Synergistic effect of multi-field force on condensable particulate matter properties and behavior in flue gas: A case study in a municipal solid waste incineration plan

Wenting Liu¹, Bowen Zhao¹, Qian Feng¹, Zhiyong Zhou¹, Jianyi Lu¹,²,*

² Coll. Environm. Sci. & Engn., MOE Key Lab Resources & Environm. Syst. Optimizat., North China Elect. Power Univ., Beijing, 102206, P.R. China

Corresponding author. Tel: +86-312-7522062; Fax: +86-312-7522062
E-mail address: lujianyi@tsinghua.org.cn

Abstract

At present, filterable particulate matter (FPM) emissions from stable source flue gases are well controlled, and the more difficult to remove condensable particulate matter (CPM) has received much attention due to its environmental hazards. In this study, we built a cold electrode electrostatic precipitator (CE-ESP) and systematically investigated the removal efficiency of CPM from municipal solid waste incineration plant flue gas by CE-ESP under three different operating modes. The results showed that hydrocarbons, esters and aromatic compounds were the main organic substances in CPM. The CE-ESP had a significant contribution to the removal of SO₄²⁻, F⁻, Al, Ni, Cr, and Pb from CPM. In contrast, it had a less effective removal of NO₃⁻ and Ca in CPM. The CE-ESP was effective for removing esters in CPM. The removal efficiency of CE-ESP for CPM could reach 76%, and the removal efficiency of organic substance was higher than that of inorganic substance. It is demonstrated that the combination of thermophoretic force and electric field in CE-ESP intensifies the turbulent agglomeration process, and the diffusion force generated by the concentration field synergistically enhances the interparticle coagulation and agglomeration. This promotes the homogeneous condensation process of CPM and the heterogeneous condensation of CPM and FPM, which is conducive to the reduction of condensable particulate matter in flue gas and can provide a theoretical basis for practical application in engineering.
Keywords: Cold electrode electrostatic precipitator, Coupling, Removal
1. INTRODUCTION

At present, filterable particulate matter (FPM) emission from stationary source flue gas has been controlled, and condensable particulate matter (CPM) emission has received attention (Peng et al., 2019). Condensable Particulate Matter (CPM) is a special type of primary particulate matter that is gaseous before being emitted. Liquid or solid particles are formed rapidly after discharge by atmospheric dilution and cooling. (Feng et al., 2018) However, in municipal solid waste incineration (MSWI) plants, due to the complexity, diversity and heterogeneity of the waste composition (Evans and Williams, 2000), the pollutants produced by MSWI are more numerous, complex, and toxic than those produced by the combustion of fossil fuels (Li et al., 2016b). Toxic pollutants from waste incineration (Li et al., 2017) have become one of the biggest constraints to the promotion of MSWI technologies.

Primary particulate matter emission from stationary sources can be divided into CPM and FPM. The main components of CPM, such as SO₃, NOₓ, heavy metals, and VOCs (Peng et al., 2021) are exactly the pollutants that are not fully controlled at present in MSWI plants. CPM should be considered as neglectful particulate pollutant (Feng et al., 2018) in both stationary source pollutant monitoring and air pollution management and control because it is formed in the smoke plume after leaving the stack. Most of the current research is focused on CPM emission and sampling, but few involvements in CPM control. Several authors have studied the effectiveness of air pollution control devices (APCDs) for CPM removal. It found that the mass concentration of CPM increased from 9.73 mg m⁻³ to 29.66 mg m⁻³ when flue gas passed through desulfurization system
Li et al. (Li et al., 2016a) collected CPM from a typical ultra-low emission power plant. The research results showed that the removal efficiency of CPM by conventional APCDs, such as wet flue gas desulfurization and wet electrostatic precipitator was low, 36.7% and 22.2%, respectively. Therefore, exploring new and efficient dust removal technologies to replace conventional devices is the key to reducing CPM emissions from stationary sources.

At this stage, the research on the removal of CPM mainly focuses on agglomerating fine particles into larger particles through physical or chemical methods (Yan et al., 2008) and then using conventional dust removal technology to improve its capture efficiency (Huang et al., 2020). More widely applied agglomeration techniques, such as condensation (Yang et al., 2019), is the typical application example in low-low temperature electrostatic precipitator. The heat exchanger is employed to reduce the inlet flue gas temperature in low-low temperature precipitator compared to the conventional electrostatic precipitator (ESP) (Qi et al., 2017), the substances such as SO$_3$ and VOCs condense and adhere to the dust surface. Therefore it can improve the removal efficiency of condensable substances from the flue gas (Wang et al., 2020).

There are few studies at home and abroad on the composition, morphology, proportion, and removal efficiency of CPM in flue gas, especially under the condition of flue gas in MSWI plants. In order to explore the detailed research, a cold electrode electrostatic precipitator (CE-ESP) was designed and self-made based on the theory of CPM condensation removal and the ESP dust capture method and employed to sample the CPM in flue gas. It combined with the EPA Method 202 for studying the multi-field force synergistically effect on CPM properties and behavior in the
flue gas of a municipal solid waste incineration plant, simultaneously to study the removal
efficiency of CE-ESP on CPM.

2. MATERIALS AND METHODS

2.1. Facilities and sampling sites

The self-developed CE-ESP is employed in this research as shown in Fig. 2. This device is built based on the tubular electrostatic precipitator. The CE-ESP tube body is made of stainless steel, with copper pipe flowing cooling circulating water outside the tube. The discharge electrode is made of zigzag barbed wire. The flue gas flows from bottom to top. The cooling water is circulated from bottom to top, and the heat exchange is controlled by controlling its flow rate to ensure the continuous uniform distribution of the water film without affecting the electric field strength. Thermocouples were set at the inlet and outlet of the flue gas and circulating cooling water of the CE-ESP. The electric field breakdown voltage is 25 kV, and the smoke residence time is 4 seconds. The device can provide 3 working modes of non-electric cold plate temperature field, conventional electric field, and electric coupling temperature field, by whether to supply circulating cooling water and voltage between the two stages. Compared with conventional ESP, it can reduce the temperature of the flue gas near the outer wall of the dust collector, provide additional thermophoretic force coupled with the original electric field force and diffusion force to increase the efficiency of particle capture by creating an external temperature field. With the modification of the dust collector structure and adjustment of the operation mode, the temperature field force
couples the electric field force and the diffusion electrophoresis force, synergistically accelerating the coagulation, agglomeration and capturing between CPM and FPM, and promote to achieve better removal effect.

The field test was carried out on unit 2 (220 MW) of an MSWI plant in Baoding City, Hebei Province. The MSWI plant treats 500 tons of garbage every day, with an annual processing capacity of more than 180,000 tons. The existing flue gas purification equipment of MSWI plants in China is denitrification, deacidification, dust removal and activated carbon adsorption. The pollution control methods in this MSWI plant are SNCR denigration, semi-dry deacidification, bag dust removal and spray activated carbon. 3 sampling sites A, B and C were arranged before and after the semi-dry reaction tower and behind the baghouse filter of this plant for these experimental studies, which are shown in Fig. 1. The study samples were collected at points A and C, and the removal effect on CPM and FPM in flue gas under different working modes by CE-ESP was measured at point B. All samples were collected under the condition of the boiler operating in full load. The working conditions of the 3 sampling sites are shown in Table 1.

The CE-ESP was divided into 4 electric fields a, b, c, d with equal area from bottom to top. After running for a period, deposited samples were taken in each field separately. The physical and chemical characteristics of inlet samples, outlet samples and electrode plate deposition samples of CE-ESP were analyzed and compared. The characteristics of CPM precursors and CPM removal efficiency under various working modes of CE-ESP were studied, including non-electric cold plate temperature field B1, conventional electric field B2 and electric coupling temperature field B3.
2.2. Sampling and measurement methods

The combined sampling device of FPM and CPM were built independently with reference to EPA Method 202 in this study. The Laoying 3012H automatic smoke and dust tester was used for on-site sampling to determine the sampling position and measure flue temperature and velocity. The universal sampling nozzle, filter cartridge and sampling probe of the particle collection system were placed in the front section of the collection, the condenser tube with a hose was placed at the end of the sampling probe, and the condensate collection bottle, buffer bottle and filter membrane were placed before the sampling pump. A thermocouple was set in the water bath box to ensure the sampling temperature was below 30°C during the whole process. Fig. 2 shows the field sampling device. Flue gas entered the pipeline, in which the FPM was captured by the filter cartridge, then it entered the circulating condensate pipe, the condensate was collected in the collection bottle under the condensation pipe, and the condensed CPM was captured in the buffer bottle. After each sampling, the device was moistened with ultra-pure water and n-hexane, respectively. The sampling flow was 50 L min\(^{-1}\), and the sampling time was 20 min. 3 groups of samples were collected at each sampling point. The samples collected including FPM filter cartridge, CPM filter membrane, ultrapure water solution, n-hexane solution, and fly ash of CE-ESP.
2.3. Sample analysis

The ash samples consisted of the fixed-point collected filter membrane and fly ash in different areas of CE-ESP. They were characterized in respect of microstructure, composition, and particle size analysis, etc. The CPM membrane was placed in a centrifuge tube and sufficient deionized water was added to the tube, which was then placed in an ultrasonic device for 3 minutes to extract the inorganic components, repeating 3 times. And the extraction solution was transferred to the ultra-pure water rinse solution. After that, acetone was added to the centrifuge tube for cleaning, and the cleaning solution was transferred to the hexane rinse solution. Then enough hexane was used to ultrasonically extract the organic components from the filter membrane, which was repeated 3 times for 2 minutes each time. Finally, the extract was transferred to the hexane rinse solution.

For the liquid phase part, the ultra-pure water rinse was first extracted using organic solvents, the extracted organic fraction was poured into a hexane rinse, and the remaining inorganic solution was titrated to neutral using NH$_4$OH. The solution was then dried in an oven at 105°C until it was nearly solid (less than 10 ml of solution remained). After that it was placed at room temperature and dried to a constant weight, weighed for its weight gain, and deducted the amount of NH$_4$OH added. The hexane rinse was then dried to constant weight in a fume hood at room temperature and the weight gain was weighed. The above procedure was followed for the condensate blank to obtain the blank weight gain. The weight gain of ultrapure water rinse and hexane rinse were deducted from the blank weight gain to obtain the condensate weight gain $m_{\text{inorganic}}$ and $m_{\text{organic}}$, respectively.
CPM's inorganic and organic components were ultrasonically dissolved with ultrapure water and n-hexane, respectively. The inorganic component solutions were separately quantified for anions (Cl\(^-\), F\(^-\), NO\(_3\)^- , SO\(_4^{2-}\)) and metal cations (Ca, Na, Mg, Ni, Al, Cr, Pb, Cd). An ion chromatograph was used to quantify the selected anions. The eluent was 20 mmol L\(^{-1}\) KOH solution. The calibration curve correlation coefficients for the detected anions were all greater than 0.999. The correlation coefficient of the calibration curve for the detection of metal elements was all greater than 0.999 using inductively coupled plasma emission spectrometry for quantitative detection of metal elements.

The composition and distribution characteristics of the organic chemicals of CPM were obtained using a gas chromatograph-mass spectrometer (GC-MS) with a semi-quantitative analytical method to test and analyze the component properties and the percentages of different components of the organic solutions.

The morphology of the CPM captured on the filter membrane and the ash samples on the anode plate were observed using a thermal field emission scanning electron microscope.

3. RESULTS AND DISCUSSION

3.1. Mass concentration of CPM

The mass concentration of CPM was calculated based on EPA Method 202. The particulate
matter emission concentrations of CPM and FPM at each sampling site were shown in Table 2. The test results show that the concentration of inorganic components in CPM has increased after passing through the desulfurization system by comparing the mass concentration of CPM at station A and station B. Because limestone slurry will be added into the system during the desulfurization process, as a desulfurizer whose active ingredient is more than 90% CaCO$_3$, Ca$^{2+}$ will be released while achieving the removal of SO$_2$ from flue gas through acid-base reaction. Compared with other soluble metal ions, Na$^+$ had higher solubility in water and was quickly brought into the flue gas, resulting in the desulfurization tower's poor effect on CPM removal. Nevertheless, comparing points A and C, the concentrations of FPM and CPM decreased significantly under the removal of APCDs in this MSWI plant. The removal efficiency of FPM, CPM and TPM was 91%, 45% and 78%, respectively. It is remarkable that APCDs had good performance in removing FPM but did not well in removing CPM. It could be concluded from Fig. 3 that the main component of TPM was FPM before sampling site C, but at sampling site C in front of the stack, the CPM accounts for 87% of the TPM. The relative trend of this proportion is similar to that in other works of literature. The proportion of CPM in the flue gas about a waste incineration plant tested by Yang (Yang et al., 2015) was 52.8% after baghouse filter and semi-dry desulfurization. Wang (Wang et al., 2018) sampled an MSWI plant, the study showed that after the baghouse filter, and the CPM ratio was as high as 96.3%. The reason for this phenomenon could be that after the high-efficiency dust removal system purified the flue gas, the concentration of FPM was significantly reduced, which increased the CPM proportion.
The proportion of CPM in TPM is higher than the concentration before emission, which may be caused by undivided SO$_2$. While the concentration of FPM had reached the ultra-low emission standard, the emission of CPM could not be ignored. The inorganic composition proportion of CPM was 76%, 80% and 92% at the 3 sampling sites A, B and C, respectively. After sampling site B, the concentration of inorganic composition in CPM increased slightly. The reason is that oxidizing substances or excess oxygen may be present during the desulfurization process, oxidize SO$_2$ to SO$_3$ in the flue gas. The escaped SO$_3$ and substances such as Ca$^{2+}$ released from limestone caused an increase in the concentration of inorganic components. Wang et al. (Wang et al., 2018) found that the inorganic composition of CPM accounted for about 77% of CPM in waste heat boilers of MSWI plants. This was consistent with the sampling results of this study. It suggested that the proportion of inorganic components of CPM in MSWI plants was significantly high, and should be paid more attention to, which could help control the emission of CPM.

Therefore, the conventional APCDs had a poor performance in removing CPM. In order to further realize the efficient operation of APCDs and complete the low-concentration emission of pollutants, we should pay more attention to the removal of CPM.

TPM in the flue gas was collected and tested using CE-ESP with different working modes at point B. It could be observed that the removal efficiency of CE-ESP under mode B1 in a non-electric cold plate temperature field on TPM was 63%, while they were 67% and 57% on FPM and CPM, respectively. Because of the high proportion of inorganic matter in CPM in MSWI flue gas, acid gases in CPM inorganic gaseous precursors may react with alkali metal oxides in FPM and be
chemisorbed. By lowering the temperature of the flue gas under the effect of the temperature field, it is possible to condense and convert some of the high condensation point temperature components of CPM into FPM and trap them. Moreover, it was removed after agglomeration on the collector plate. It showed that CE-ESP had a specific removal effect on TPM caused by the effect of condensation and thermophoresis under the working mode B1. The removal efficiencies of CE-ESP under mode B2 in a conventional electric field on TPM, FPM and CPM were 74%, 87% and 47%, respectively. Compared with the CE-ESP under mode B1, mode B2 had better removal efficiency for FPM. However, due to the small particle size of CPM, and the state of particulate matter in the flue was different from that of FPM, most of them escaped in the form of gaseous precursors in the baghouse filter, hence the removal efficiency of CPM was low, especially the inorganic composition of CPM. Compared with the other 2 working modes, the removal efficiencies under the B3 mode in the electric coupling temperature field on TPM, FPM and CPM were 97%, 94% and 76%, respectively. The temperature gradient in the coupled field produced thermophoretic force on CPM, coupled with the electric field strengthened turbulent agglomeration, and the diffusion force generated by the concentration field synergistically enhanced the coagulation and agglomeration between particles, which promoted the homogeneous coagulation process of CPM and the heterogeneous coagulation of CPM and FPM. On the one hand, the cold anode electrode could reduce the temperature of the flue gas near the outer wall of the dust collector, provide additional thermophoretic force coupled with the original electric field force and diffusion force to increase the efficiency of particle capture by creating an external temperature, so that CPM
could coagulate into the particulate state. On the other hand, CPM was mainly composed of water-soluble ionic components, which meant that CPM with small particle size was more likely to nucleate, condense and grow up, and be removed. Thus, CE-ESP under mode B3 achieved the optimal capturing effect on TPM.

3.2. Removal and characteristics of inorganic chemicals in CPM

3.2.1. Removal and characteristics of metal cations

The concentrations of CPM inorganics were detected, and the results were shown in Table 3. As a essential part in CPM inorganics, the metal element concentration was shown in Fig. 4. Among the elements analyzed, the concentrations of Ca, Na and Mg account for the significant parts, which were 56.35 μg m⁻³, 42.83 μg m⁻³, 39.75 μg m⁻³ at sampling site A, respectively. These 3 elements accounted for 37%, 29%, and 26% of the CPM metal ion concentration, respectively. Ca originated from the reaction between desulfurizer and acid gas, Mg and Na accounted for the significant components of kitchen garbage (Xu et al., 2016). Heavy metals such as Ni, Cd, Cr, and Pb mainly came from colored newspapers, thin plastics, kitchen waste, fabrics, batteries, etc. (Liu et al., 2017). Heavy metals are one of the crucial components of household waste. Because of the complexity of the sources and types of waste, most waste containing heavy metals is difficult to recycle. In the combustion process, it will volatilize and mix with other components, so that the heavy metal content in the flue gas will increase and be enriched in the micro-particulate matter. However,
traditional APCDs have low capture efficiency for fine particles and cannot altogether remove heavy metals, resulting in escaping and emission of heavy metals.

Comparing the changes in the composition of condensable particles, the concentration of metal components in the CPM at sampling site C was significantly lower than that at sampling site A, which was consistent with the test results of the concentration of CPM. It showed that the desulfurization tower had a specific effect on removing heavy metal ions in CPM. However, the concentration of Ca increased at site B, this might be caused by the limestone slurry in the desulfurization system entering the test system after evaporation, and CPM were formed after condensation.

Comparing the results at sampling site B under various working modes, it could be seen that the removal efficiency of the CE-ESP under mode B3 on Na, Ni, Cr, Mg, and Pb had reached more than 70%. Because the metal compound was relatively stable and was less affected by flue gas temperature, the removal effect of CE-ESP under mode B1 was slightly worse than that of B2. However, the removal effect of the CE-ESP under mode B3 with coupling field on the metal compound was consistent with that on the overall CPM.

3.2.2. Removal and characteristics of water-soluble anions

Water soluble anions have been studied more in previous studies on CPM, which are important components of CPM (Zhang et al., 2018; Liu et al., 2022). Some studies have shown that water-soluble anions ions contribute to haze. The test results were shown in Fig. 5. In inorganic
component anions, the concentration of Cl\textsuperscript{-} and SO\textsubscript{4}\textsuperscript{2-} account for the main part. The concentration of F\textsuperscript{-} was low, the measurement error was large, so it was not shown in this Figure. SO\textsubscript{4}\textsuperscript{2-} as the main inorganic pollutant has two sources. Both waste incineration with sulfur-containing compounds (Ngo et al., 2022) and the combustion of mixed pulverized coal produce SO\textsubscript{2} (Wu et al., 2021). SO\textsubscript{2} reacts with limestone slurry to produce SO\textsubscript{4}\textsuperscript{2-}. Cl\textsuperscript{-} could be originated from the emission of kitchen waste, and it was a highly volatile element. The Cl element compounds in garbage such as NaCl and CaCl\textsubscript{2} easily produce HCl at high temperature. The organic fluorine in the organic substances was combined on the carbon-hydrogen bond, and it was easy to form HF with the H element under high temperature environment (Xu et al., 2018). The NOx produced in the MSWI process, the fuel NOx caused by the nitrogen element in the waste accounts for 70% to 80% (Yang et al., 2022). Some studies on PM\textsubscript{2.5} showed that SO\textsubscript{4}\textsuperscript{2-} was one of the main ionic components. The research indicated that, the inorganic components of CPM emitted by MSWI plants were likely to have a direct contribution to the water-soluble ions of PM\textsubscript{2.5}. Therefore, further removal of these components in the flue gas would be beneficial to control the emission of the inorganic part of CPM.

Comparing the proportion of anions in the CPM at sampling sites A and B, the concentrations of Cl\textsuperscript{-}, NO\textsubscript{3}\textsuperscript{-} and F\textsuperscript{-} all decreased. Due to the entrainment of slurry droplets from the desulfurization tower and the aerosol particles of sulfur trioxide that had not been wholly scrubbed and oxidized to sulfate, increasing concentration of SO\textsubscript{4}\textsuperscript{2-}. These led to the poor effect of the desulfurization tower on CPM removal. Comparing sites B and C, the concentration of each ion at site C decreased,
indicating that APCDs had a particular removal effect on CPM, but the effect was not good. While removing CPM, CE-ESP under mode B3 had the highest removal efficiency for Cl\(^{-}\) and SO\(_4^{2-}\). And the Cl\(^{-}\) containing compounds were readily soluble in water and the droplets produced by the phase change condensation underwent a chemical reaction (Wang et al., 2021), which made CE-ESP had a better removal effect on Cl\(^{-}\). The decrease in the flue gas temperature could reduce the wind speed of the electric field, thereby increasing the gas residence time and further increasing the removal efficiency. As the flue gas enters the CE-ESP, the temperature drops slowly until it drops below the acidic dew point at the outlet, and most SO\(_3\) would be converted into gaseous H\(_2\)SO\(_4\), reducing a part of the concentration of CPM, thereby increasing the removal efficiency of CE-ESP on SO\(_4^{2-}\). A low concentration of SO\(_3\) in flue gas leads to higher viscosity and lower specific resistance of particles, which enhances the removal efficiency of CE-ESP.

### 3.3. Removal and characteristics of organic chemicals in CPM

Organic substances were an important part of CPM and were mainly produced by incomplete combustion of fuel with complex compositions. As CPM contained more than 140 organic components (Li et al., 2016a; Song et al., 2020), it was difficult to quantify its organic components. Therefore, a semi-quantitative analytical method was used to test and analyze the component properties and the percentage of different components of the organic solution by GC-MS. The test results showed that alkanes, esters, and aromatic compounds were the main organic components in CPM. The percentage of the organic substances in CPM was shown in Fig. 6, in which the other
organics in CPM at sampling site A was as high as 60.45%. Then as the flue gas passed through the semi-dry reaction tower and the baghouse filter, most of the other organics were removed with the removal of CPM. The removal of hydrocarbons and esters was slightly lower than that of the other organics, resulting in the hydrocarbons and esters accounting for the major components of the organic substances in CPM, and the proportion of the other organics was only 1.88% at sampling site C.

As the organic substances entered the CE-ESP with flue gas, they could be removed in the CE-ESP under different working modes, the proportion of the other organic substances even decline to 9.73% under B3 mode. Comparing with sampling site C, the CE-ESP was more effective in removing esters than baghouse filter under 3 different modes, especially under B3 mode. Because the CE-ESP has better results in the removal of esters compared to a normal electric precipitator.

Under the condition of lowering the flue gas temperature, the highly hydrophilic esters are removed together with the condensation process.

3.4. Microscopic analysis of morphology

The particle morphology of samples from points A, B and C were shown in Fig. 7 from left to right. At sampling site A, it could be observed that particles were attached to the surface of the filter membrane in large quantities and accumulated to form agglomerates to fill the surface of the filter membrane fibers and their voids, with larger particle sizes. After the flue gas passed through the desulfurization tower, the number of particles in the sample taken in front of the semi-dry
reaction tower was less than that in front of the baghouse filter, and most of the particles were agglomerates formed by the agglomeration of small particles. The particles in front of the stack were more dispersed on the fiber surface, significantly reduced the number, and the particle size was small.

Samples were taken in 4 different electric fields areas of the CE-ESP and analyzed by scanning electron microscopy to obtain the following Fig. 7. As shown in the following 4 images, a, b, c, and d represent 4 different electric field areas from bottom to top of the CE-ESP. This is a good proof of the difference between the CE-ESP and the traditional ESP, which gives priority to the removal of large particle size, the smaller the particle size the weaker the electric field force is, and the particle size of fly ash gradually decreases in each electric field. The CE-ESP is able to remove more tiny particles after agglomeration by reinforcing the agglomeration effect of particles through thermophoretic force coupled with electric field force. The closer to the CE-ESP outlet, the larger the particle size is precisely the proof of the agglomeration process.

3.5. Mechanism analysis

The CE-ESP system differs from the wet electrostatic precipitator with water or sprays on the anode plate. Additional circulating water is used to cool the dust collection plates on CE-ESP, reducing the local flue gas temperature, and causing the temperature gradient between cold anode electrode to discharge pole. The low temperature field formed by circulating water on the surface of the cold electrode induces the phase change of water vapor to coalesce into dusty saturated wet
flue gas. In the process of cooling, condensation, and heat transfer, with the phase change and condensation of water vapor, it condenses into countless fine droplets, increasing the specific surface area of collision contact with CPM. At the same time, the FPM in the flue gas provides condensation nodules, which can promote the heterogeneous condensation process of CPM.

Moreover, during the contact between the wet flue gas and the cold electrode, the flue gas is cooled and condensed. Because of a temperature difference between the flue gas and the cold electrode surface, a temperature gradient from the flue gas main body to the cold electrode surface is generated. Under the effect of temperature gradient, the cold electrode plate produces thermophoretic force on the microfine particles and produces turbulent agglomeration under the coupled electric field and temperature field. The flow field disturbance causes inter-particle velocity difference, which makes the local particle enrichment in the flow field and the radial velocity between particles hugely uneven, producing obvious particle nucleation and coagulation, and prompting the microfine particles to move to the cold electrode plate and deposited and then captured. As the concentration of particles near the cold electrode plate decreases, the diffusiophoresis generated by the concentration field also synergistically enhances the coagulation and agglomeration among the particles. Therefore, the thermophoresis and diffusiophoresis formed by the temperature and concentration fields are coupled with the electric field force, which has a more significant effect, and synergistically promotes the condensation, agglomeration and directional movement and deposition of TPM in the electric field. The multi-field force coupling can greatly enhance the possibility of agglomeration and captured of TPM, especially CPM in the
flue gas.

4. CONCLUSIONS

In summary, this study analyzes the influence of CPM characteristics and behavior in the flue gas of municipal solid waste incineration plants. The concentration of FPM in the flue gas after conventional APCD treatment in the MSWI plant was found to be 3.14 mg m\(^{-3}\), while the concentration of CPM was 8.16 mg m\(^{-3}\). This proves that the existing process is very ineffective for the removal of CPM from flue gas. The highest percentage of organics in CPM emissions from MSWI plants are hydrocarbons, esters and aromatic compounds. High-carbon alkanes exist as solids at room temperature with very low volatility and are difficult to remove with conventional APCDs. The effect of CE-ESP on ester removal was significantly enhanced by the synergistic effect of temperature field. The inorganic components of CPM discharged from MSWI plant mainly included \(\text{SO}_4^{2-}\), \(\text{Cl}^-\), \(\text{Na}^+\) and \(\text{Ca}^{2+}\). CE-ESP enhances the removal of \(\text{SO}_4^{2-}\), \(\text{F}^-\) and smaller \(\text{Ni}, \text{Al, Cr}\) and \(\text{Pb}\) components significantly by promoting the coagulation of CPM, which increases its particle size and strengthens the force of the pole plate on the particles. This study verified that the combination of thermophoretic force and electric field enhanced the turbulent agglomeration process by comparing the removal efficiency of CPM by conventional APCD and CE-ESP, and provided a theoretical basis for the engineering application of CE-ESP.
ACKNOWLEDGEMENT

This work was supported by Beijing Natural Science Foundation (Grant No.3202029). The authors have declared no conflict of interest.

DISCLAIMER

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.

REFERENCE


https://doi.org/10.1109/ICBBE.2010.5517175


<table>
<thead>
<tr>
<th>Sampling sites</th>
<th>Smoke temperature (°C)</th>
<th>Sampling time (min)</th>
<th>Gas velocity (m s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>263</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>B</td>
<td>155</td>
<td>30</td>
<td>11</td>
</tr>
<tr>
<td>C</td>
<td>150</td>
<td>30</td>
<td>9</td>
</tr>
<tr>
<td>Sampling Site</td>
<td>CPM</td>
<td>FPM</td>
<td>TPM</td>
</tr>
<tr>
<td>--------------</td>
<td>-------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td></td>
<td>CPM inorganic</td>
<td>CPM organic</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>12.53</td>
<td>4.03</td>
<td>56.19</td>
</tr>
<tr>
<td>B</td>
<td>13.68</td>
<td>3.395</td>
<td>35.31</td>
</tr>
<tr>
<td>B1</td>
<td>3.13</td>
<td>1.74</td>
<td>11.54</td>
</tr>
<tr>
<td>B2</td>
<td>7.82</td>
<td>1.12</td>
<td>6.709</td>
</tr>
<tr>
<td>B3</td>
<td>2.83</td>
<td>0.41</td>
<td>2.24</td>
</tr>
<tr>
<td>C</td>
<td>7.49</td>
<td>0.67</td>
<td>3.14</td>
</tr>
</tbody>
</table>
Table 3 Ion emission concentration at each sampling site ($\mu$g m$^{-3}$)

<table>
<thead>
<tr>
<th>Element tags</th>
<th>A</th>
<th>B</th>
<th>B1</th>
<th>B2</th>
<th>B3</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>56.3512</td>
<td>69.2166</td>
<td>51.8659</td>
<td>46.5207</td>
<td>29.3764</td>
<td>23.9656</td>
</tr>
<tr>
<td>Na</td>
<td>42.8312</td>
<td>24.1563</td>
<td>22.5965</td>
<td>6.7466</td>
<td>5.2734</td>
<td>7.1611</td>
</tr>
<tr>
<td>Mg</td>
<td>39.7566</td>
<td>35.2691</td>
<td>10.3047</td>
<td>7.0922</td>
<td>6.4024</td>
<td>5.9812</td>
</tr>
<tr>
<td>Ni</td>
<td>6.6509</td>
<td>9.1483</td>
<td>0.1379</td>
<td>0.0663</td>
<td>0.0639</td>
<td>0.1480</td>
</tr>
<tr>
<td>Al</td>
<td>1.5324</td>
<td>1.1083</td>
<td>0.0113</td>
<td>0.0277</td>
<td>0.0056</td>
<td>0.0914</td>
</tr>
<tr>
<td>Cr</td>
<td>1.4348</td>
<td>2.5345</td>
<td>0.0008</td>
<td>0.0001</td>
<td>0.0005</td>
<td>0.0019</td>
</tr>
<tr>
<td>Pb</td>
<td>0.4648</td>
<td>0.4216</td>
<td>0.0001</td>
<td>0.0003</td>
<td>0.0001</td>
<td>0.0005</td>
</tr>
<tr>
<td>Cd</td>
<td>0.0574</td>
<td>0.3027</td>
<td>0.0120</td>
<td>0.0063</td>
<td>0.0032</td>
<td>0.0001</td>
</tr>
<tr>
<td>SO$_4^{2-}$</td>
<td>121.3912</td>
<td>157.7666</td>
<td>87.2635</td>
<td>92.3621</td>
<td>29.6434</td>
<td>45.5235</td>
</tr>
<tr>
<td>Cl$^-$</td>
<td>93.5236</td>
<td>72.1619</td>
<td>69.4511</td>
<td>45.1011</td>
<td>24.7053</td>
<td>53.7200</td>
</tr>
<tr>
<td>NO$_3^-$</td>
<td>54.9139</td>
<td>41.1515</td>
<td>39.9639</td>
<td>35.6360</td>
<td>14.8122</td>
<td>22.3469</td>
</tr>
<tr>
<td>F$^-$</td>
<td>1.8882</td>
<td>1.6139</td>
<td>0.7974</td>
<td>0.9105</td>
<td>0.3872</td>
<td>0.1094</td>
</tr>
</tbody>
</table>
Fig. 1 Sampling sites in municipal solid waste incineration plant
Fig. 2 Cold electrode electrostatic precipitator and field sampling system
Fig. 3 TPM emission and removal efficiency under different sampling positions and working modes
Fig. 4 Distribution of CPM metal elements at different sampling sites
Fig. 5 Water soluble anion concentration of CPM at different sampling sites
Fig. 6 Percentage composition of CPM organic components
Fig. 7 Particulates morphology at different sampling sites and 4 different electric fields of cold electrode electrostatic precipitator