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RESEARCH ARTICLE

The effect of air pollution control devices in coal-fired power plants on the removal of condensable and filterable particulate matter

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Abstract
Total particulate matter (TPM), including condensable and filterable particulate matter (CPM and FPM), is one of the pollutants that need to be controlled in the coal combustion process. In this study, CPM and FPM were sampled from sixteen coal-fired power units and two coal-fired industrial units. The removal effects of air pollution control devices equipped in the units on the migration and emission of particles were investigated by analyzing samples from inlets and outlets of apparatus. The average removal efficiency of TPM by dry-type dust removal equipment, wet flue gas desulfurization devices, and wet-type precipitators reached 98.57 ± 0.90%, 44.89 ± 15.01%, and 28.45 ± 7.78%, respectively. The removal efficiency of dry-type dust removal equipment and wet-type precipitators to TPM is mainly determined by the purification effect of FPM and CPM, respectively, and both types of particles contribute to the removal efficiency of desulfurization systems to total TPM. The concentrations of CPM (12.01 ± 5.64 mg/Nm^3) and FPM (1.95 ± 0.86 mg/Nm^3) emitted from ultra-low emission units were the lowest, and CPM is the dominant particle, especially the higher proportion of organic components in CPM.

Keywords Coal combustion process · CPM · FPM · APCDs · Removal efficiency · Migration and emission

Introduction

Coal combustion, especially coal-fired power plants is the most significant source of air pollutants in the atmosphere, which emits large amounts of particulate matter (PM) except NO_x and SO_x (Ouyang et al. 2021, Yan et al. 2016). Total PM (TPM) emitted from coal combustion can be categorized as filterable PM (FPM) and condensable PM (CPM) according to its physical and chemical properties, which not only causes serious haze phenomena but also enters the human body through the respiratory tract and causes health hazards (Anderson et al. 2011; Brook et al. 2010). Despite the continuous improvement of the energy mix, the proportion of coal in China's energy structure is still as high as 57% in 2020 (BP 2021), and the energy structure dominated by coal will not change substantially in the short term. As the world's largest consumer of coal, coal-fired power generation accounts for more than 50% of total coal consumption (Hsu et al. 2020; Lin et al. 2018; Wang et al. 2020). In addition, coal-fired industrial plants also contribute a significant amount of coal consumption (Gao et al. 2021; Sun et al. 2021). Therefore, exploring the removal effect of particulate in coal-fired sources which consume most of the coal bears practical significance, and this could bring prominent environmental and economic benefits (Wang et al. 2016).

At present, tremendous applied research has focused on the emission concentration of FPM and CPM from coal-fired power plants (Li et al. 2017a; Morino et al. 2018; Yang et al. 2018, 2014; Zheng et al. 2018). Chen et al. (2021) performed sampling at a coal-fired power plant in Taiwan and found the concentrations of FPM and CPM were 0.9 ± 0.006 mg/Nm^3 and 37.4 ± 6.3 mg/Nm^3. Ruan et al. (2019) found the final PM_{10} (aerodynamic diameter ≤ 10 μm) emission of the 660 MW unit with ultralow pollutants emission was 2.04 mg/Nm^3. The emission concentration of CPM and FPM in the stack from an ultralow-emission coal-fired power plant was 1.6 mg/Nm^3 and 7.9 mg/Nm^3 in Li et al.'s (2017b) research. Many field data in recent years show that the concentrations of FPM emitted from coal-fired power plants appear to meet the ultra-low emission limits (< 5 mg/Nm^3).

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However, due to the limited removal effect of air pollution control devices (APCDs) on CPM, the emission concentration of TPM is much higher than 5 mg/Nm^3. The research findings provide valuable guidance for effectively improving the TPM removal efficiency by selectively removing particles with different fractions.

The air pollution control devices (APCDs) of coal-fired power or industrial plants almost all consist of denitration devices, dry-type dust removal equipment, desulfurization systems, and wet-type dust removal equipment, which are applied to purify pollutants such as NO_x, SO_x, and PM in the coal-fired flue gas (Dai et al. 2019; Wu et al. 2021a). Some field tests on the dust removal function of a single device were completed in the previous study (Qi et al. 2017; Song et al. 2020; Wu et al. 2018, 2021b). The decontamination of APCDs may result in the interconversion or removal of FPM and CPM in the flue gas; however, the effects of such APCDs on FPM with different particle sizes and CPM with different components migrations and emissions have been studied little, and are poorly understood. Thus, research on the removal effects of APCDs on the behaviors of particle and TPM emissions from typical coal-fired sources bears practical significance. The conclusions are expected to assist managers of power or industrial plants in selecting appropriate methods for controlling TPM emissions from coal combustion.

In this work, we conducted a field sampling of FPM and CPM from thirteen ultra-low emission coal-fired power units, three non-ultra-low emission coal-fired power units, and two coal-fired industrial units. The existing representative APCDs installed in the typical coal-fired sources, such as dry-type dust removal equipment, wet flue gas desulfurization devices, and wet-type precipitators, the removal effect of the devices on FPM and CPM was explored. In addition, the migration process of TPM in coal-fired flue gas purification systems and the emission concentration of TPM from different types of coal-fired sources were studied.

Experimental section

Facility and sampling sites

Thirteen ultra-low emission coal-fired power units (e.g., P1, P2, P3, P4, P5, P6, P7, P8, P10, P11, P12, P13, and P14), three non-ultra-low emission coal-fired power units (e.g., P9, P15, and P16), and two coal-fired industrial units (e.g., I1 and I2) were selected to make a comprehensive analysis of the removal efficiency of various existing APCDs for FPM and CPM, the migration, distribution, and emission of different types of particle concentrations during the flue gas purification process. Table 1 and Table S1 show the specific and detailed information of all tested coal-fired units and the categories of coal burned in boilers.

Table 1 A detailed description of tested coal-fired sources

Sources	Coal-fired power units									Coal-fired industrial units	
	P1	P2	P3	P4	P5	P6	P7	P8	P9	I1	I2
Rated capacities (MW)	300	1000	1000	1000	350	600	1030	660	660	75 t/h	130 t/h
Operating loads (MW)	300	1000	500/1000	1000	350	600	1030	660	660	52.5 t/h	130 t/h
M_{ad} (%)	2.11		3.77		5.67		6.53	2.75	3.50	6.00	7.34
A_{ad} (%)	15.19		18.23		23.39		22.68	15.81	18.26	35.89	17.82
V_{ad} (%)	28.01		27.06		17.76		20.28	31.50	27.20	15.67	28.70
FC_{ad} (%)	54.69		50.94		53.18		50.51	49.94	51.04	42.44	46.14
S_{ad} (%)	0.60		0.51		1.34		0.50	0.84	0.44	0.45	0.60
$Q_{net,v,ad}$ (MJ/kg)	25.43		22.49		21.25		22.67	22.73	22.59	23.48	19.43
Coal species	Bituminite		Blended coal		Blended coal		Bituminite	Bituminite	Bituminite	Bituminite	Blended coal
APCDs	SCR; LLT-ESP; WFGD; WESP				SCR; ESP; WFGD; WESP		SCR; REEP; WFGD; WESP	SCR; LLT-ESP; WFGD; WESP	SCR; ESP; WFGD	SNCR; EFIP; AFGD; UD	SNCR; BF; WFGD; WESP
Ultra-low emission	√				√		√	√	×	√	√

Note: *ad* air dry basis, *M* moisture content, *A* ash content, *V* volatile content, *S* sulfur content, Q_{net} net calorific value

All coal-fired power units are equipped with a selective catalytic reduction (SCR) denitration device, an electrostatic precipitator (ESP), and a wet flue gas desulfurization (WFGD) system for NO_x, PM, and SO_2 removal. However, in order to meet the requirements of ultra-low emission indicators, ESP has been modified to low-low temperature ESP (LLT-ESP) in units P1 ~ P4, P8, and P10 ~ P14, and rotating electrodetype ESP (REEP) in unit P7. Furthermore, a wet ESP (WESP) was installed before the stack in all ultra-low emission coal-fired power units to deep remove fine particles, organics, and other pollutants, while not installed in non-ultra-low emission coal-fired power units. The two coal-fired industrial units I1 and I2 are installed with a selective non-catalytic reduction (SNCR) denitration device, an electrostatic-fabric integrated precipitator (EFIP), the combined system of an ammonia flue gas desulfurization device (AFGD), and an ultrasonic dedusting (UD) and an SNCR denitration device, a bag filter (BF), a WFGD system, and a WESP to remove NO_x, PM, and SO_2, respectively. Table S2 detailedly lists the sampling sites of all coal-fired units and the sampling time of all FPM and CPM samples. All coal-fired units maintained a stable operation load and the properties of the feeding coal were steady during sampling. The APCDs of the coal-fired units were operated immobile during the sampling process. During these studies, the other parameters were kept constant unless otherwise specified, and the tests were all conducted under stable conditions.

Sampling equipment and methods

Fig. S1 shows the schematic of the simultaneous sampling system of FPM and CPM in the coal-fired flue gas, which was applied to the field sampling of all units in this study. The portable dust direct reading instrument (ZR-7100) was located at the end of the system to provide power and guarantee the gas flow rate (10 L/min) during the sampling. The flue gas in the funnel entered the stainless-steel sampling tube from the isokinetic nozzle, passed through the tube and the Dekati PM_{10} impactor, and the full-range heat tracing was adopted before reaching the condenser to eliminate the influence of moisture on measurements. FPM with different particle sizes in the coal-fired flue gas was captured by the impactor, so the mass of the FPM in the four particle size ranges (≥ 10 μm, 10 ~ 2.5 μm, 2.5 ~ 1.0 μm, and ≤ 1.0 μm) can be obtained. Subsequently, the CPM in the flue gas was collected by the condenser, short and long stem impactors placed in the water bath, as well as the membrane in the tail filter. Noted, the sampling time at the sites in front of the dry-type dust removal equipment in all coal-fired units is 15 min per sample, and 90 min per sample at other sampling sites. Besides, the FPM and CPM concentrations were converted to the standard concentration under the condition of 6% oxygen and a drying schedule.

Analytical procedure for FPM and CPM samples

The foil films and polyester filters in the Dekati PM_{10} impactor are used to adsorb FPM with particle sizes larger than and smaller than 1 μm, respectively. The mass of FPM with each particle size range is obtained by the weight gain of the foil films and polyester filters before and after the field sampling. According to the volume of the coal-fired flue gas, the mass concentration of FPM can be calculated.

Based on the U.S. EPA Method 202, CPM sampled in the coal-fired flue gas requires a series of pretreatments in the laboratory. Fig. S2 shows the detailed process of CPM samples from coal combustion. Previous research (Wu et al. 2021c, 2022) has also described this process systematically and in detail, which will not be repeated in this study. Noted, the organic and inorganic components in CPM are treated separately, and the sum of the masses of the two fractions is the total mass of CPM.

Quality assurance and control are made to ensure the accuracy and reliability of research results in this study: regular inspection and maintenance of the sampling and the detecting instrument to ensure its normal operation, especially the leak detection of the sampling system before the field sampling. The section of CPM collection devices needs to be immediately purged with high-purity nitrogen (10 L/min) for 60 ~ 90 min to reduce the influence of the dissolved SO_2 at the end of each sampling. Furthermore, three consecutive samples and three groups of field blank tests were performed at each sampling site; the mean value was used to calculate CPM concentration, and the blank increment was deducted. The minimum detection limit of the GC/MS system applied in all detection of this study reached 0.288 mg/Nm^3 for organic components and 0.800 mg/Nm^3 for inorganic components in CPM.

Results and discussion

The removal effect of dry-type dust removal equipment on CPM and FPM

This section selected four types of dry-type dust removal equipment (LLT-ESP, REEP, EFIP, and BF) in units P1, P2, P3, P4, P7, I1, and I2. It can be observed that LLT-ESP is a more widely used dust removal device in coal-fired power plants. The LLT-ESP is based on the ESP to reduce the temperature of the inlet flue gas by adding a flue gas heat exchanger in front of the ESP. The decrease in flue gas temperature reduces the volume of flue gas and the velocity of flue gas flow, resulting in an increase in the residence time of the flue gas in the dust collector. It is worth noting that the specific resistance of the dust decreases significantly with the reduction in coal-fired flue gas temperature, making it easier for the dust to be trapped after being charged by the precipitator. In addition, the flue gas temperature drops below the acid dew point, and most SO_3 are present in the form of H_2SO_4 micro droplets, which bind to PM and be removed together. REEP is also a kind of high-efficiency ESP, its dust collection principle is the same as that of conventional ESP, and the structure is composed of fixed electrode electric fields and a rotating electrode electric field. Two categories of dry-type dust removal equipment in coal-fired industrial plants (Wu et al. 2021c), EFIP and BF, are selected to contrast with apparatus in coal-fired power plants.

As shown in Fig. 1a, the LLT-ESP, REEP, EFIP, and BF all show excellent removal effects on $FPM_{2.5}$ and FPM_{10} (aerodynamic diameter ≤ 2.5 μm and ≤ 10 μm), with removal efficiencies of 96.86 ~ 99.87% and 97.50 ~ 99.91%, respectively. In other words, dry-type dust removal equipment shows an excellent purification effect on FPM with different particle sizes, so that most of the FPM in the coal-fired flue gas is removed at this stage. However, the removal effect of CPM with different components varied greatly from different devices. Figure 1a shows that except for the dust collectors in the unit P4 and two industrial units, the removal efficiency of CPM_o (organic components in CPM) by other equipment was all higher than that of CPM_{in} (inorganic components in CPM). Compared with the high removal efficiency of the dry-type dust removal apparatus for $FPM_{2.5}$ and FPM_{10}, the average removal efficiency of CPM_o and CPM_{in} was only 63.64 ± 41.81% and 77.99 ± 14.72%. It can be observed that a variety of dust removal equipment had an acceptable removal effect on CPM_{in}, and the efficiency was stable, all of which were about 80%. It is worth noting that the dry-type dust collector in each coal-fired unit had a large gap in the removal effect of CPM_o, especially the negative growth of CPM_o purified by BF installed in unit I2. Combined with previous experimental research studies (Ko et al. 2018; Yang et al. 2019), one possible reason is that the fuel of the unit was mixed with sludge, resulting in instability of the coal quality during the feeding process. The other lies in the chemical reaction of the organic precursor of the synthesis of PM to generate the CPM_o after passing through the dust collector. Figure 1b shows the removal efficiency of the dry-type dust removal equipment for CPM, FPM, and TPM. Obviously, the removal effect of dedusting equipment in different units on CPM was relatively different. However, noted that during the process of dust removal, the removal efficiency of TPM is almost determined by the purification degree of FPM during the coal combustion. As shown in Fig. 2, FPM accounted for 96% of the TPM before the dust removal, which also indicates that the removal rate of FPM is crucial in this stage. Besides, the proportion of CPM_o and CPM_{in} in CPM was almost unchanged at the inlet and

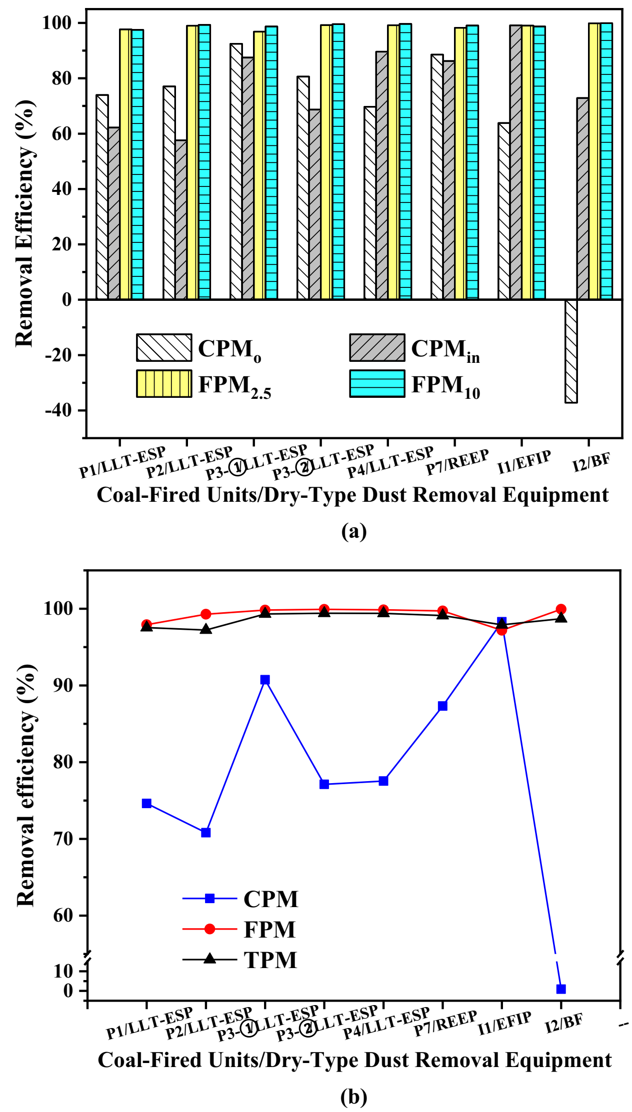


Fig. 1 Removal effect of CPM (CPM_o and CPM_{in}, organic and inorganic components in CPM), FPM ($FPM_{2.5}$ and FPM_{10}, aerodynamic diameter ≤ 2.5 μm and ≤ 10 μm), and TPM (CPM and FPM) by dry-type dust removal equipment

outlet of the dry-type dust removal equipment. The ratio of $FPM_{2.5}$ to FPM had grown from 24 to 67%, indicating that the deep purification of fine PM by dry-type dust collectors will become a challenge and a focus in the future.

LLT-ESP is the most widely used dry-type dust removal equipment in coal-fired power plants. In addition to having excellent removal efficiency for FPM, LLT-ESP also has a certain purification effect on CPM. The drop in the flue gas temperature at the inlet of LLT-ESP leads to a decrease in the flue gas velocity in the equipment, increasing the residence time of FPM and CPM, which can be removed more efficiently by the device. Furthermore, the temperature of the flue gas decreases, so that the organic compounds in the flue gas will condense to form a condensation core, and inorganic substances such as

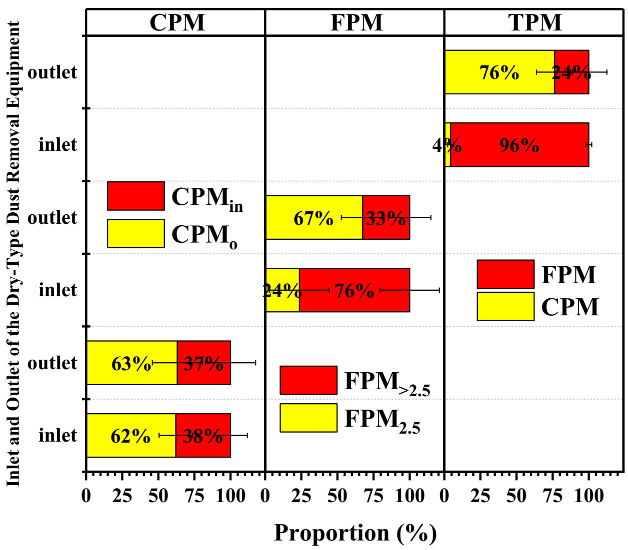


Fig. 2 The proportion of CPM (CPM_o and CPM_{in}), FPM ($FPM_{2.5}$ and $FPM_{>2.5}$), and TPM (CPM and FPM) at the inlet and outlet of the dry-type dust removal equipment

SO_3 will condense to form sulfuric acid droplets. During the process of FPM being removed in large quantities, the condensation core and inorganic droplets will be attached to the FPM and removed together. The high-voltage electricity generated during the operation of the device may break the precursors of some macromolecular particles, causing them to be captured by the electrode plate after being charged. The research on the removal mechanism of PM by dry-type dust collector represented by LLT-ESP is conducive to the exploration of deep purification of unconventional pollutants such as fine, ultrafine, and condensable particulate matter.

The removal effect of wet flue gas desulfurization devices on CPM and FPM

This section selected five desulfurization systems installed in units P1, P2, P5, P7, and P9. Obviously, almost all coal-fired units are equipped with WFGD for the removal of sulfur oxide. WFGD is a traditional coal-fired flue gas pollutant control device, usually installed behind dry-type dust removal equipment in coal-fired power plants. The liquid or slurry in WFGD carries out the desulfurization process and processes the products after desulfurization under certain humidity conditions, which has the characteristics and advantages of fast desulfurization reaction and high efficiency. The five WFGD selected in this study all used calcium-based desulfurization technology, that is, limestone slurry was used as a desulfurizer to spray and wash the flue gas containing SO_2 in the absorption tower, and the desulfurization efficiency of SO_2 in the coal-fired flue gas reached more than 90% in all units. In addition, the pH value of the slurry affects the desulfurization rate, oxidation rate, absorbent utilization rate, and system fouling during the operation of WFGD, which needs to be monitored and controlled. The pH of the slurry was maintained by supplementing with fresh limestone slurry, and the pH of slurries in WFGD selected for this study was between 5.0 and 5.8.

Figure 3 shows the removal effect of organic and inorganic components in CPM and FPM with different particle sizes by WFGD equipped in five plants. Combined with the control of the five WFGD for CPM_o (4.83 ~ 32.54%) and CPM_{in} (26.23 ~ 72.05%) in coal-fired flue gas (Fig. 3a and b), the removal efficiency of CPM_{in} was higher. It is speculated that the flue gas temperature decreases rapidly after entering WFGD, and the change of flue gas temperature has a

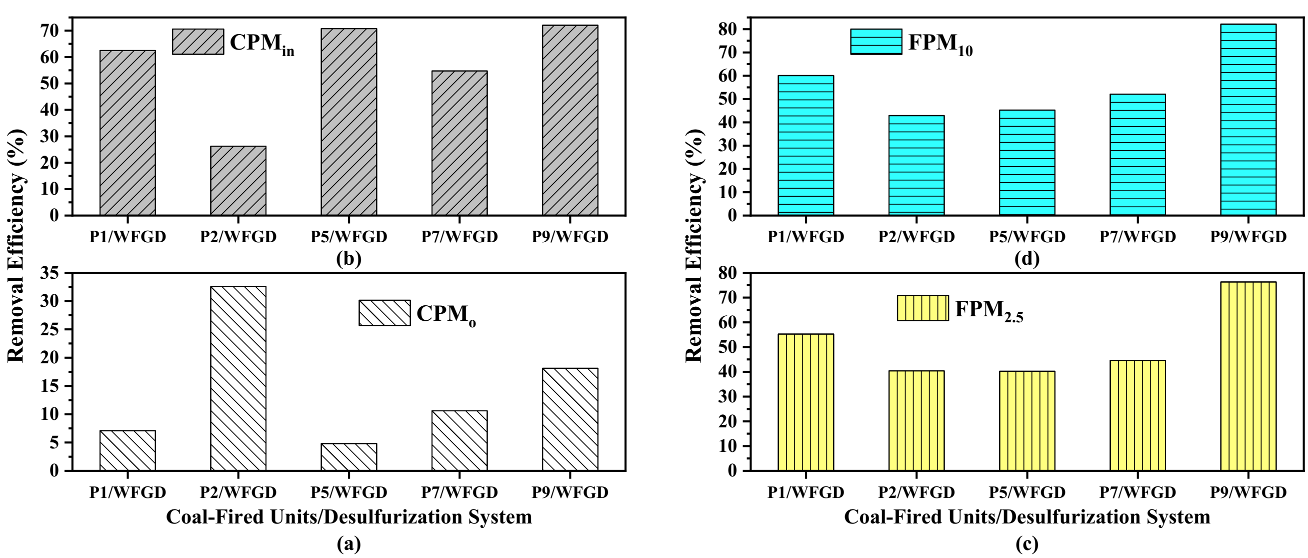


Fig. 3 Removal effect of CPM (CPM_o and CPM_{in}, organic and inorganic components in CPM) and FPM ($FPM_{2.5}$ and FPM_{10}, aerodynamic diameter ≤ 2.5 μm and ≤ 10 μm) by desulfurization system

greater impact on the inorganic components according to the removal effect of LLT-ESP on CPM_{in}. On the other hand, in the process of WFGD operation, the flue gas passes through the spray device, and the inorganic fractions are more easily dissolved in the spray solution and removed. Some inorganic components may interact with the reactants and products in the desulfurization process, resulting in the removal rate of CPM_{in} being higher than that of CPMo. As shown in Fig. 3c and d, compared with the dry-type dust removal equipment, WFGD had a considerable reduction in the removal efficiency of FPM_{10}, especially the removal rate of $FPM_{2.5}$ was reduced to 40.25 ~ 76.27%. According to the emissions data from four coal-fired power plants in the study of Liu et al. (2022), the removal efficiency of $FPM_{2.5}$ by four WFGD did not exceed 50%, and even the concentration of FPM in one unit showed negative growth after passing through WFGD. Results demonstrated that WFGD has pronounced limitations on the control of fine particles (CPM and $FPM_{2.5}$).

As shown in Fig. 4, the average removal efficiency of WFGD to FPM (53.05 ± 17.75%) was evidently higher than that of CPM (37.97 ± 18.16%), while TPM was in between. Previous studies (Álvarez-Ayuso et al. 2006, Meij and Te Winkel 2004, Wang et al. 2008) have found that the maximum removal efficiency of WFGD on FPM in the flue gas was over 80%, and the hierarchical removal efficiency decreased significantly with the decrease of particle size. WFGD can effectively remove particles with particle size greater than 2.5 μm, but the control effect on $FPM_{2.5}$ was not obvious. Furthermore, it can be found in Fig. 5 that even though WFGD had a certain removal effect on $FPM_{2.5}$, the proportion of $FPM_{2.5}$ in FPM still increased by 4%. The proportion of CPM_o in the outlet of WFGD increased prominently compared with the inlet, and the control and removal of the organic components may be more complicated than the inorganic components, which is not only related to the complex and diverse composition of the organic fractions but also related to the physicochemical properties of the organic components. Organic components generally show hydrophobicity, it is difficult to adsorption, dissolution, reaction, and other processes with spray fluid in WFGD. Noted that WFGD had better control over CPM_{in}, resulting in CPM_o dominating CPM in the flue gas at the outlet of WFGD. Besides, CPM accounted for the main part of TPM in the flue gas at the inlet of WFGD, and after dust removal, it is still necessary to deeply purify the CPM from the other apparatus. After the flue gas enters WFGD, the temperature drops rapidly, and CPM is condensed and adsorbed, which may be removed with the desulfurization slurry. The spray slurry can also make the CPM further removed during the washing process of the flue gas. Noted that the deep removal of WFGD on CPM may be limited by the concentration of CPM, and when the inlet concentration is too low, it is impossible to further deeply remove CPM.

The removal effect of wet-type precipitators on CPM and FPM

This section selected six WESP installed in units P1, P2, P5, P6, P7, and P8 as representatives of the wet-type precipitator. The principle of dust collection of WESP and ESP is the same, both rely on high-voltage corona discharge to charge the dust, and adsorb on the plate or polar line under the

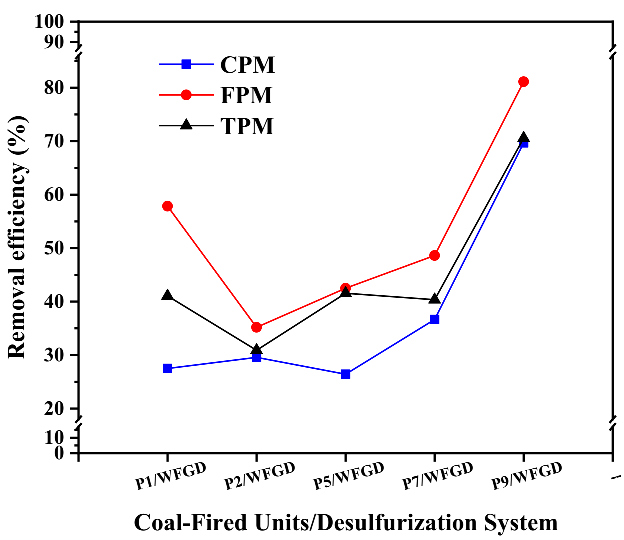


Fig. 4 Removal effect of TPM (CPM and FPM) by desulfurization system

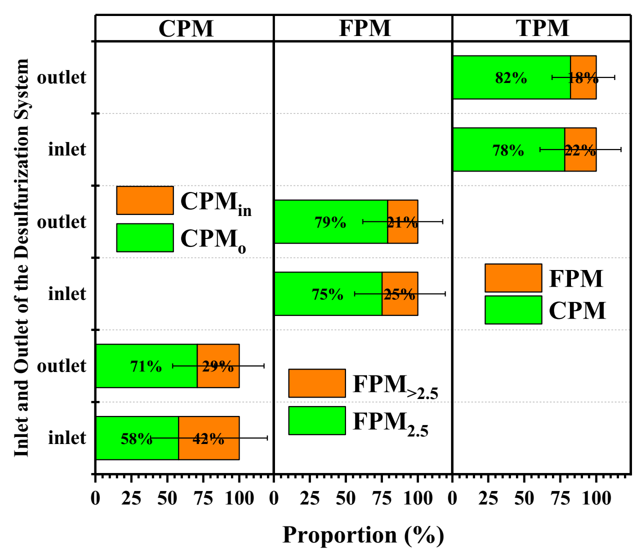
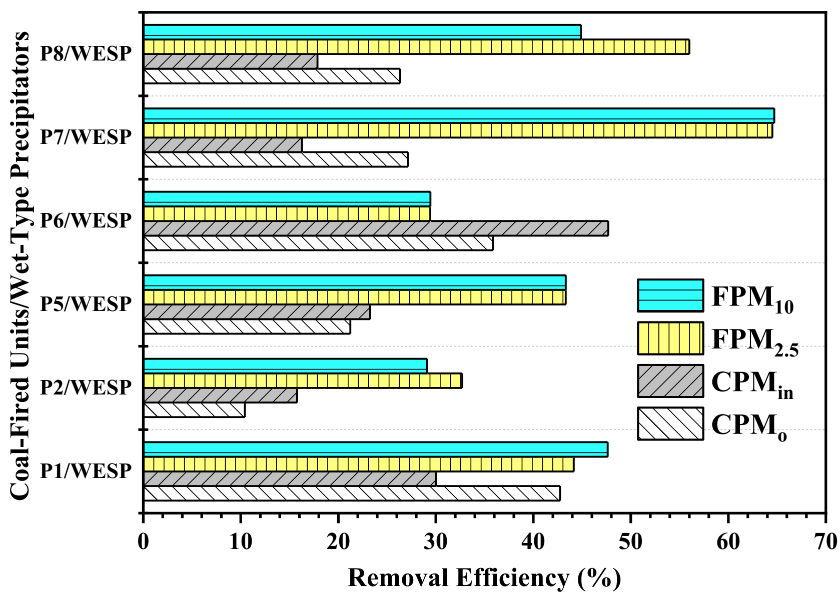


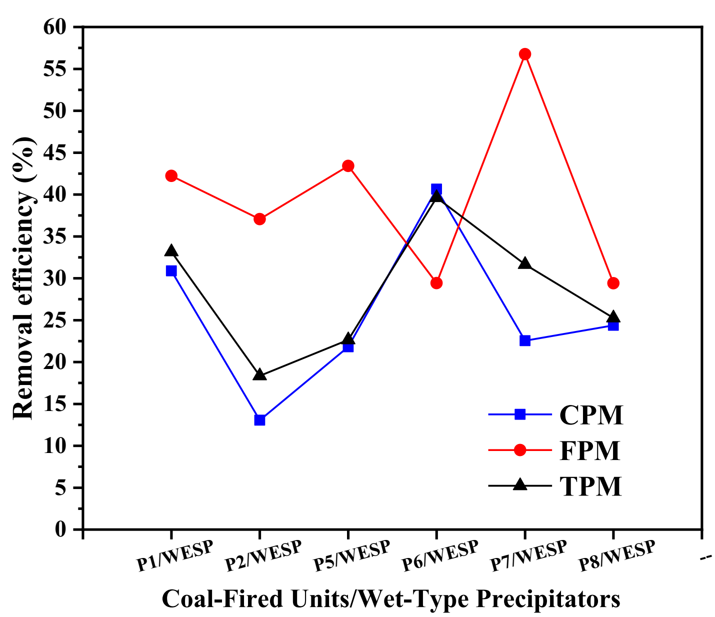
Fig. 5 The proportion of CPM (CPM_o and CPM_{in}, organic and inorganic components in CPM), FPM ($FPM_{2.5}$ and FPM_{10}, aerodynamic diameter ≤ 2.5 μm and ≤ 10 μm), and TPM (CPM and FPM) at the inlet and outlet of the desulfurization system

action of the electric field force, so as to purify the flue gas. The WESP uses scouring liquid to wash the electrode and form a continuous liquid film on the plate so that the dust can be removed with scouring. The WESP has the characteristics of small pressure loss, no re-entrain dust, and has a high dust removal efficiency, especially fine particulate.

As shown in Fig. 6a, WESP also had a good control effect on FPM with different particle sizes, especially the average removal efficiency of $FPM_{2.5}$ reached 45.02 ± 13.41%. Under the circumstance that the concentration of FPM in the flue gas at the inlet of WESP is already very low, the result indicates that the device has a deep purification effect on filterable fine particles. However, the purification efficiency of WESP for both CPM_o and CPM_{in} was just over 25%. The results suggested that WESP had a considerable removal effect on CPM, but further tests were needed to explore its control mechanism on CPM. It can be found in Fig. 6b, contrary to the purification process of the dry-type dust removal equipment, the removal efficiency of TPM is almost determined by the purification degree of CPM from coal combustion. Figure 7 shows the proportion of different categories of particles at the inlet and outlet of the wet-type



(a)



(b)

Fig. 6 Removal effect of CPM (CPM_o and CPM_{in}), FPM ($FPM_{2.5}$ and FPM_{10}), and TPM (CPM and FPM) by wet-type precipitators

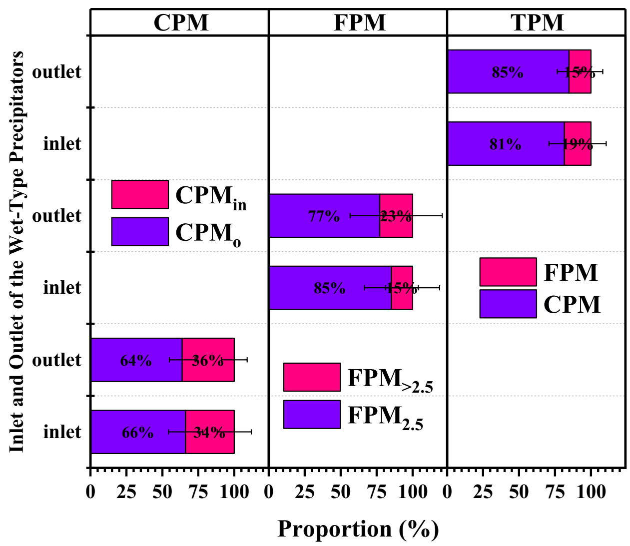


Fig. 7 The proportion of CPM (CPM_o and CPM_{in}), FPM ($FPM_{2.5}$ and $FPM_{>2.5}$), and TPM (CPM and FPM) at the inlet and outlet of the wet-type precipitators

precipitators. The proportion of CPM_o and CPM_{in} has not changed much at the inlet and outlet of WESP, and the percentage of CPM_o was around 65%, which was still the main component of CPM. It is noteworthy that the proportion of $FPM_{2.5}$ in FPM has decreased, which is different from the effect of the other two types of APCDs. This conclusion also indicates that WESP has a deep purification effect on $FPM_{2.5}$ in the coal-fired flue gas. CPM and FPM accounted for 84.75 and 15.25% at the outlet of the WESP, respectively. After the coal-fired flue gas has been purified by WESP, CPM has completely become the dominant particles discharged into the environment. The recent studies (Feng et al. 2018, Feng et al. 2021, Feng et al. 2020) have also demonstrated that CPM concentrations are higher in TPM emitted from chimneys in coal-fired power plants than in FPM. Thus, it is necessary to improve the removal efficiency of CPM by WESP to reduce TPM emissions.

Migration and emission characteristics of CPM and FPM in purification system

This section selected three representative ultra-low emission coal-fired power units (units P1, P2, and P7) to explore variations in CPM and FPM concentrations at the inlet and outlet of different APCDs. Moreover, thirteen ultra-low emission coal-fired power units (units P1, P2, P3, P4, P5, P6, P7, P8, P10, P11, P12, P13, and P14), three non-ultra-low emission coal-fired power units (units P9, P15, and P16), and two coal-fired industrial units (units I1 and I2) were selected to explore the emission characteristics of CPM and FPM from coal combustion. As shown in Fig. 8, in the whole flue gas purification process, the concentration of CPM and FPM showed a decreasing trend. It can be found that although the removal efficiency of SCR was detected on only one unit, the removal effect of SCR on CPM seemed to be good, reaching 55.79% in unit P1. Presumably, the reason may be due to the fact that the concentration of CPM at the inlet of SCR is very high compared to the other sampling sites. The other explanations may lie in the catalyst present in the SCR system causing physicochemical changes in the composition of CPM, resulting in removal with FPM. However, the current basic data for CPM removal by SCR is very limited, and more field tests are needed to support this conclusion in the future. The dry-type dust removal equipment had the best removal effect on particulates, and the concentration of FPM and CPM decreased from 2036.31 ~ 2485.40 and 85.69 ~ 178.89 mg/Nm^3 to 5.37 ~ 7.20 and 8.69 ~ 17.41 mg/Nm^3 after passing through the apparatus. In other words, the purification effect of the dry-type dust removal equipment converted the dominant particles in TPM from FPM to CPM in the coal-fired flue gas. Subsequently, after the removal of the flue gas from WFGD, the concentrations of FPM and CPM continued to decrease to 2.963.70 mg/Nm^3 and 6.30 ~ 12.26 mg/Nm^3, and the proportion of CPM in TPM was observed to increase again. Eventually, the concentrations of FPM and CPM have been reduced to 1.612.19 mg/Nm^3 and 4.48 ~ 10.66 mg/Nm^3 after the coal-fired flue gas was purified by WESP. It can be observed that in the TPM emitted into the environment from the existing typical ultra-low emission coal-fired units, CPM has played an absolutely dominant particulate. In summary, the concentration of FPM and CPM in the flue gas throughout the purification system is a continuous downward trend, and the removal efficiency of the components in the TPM by different APCDs has a

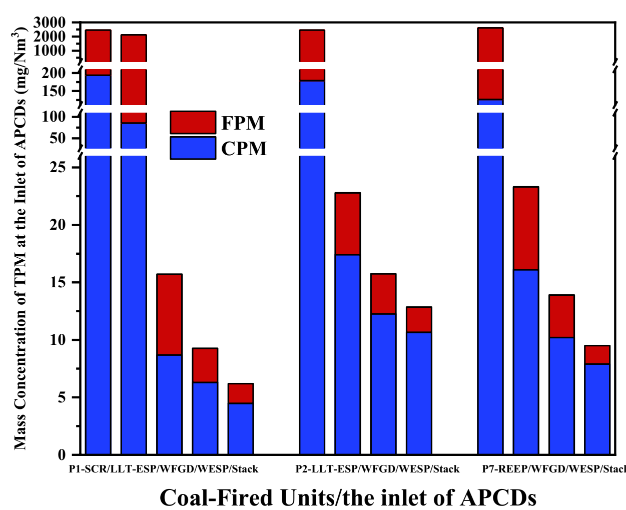


Fig. 8 The concentrations of CPM and FPM at the inlet and outlet of APCDs

considerable impact on the total removal efficiency of the TPM from coal combustion. Combined with Figs. 1b, 4, and 6b, the removal efficiency of dry-type dust removal equipment and wet-type precipitators to TPM is mainly determined by the purification effect of FPM and CPM, respectively, and both types of particles contribute to the removal efficiency of desulfurization systems to total TPM.

Figure 9 shows the average emission concentration and proportion of FPM with different particle sizes and CPM with different components from ultra-low emission coal-fired power units, non-ultra-low emission coal-fired power units, and coal-fired industrial units, respectively. Obviously, the average emission concentration of FPM and CPM of ultra-low emission coal-fired units was 1.95 ± 0.86 and 12.01 ± 5.64 mg/Nm^3, both of which are the lowest. However, the average emission concentration of TPM of non-ultra-low-emission coal-fired power units exceeded that of industrial units and was the highest. Noted, according to the emission limits of pollutants proposed by ultra-low emission standards, the emission concentrations of FPM of the three types of coal-fired units all meet the requirements of ultra-low emission indicators (the emission concentration of PM < 5 mg/Nm^3). Therefore, the exploration of the formation mechanism of CPM from coal burning and the development of control methods will be a challenge in the process of coal clean utilization. In terms of the proportion of different components in particulates, the proportion of $FPM_{>2.5}$ (aerodynamic diameter > 2.5 μm) in FPM emitted from coal-fired power units was significantly lower than that of coal-fired industrial units, indicating that the removal of $FPM_{2.5}$ is the key to controlling the emission of FPM from coal-fired power plants. Another aspect also shows that the installation of equipment for deep purification of fine particles represented by WESP in coal-fired power plants is an important measure to achieve ultra-low emission of pollutants from coal-fired flue gas. In the CPM emitted from non-ultra-low emission coal-fired power units and coal-fired industrial units, the proportion of CPM_o was very close, and both were nearly 20% higher than that of ultra-low emission coal-fired power units. According to the above section, the removal efficiency of CPM_o by each APCDs was usually lower than that of CPM_{in}, and the dominant component in the CPM emitted from the stacks had become organic fractions. Results demonstrated that the key to the lowest concentration of CPM discharged from ultra-low emission coal-fired power units is to limit the organic components, and the effective removal of CPM_o is the core of reducing CPM emission concentration. Besides, the proportion of CPM in TPM emitted from coal-fired power plants was higher than that of coal-fired industrial plants. Combined with the field data obtained in many coal-fired power plants in recent years (Liu et al. 2019; Sui et al. 2016; Tong et al. 2018; Wu et al. 2021d), it can be concluded that the emission concentration of FPM can be almost controlled below 3 mg/Nm^3 in large coal-fired units with ultra-low emission transformation. Therefore, the removal of TPM should focus on the purification of CPM, especially the organic components that are difficult to remove.

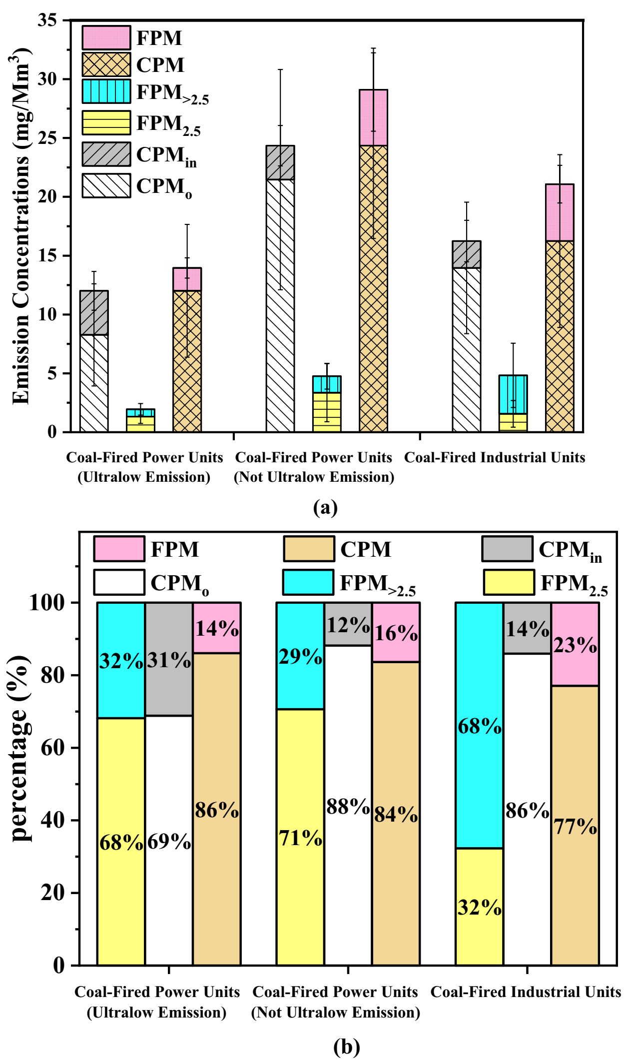


Fig. 9 The emission concentration (**a**) and proportion (**b**) of different kinds of particulate matter from different coal-fired units

Conclusions

FPM and CPM in the flue gas from sixteen coal-fired power units and two coal-fired industrial units with APCDs were sampled. The removal efficiency of TPM by dry-type dust removal equipment, desulfurization systems, and wet-type precipitators installed in the typical coal-fired units was studied. The migration process and emission concentrations of CPM and FPM in the purification system were also investigated. The analysis results are as follows: (1) the dry-type dust removal equipment represented by LLT-ESP had the best effect on the removal of TPM (98.57 ± 0.90%), and the removal efficiency of TPM mainly depends on the control of FPM. The concentration quantity relationship between CPM and FPM was reversed at the devices, and the CPM concentration in the flue gas after the outlet of the apparatus was higher than the concentration of FPM. (2) The desulfurization systems represented by WFGD had a removal efficiency of 44.89 ± 15.01% for TPM, and the control of FPM and CPM contributes to the removal efficiency of TPM. WFGD had a comparative removal effect on both FPM and CPM in the coal-fired flue gas, especially FPM_{10} and CPM_{in}. (3) The wet-type dust removal equipment represented by WESP had a removal efficiency of 28.45 ± 7.78% for TPM, and the key to controlling TPM is to limit CPM emissions. Note that WESP has a deep purification effect on $FPM_{2.5}$ in the coal-fired flue gas. (4) Due to the removal effect of APCDs, the concentration of FPM and CPM in the entire flue gas purification system continued to decrease. The concentrations of FPM and CPM (1.95 ± 0.86 and 12.01 ± 5.64 mg/Nm^3) emitted from ultra-low emission units were the lowest. The concentration of CPM in TPM emitted from stacks was much higher than that of FPM, especially the higher proportion of organic components in CPM.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

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Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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