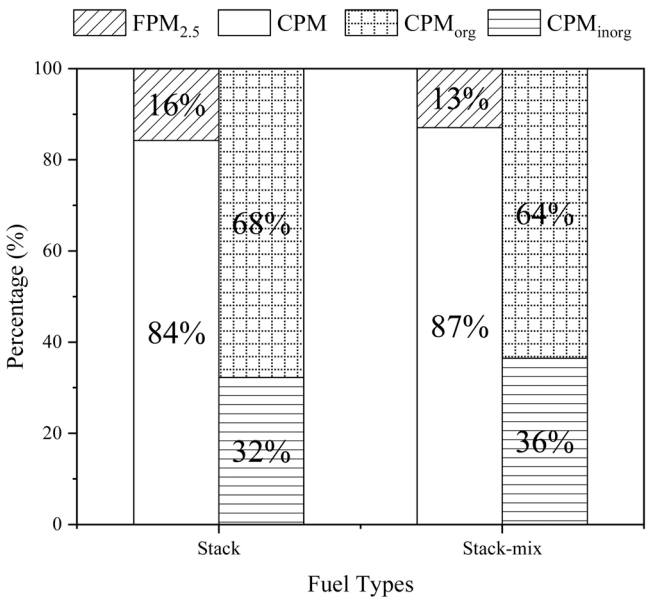

Fig. 9. Mass percentage distribution of components in $PM_{2.5}$ and CPM of different fuels.

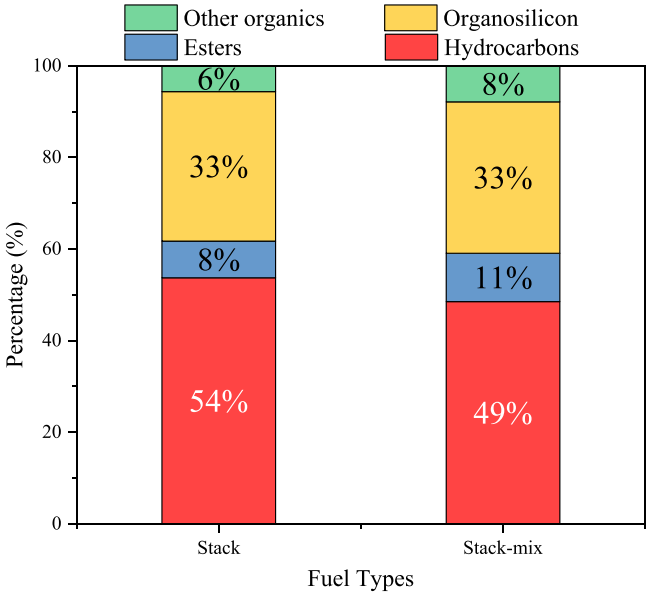

Fig. 10. Distribution of organic fraction in CPM of different fuels.

between the two fuels. The most abundant compounds in CPM of this two fuels was hydrocarbons, followed by organosilicon. However, it can be seen that the proportion of esters and other organic matter increased slightly when coal was mixed with sludge. It was also found in laboratory experiments that the organic components in CPM produced by different kinds of coal combustion were different [21].

4. Conclusions

CPM and FPM in flue gas from a 300 MW ultra-low emission coal-fired power plant had been sampled and analyzed. Five sampling sites are selected in this work, which are the inlet of the SCR denitration device, LLT-ESP, WFGD system, WESP, and at the stack. In particular, the PM samples of bituminous coal combustion and coal mixed with sludge combustion were collected at the stack. The results show that the emission concentration of CPM rose from 5.15 mg/Nm^3 to 7.19 mg/

Nm^3 at the stack when coal mixed with sludge. And $FPM_{2.5}$ accounted for a large proportion of $PM_{2.5}$ before the flue gas passed through the LLT-ESP, but after it, CPM accounted for a larger proportion. LLT-ESP has the most significant removal effect on FPM and CPM in different APCDs. However, SCR denitration device would increase the content of inorganic components in CPM, resulting in the increase of CPM concentration in flue gas. This was also the reason why no unit accounts for a large proportion of CPM at the inlet of LLT-ESP. The organic components in CPM were mainly hydrocarbons, esters, and organosilicon, among which organosilicon needed further study. In the case of co-combustion of sludge and coal, the distribution trend of CPM and FPM was consistent with that of the non-combustion sludge, but the concentrations of CPM and FPM in flue gas increased from 5.15 mg/Nm^3 and 6.97 mg/Nm^3 to 7.19 mg/Nm^3 and 9.14 mg/Nm^3, respectively, which also led to an increase in the proportion of CPM in $FPM_{2.5}$ and the proportion of inorganic fractions in CPM. At the same time, there was no significant difference in the distribution of organic components in CPM of the two different fuels.

CRediT authorship contribution statement

Zhenyao Xu: Conceptualization, Formal analysis, Data curation, Writing – original draft. **Yujia Wu:** Reviewing and Editing. **Siqi Liu:** Investigation. **Minghui Tang:** Methodology. **Shengyong Lu:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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