

Co-Benefits of Pollutant Removal, Water, and Heat Recovery from Flue Gas through Phase Transition Enhanced by Corona Discharge

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Read Online Cite This: Environ. Sci. Technol. 2022, 56, 8844-8853 ACCESS III Metrics & More Article Recommendations s Supporting Information ABSTRACT: Pollutant removal and resource recovery from high-Without WESP With WESP Flue gas Corona discharge humidity flue gas after desulfurization in a thermal power plant are 4 crucial for improving air quality and saving energy. This study Gas cooling developed a flue gas treatment method involving phase transition

enhanced by corona discharge based on laboratory research and established a field-scale unit for demonstration. The results indicate that an adequate increase in size will improve the ease of particle capture. A wet electrostatic precipitator is applied before the condensing heat exchangers to enhance the particle growth and capture processes. This results in an increase of 58% in the particle median diameter in the heat exchanger and an emission concentration below 1 mg/m³. Other pollutants, such as SO₃ and Hg, can also be removed with emission concentrations of 0.13 mg/m³ and 1.10 μ g/m³,



respectively. Under the condensation enhancement of the method, it is possible to recover up to 3.26 t/h of water from 200 000 m³/ h saturated flue gas (323 K), and the quality of the recovered water meets the standards stipulated in China. Additionally, charge-induced condensation is shown to improve heat recovery, resulting in the recovery of more than 43.34 kJ/h·m³ of heat from the flue gas. This method is expected to save 2628 t of standard coal and reduce carbon dioxide emission by 2% annually, contributing to environmental protection and global-warming mitigation.

KEYWORDS: pollutant control, waste heat recovery, water recovery, corona discharge, condensation, carbon reduction

INTRODUCTION

The global coal consumption for energy generation is expected to reach 25.93 billion tons by 2050.¹ This has raised concerns that have highlighted the need for energy conservation and environmental protection through the use of clean energy. As of 2020, coal still supplied more than 50% of China's total energy. If coal must be employed to meet the global energy needs, the eco-friendliness and efficiency of coal-related processes must enhanced to improve the air quality, reduce carbon emissions, and mitigate climate change.²

High humidity coal-fired flue gas after wet flue gas desulfurization (WFGD) contains particulate matter (PM),^{3,4} sulfur trioxide,⁵ heavy metals,⁶ and other pollutants, which require further treatment to meet strict emission standards. Thus, many flue gas treatment methods have been proposed to achieve high-humidity flue gas purification.⁷ The wet electrostatic precipitator (WESP), which shows excellent particle-removal performance in high-humidity flue gas, has been widely applied as a popular air-pollutant control device to realize ultralow emissions.⁸ Furthermore, the particle-removal efficiency can be enhanced by the high water vapor content of the flue gas after WFGD.⁹ However, the particle-capturing mechanism of the WESP is inefficient for particles in the size

range of 0.1-1 μ m because of the inherent low electrical mobility.¹⁰ Moreover, the WESP has other limitations, including its high operating expense and high water consumption. Researchers have suggested that enlarging the particle-size is a feasible method for increasing the efficiency of fine-particle-removal.^{11,12} Additionally, it is possible to achieve particle growth in high supersaturation by optimizing the water vapor condensation process on the particle surface and the agglomeration between particles.¹³ In our previous study, cooling¹⁴ and external electric fields¹⁵ were applied to activate the particle growth substantially. Diffusiophoretic and thermophoretic depositions can also be effective for particle capture in the flue gas cooling process.¹⁶ Therefore, a condensing heat exchanger (CHE) installed after WFGD has been applied to remove pollutants while recovering the waste heat and water from the flue gas.⁵

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Figure 1. (a) Schematic diagram of the demonstration system, and (b) photographs of WESP+CHE

The CHE is essential for the recovery of waste heat and water from high-humidity flue gas for energy conservation, and increasing the condensation rate of water vapor can be a good strategy for achieving this goal.¹⁸ Consequently, many studies have been conducted to increase the condensation rate of water vapor and the recovery of exhaust heat.^{19,20} Xiong et al.²¹ proposed a fluoric plastic heat exchanger for recovering water and heat from low-temperature flue gas (below the acid dew point), and they applied it in a 660 MW power plant. Today, most condensing heat exchangers are installed directly after WFGD^{9,16} and often act as pretreatment equipment before the sample reaches the WESP. Thus, they improve the particle-removal efficiency by facilitating particle growth, agglomeration, and partial capture in advance.²² This approach was demonstrated to exhibit good pollutant removal efficiency in our previous research.²³

However, during operation using the above-mentioned method, corrosion and ash deposition occur because of the high concentration of pollutants, which decrease the heat transfer coefficient and increase the maintenance costs.²⁴ Moreover, the presence of slurry droplets and sulfuric acid aerosol could deteriorate the water quality, resulting in the scaling or jamming of pipelines.²⁵ Therefore, it is crucial to pretreat the high-humidity flue gas before it enters the CHE to reduce operational problems. WESP is a good choice because of its good performance in high-humidity flue gas purification. Moreover, the water vapor condensation can be induced by an electric field and a high ion density because of the corona discharge.^{26,27} This increases the rates of water recovery and the absorption of the heat released by the gas cooling process.

In the present study, a comprehensive flue gas treatment method is proposed involving the installation of corona discharge section before CHE. Additionally, we evaluated its application effect in a typical ultralow emission system, as well as its pollutant removal and resource recovery efficiencies in actual flue gas. This research is essential for the development of flue gas purification and energy-recovery technologies.

MATERIALS AND METHODS

Experimental System. Prior to the industrial demonstration, experiments on the particle growth and deposition mechanisms under gas temperature drop and corona discharge conditions were carried out using a laboratory-scale experimental setup, which served as the basis for the proposed method. The descriptions of the experimental setup (Figure S1) and the experimental method are shown in the Supporting Information (SI). The results show that the corona discharge had a significant effect on the particle growth, deposition, and water vapor condensation. Thus, based on the experimental results, a comprehensive flue gas treatment method was proposed for further industrial application.

Thereafter, to explore the cobenefits of pollutant removal and resource (water and heat) recovery from the flue gas through phase transition enhanced by corona discharge, a fieldscale coal-fired unit with an ultralow emission system was designed and established as the demonstration system. As shown in Figure 1(a), the system includes a circulating fluidized bed (CFB) boiler, a selective noncatalytic/catalytic reduction—denitrification device, an electrostatic fabric filter (EFF), a WFGD, and a WESP combined with a CHE. After the devices, the purified flue gas was discharged into the atmosphere through the stack.

Furthermore, to reduce the water consumption of the unit, the wastewater generated by the spraying process was treated and transported to the WFGD for reuse. The water recovered from the flue gas by CHE was stored in a water tank below the device and subsequently transported to the cooling tower (shown in Figure 1(a)).

The proposed flue gas treatment technology was realized by installing WESP as a pretreatment equipment before the sample enters the CHE (Figure 1(b)). After WFGD, the highhumidity flue gas (gas temperature: 322-327 K) entered the WESP with a high concentration of fine particles $(d_p < 1 \ \mu m)$ and droplets charged by the corona discharge. The WESP was equipped with a spike electrode in a single-stage electrostatic field. To avoid unwanted vapor condensation on the insulator surface, the hot-air stream was introduced into the insulator section. Most of the charged particles and droplets migrated to the collector plate under the action of the electrostatic field, and the particles that had not been removed entered the CHE with the flue gas. The CHE was a tubular heat exchanger applied with fluoroplastic steel material, which was made of polytetrafluoroethylene molded directly on the surface of steel pipe. The materials could resist acid corrosion and could be combined seamlessly. The particle was captured by the water film or the falling droplets generated by the water vapor condensation because of the decrease in the temperature of the flue gas, which ultimately contributes to the discharge of clean flue gas into the atmosphere. Further, this process can be enhanced by the presence of some charged particles and droplets.

Experimental and Analytical Method. *Materials.* In this demonstration system, the coal–sludge blend was selected as the fuel, which would result in more pollutants (i.e., high concentrations of sulfur oxides, hydrogen chloride, etc.)²⁸ and hinder the flue gas treatment. To this end, the proximate and ultimate analyses of the fuel were conducted first. SI Table S1 shows that the heating value decreased because of the mixing sludge, while the ash and sulfur contents of the fuel increased. This indicates that more pollutants, such as sulfur dioxide and PM, are generated after combustion, necessitating flue gas treatment to protect the environment.

PM Measurement. Due to the submicrometer or nanoscale size of the fine PM (i.e., sulfuric acid aerosol, sulfate aerosol, etc.), traditional optical in situ methods cannot measure the particle-size distribution effectively.²⁹ Therefore, the electrical low-pressure impactor (ELPI⁺, Dekati, Ltd., Finland) was chosen to measure the concentration and size distribution of the particles. The impactor exhibited a rapid time response characteristic, which is useful particularly for unstable concentration and particle-size distribution measurements.³⁰ To ensure the accuracy of the particle measurement, the sampling-system temperature was kept constant with the flue gas. Additionally, a single-stage diluter (Diluter DI-1000, Dekati Ltd., Finland) was utilized to dilute the flue gas with filtered clean air to obtain reliable data with the dilution of 8. The unit condition was kept stable during the measurement period, and three repetitive tests were carried out under the same test conditions, with a sampling time of 60 s for each test.

The particle-size distribution is expressed as $dp - dn/d \log d_p$, which can be represented by the following equation:

$$dn/d\log d_{\rm p} = \frac{\Delta n}{\log d_{\rm i,up} - \log d_{\rm i,low}} \tag{1}$$

where *n* is the number concentration (cm⁻³) of the particle, d_p is the diameter (μ m) of the particle, and $d_{i,up}$ and $d_{i,low}$ represent the upper and lower diameters (μ m) for a certain size range, respectively.

Considering the simultaneous growth and deposition of particles in the heat exchanger, we determined the median size

based on the particle-number concentration and represented the particle growth using the relative median size $(\overline{d}_{outlet}/\overline{d}_{inlet})$ to some extent. The mean diameter was calculated by the arithmetic mean of the number distribution, as follows:

$$\overline{d} = \frac{\sum n_i d_i}{n} \tag{2}$$

The particle-capturing efficiency was calculated with the particle-mass concentration, as follows:

$$\eta = 1 - \frac{m_{\text{outlet}}}{m_{\text{inlet}}} \tag{3}$$

where m_{outlet} and m_{inlet} represent the particle-mass concentrations (mg/m³) of the outlet and inlet measured by ELPI⁺, respectively.

 SO_3 Measurement. A continuous monitor (RJ-SO₃-M, Ruijing Co Ltd., China),³¹ designed based on U.S. EPA method 8, was chosen to measure the SO₃ concentration along the WESP and CHE. The monitor's working principle is based on the selective absorption of SO₃ into isopropanol and a spectrophotometry determination method with data acquired in real time. The instrument can be adapted for the highhumidity flue gas measurement and to reduce the effect of other pollutants on the measurement with sampling, absorption, and liquid circulation modified.

Hg Measurement. Given the relatively low particle concentration in flue gas after EFF, EPA method 30B, which exhibits ease of use and robustness merits,³² was chosen to measure the mass concentration of gaseous Hg. The flue gas sample was first extracted by a probe with a quartz fiber filter maintained at 393 K to prevent the condensation of water vapor and the adsorption of Hg vapor on the inner face of the filter. Hg^p was collected on a quartz fiber filter, and the sample gas after filtration subsequently was flowed through paired traps filled with potassium iodide-treated activated carbon (AC-KI) to capture the gaseous mercury (Hg⁰, Hg²⁺). The total mass concentration of Hg was measured by a mercury analyzer (Hydra II_C Mercury Analyzer, Teledyne Leeman Laboratories, Mason, OH).

Heat and Water Resource Recovery Analyses. For the high-humidity flue gas, after the WFGD system, the heat transfer in the CHE occurs via convection, conduction, and condensation. During the cooling process of the flue gas in CHE, the condensation of water vapor formed a water film around the tube surface.³³ The total heat was transfer through the water film, the tube wall, and the boundary layer around the inner surface of the tube to the cooling water, resulting in heat loss during the heat transfer. Consequently, the heat absorbed by the cooling water can be defined as the heat recovered from the flue gas via heat transfer:

$$Q_{\rm R} = \frac{1000m_{\rm c}}{3600} \times \frac{C_{\rm c,in} + C_{\rm c,out}}{2} \times (T_{\rm c,out} - T_{\rm c,in})$$
(4)

where m_c is the mass-flow rate of cooling water, t/h; C_c is the specific heat capacity of cooling water, kJ/(kg·K); and T_c represents the temperature of cooling water, K.

The actual amount of recovered water was calculated based on the change in the water tank level (the valve at the tank outlet was closed during the test), which can be expressed as

$$H_{\rm a} = \frac{\pi \times r^2 \times \Delta h}{\Delta t} \tag{5}$$



Figure 2. (a) CFD study at different wall temperatures, (b) change in the relative particle median diameter and particle-number concentration in the tube, (c) particle deposition ratio at different wall temperatures, (d) particle-size distribution under different applied voltages, (e) particle-mass concentration evolution along the tube under different applied voltages, and (f) comparison of the particle deposition ratios with and without the applied voltage.

where r is the radius of the cylindrical water tank, Δh is the change in the water tank level, and Δt is the time interval of each record.

Moreover, the WFGD slurry, WESP wastewater, and recovered water from CHE were collected by the tetrafluoroethylene bottles to analyze the ion components and water quality. The concentrations of K^+ , Na^+ , and Ca^{2+} were obtained using an atomic-absorption spectrophotometer (AAS, Agilent Technologies, Santa Clara, CA). Further, the concentration of other ions was obtained by inductively coupled plasma mass spectrometry (ICP-MS, Agilent Technologies, USA).

The particle-size and concentration, sulfur trioxide concentration, and mercury concentration in flue gas were determined separately (the sampling points are shown in Figure 1(a). During the field test, the boiler was required to operate at 100% load to ensure stable and reliable results of the related parameters. At least three samplings were conducted under each condition, and the average values are reported.

RESULTS AND DISCUSSION

Understanding the Particle Growth and Deposition via the Laboratory Experiment. To understand the growth and deposition of particles promoted by corona discharge and provide a theoretical basis for the proposed phase transition enhancement method, we first carried out laboratory-scale experiments to clarify the effect of gas cooling and corona discharge on the particle growth and deposition.

Effect of Gas Cooling. Heterogeneous condensation is generally driven by a saturation ratio. The gas temperature is one of the most important activation factors to change that ratio. In this study, we adjusted the water temperature in the wall to adjust the temperature difference between the gas and the wall (the CFD temperature distribution in the tube is shown in Figure 2(a), while the actual measurement results are shown in SI Figure S2). Figure 2(b) indicates that the condensation growth of particles was enhanced by the gas cooling process along the tube, and the median diameter of the outlet was 1.17 times that of the inlet. Moreover, the particle growth could be accelerated from the center to the wall because of the increasing temperature gradient. Moreover, the particle-number concentration decreased significantly near the tube wall. For further exploration of the particle deposition caused by the temperature difference between the gas and the wall, the particle deposition ratio under different temperature differences was compared. Figure 2(c) shows that the particle deposition was enhanced as the temperature difference between the gas and the wall increased. However, particles with sizes in the range of 0.07–0.25 μ m showed the opposite trend, which could be explained by the "equilibrium" between the concentration increase by particle growth and the concentration decrease by particle deposition. In general, the high-humidity gas cooling could enhance the particle growth and particle deposition on the heat-exchange interface.

Effect of Corona Discharge. Compared with the neutral particle, an additional electrical force impacted the motion of the charged particle, which increased the relative motion, thereby enhancing the particle growth. Figure 2(d) shows that the particle-size corresponding to the peak-number concentration increased under the action of the corona discharge, while the total concentration decreased. This phenomenon can be ascribed to the fact that the collision frequency is positively influenced by the number concentration and the external force. Additionally, due to the mass transfer from the gas to the aerosol phase under a supersaturated gas condition, the particle-mass concentration increased along the tube (Figure 2(e)). Further, a surprising increase was observed in the ratio of the mass concentration with increasing the applied voltage. Consequently, the average-particle deposition ratio on the wall increased by more than 8.5 times in comparison to that observed without the corona discharge (Figure 2(f)). In particular, the particle-size range (0.04–0.25 μ m) increased by over 14 times. The appearance of visible droplets on the inner surface of the growth tube also validated such an analysis. The findings show that the flue gas treatment technology based on



Figure 3. (a) Schematic diagram of the particle growth process, (b) particle-number concentration at the CHE inlet and outlet, (c) change in the particle-size under different temperature differences, and (d) relative particle median diameter under different applied voltages.

phase transition enhanced by corona discharge can be evaluated.

Therefore, we established a demonstration system, with installing corona discharge section before CHE, and investigated its pollutant removal and resource (water and heat) recovery performances from flue gas through phase transition enhanced by corona discharge.

Flue Gas Purification Performance. Particle Growth and Removal. Enhancement of Particle Growth. Recently, many high-humidity flue gas PM capture technologies, such as demister¹¹ and WESP, have been developed to capture fine particulate matter and droplets in flue gas after desulfurization. Numerous studies have shown that regardless of the collection method, the removal of particles in a high-humidity environment is significantly affected by the particle size. Therefore, the method for promoting particle growth is very important for the purification of flue gas.

In CHE, a high supersaturation is realized around the tube wall because of the drop in the temperature of the highhumidity flue gas, which results in the water vapor condensation. As shown in Figure 3(a), the surfaces of the particles in the flue gas act as the condensation nucleus, enabling the water vapor condensation that leads to particle growth. Moreover, the particle coagulation and agglomeration occur because of the collisions between particles, which further increase the particle size.³⁴ In the above-mentioned process, the number concentration of small particles decreased significantly because of the coagulation and deposition on the tube surface, while the growth of the particles increased the number of large-size particles, which will also be deposited (shown in Figure 3(b)). The results proved that particle growth occurred inside the heat exchanger. The particle size distribution of the test is shown in SI Figure S3.

Based on the mechanism of the particle growth, the change in the flue gas temperature would substantially affect the condensation process of water vapor, thereby affecting the growth of the particles. Since it is difficult to detect the flue gas temperatures during operation, the flue gas cooling is controlled by changing the temperature and flow of the cooling water in the heat exchanger, which is reflected in the temperature difference between the flue gas at the CHE inlet and outlet.²³ Theoretically, the more the flue gas temperature decreases in the CHE, the higher the water vapor condensation rate, which would increase the particle size. During the test, we explored the change in particle size under different flue gas temperature differences between the CHE inlet and outlet by changing the cooling water flow rate (shown in Figure 3(c)). The results show that the median diameter of the particle at the outlet of CHE increased with the temperature difference. When the temperature difference of flue gas reached 5 K, the median diameter of the particles increased to 0.171 μ m from 0.108 μ m, which is a 58.4% increase compared to that at the inlet of the CHE.

The particle growth process would also be affected by the applied voltage of WESP. With the external electrical field, the electric charge of fine particles reduced the Gibbs free energy for nucleation and condensation,³⁵ which accelerated the particle growth. Our basic research in the above section also revealed that the corona discharge promotes the processes of particle coagulation and agglomeration. Meanwhile, the dielectrophoresis or the dielectrophoretic nucleation of the vapor on electrically charged centers can be enhanced by increasing the applied voltage, which, in turn, enhances the particle growth. As shown in Figure 3(d), although most of the particles were removed inside the device, the relative particle median diameter still increased with the applied voltage, in contrast to the case of no applied voltage (1.16). When the voltage reached 40 kV, the relative particle median diameter reached a maximum of 1.44. This phenomenon demonstrated that the particle growth is enhanced by the corona discharge. The grown particle was considered to be captured more effectively, which means that the growth of the particle would affect its removal efficiency.

Enhancement of the Particle-Removal Efficiency. The particles in the flue gas were deposited on the collecting plate under the effect of the electrostatic field when passing through WESP, resulting in a substantial reduction in the concentration. In CHE, when the flue gas flowed through the tube row, the particle was intercepted by the water film on the tube surface under the action of inertial impact. Additionally,



Figure 4. (a) Schematic of the particle deposition in the CHE, (b),(c) particle-removal performance of WESP+CHE under different applied voltages, and (d) particle-removal performance under different temperature differences.



Figure 5. (a) Mercury removal performance of WFGD, WESP, and CHE based on mercury mass balance, and (b) SO_3 removal performance of WESP+CHE based on the SO_3 concentration in flue gas.

thermophoresis and diffusion electrophoresis, caused by temperature gradients, facilitated the particle migration to the tube surfaces (shown in Figure 4(a)). Moreover, some of the charged particles were deflected in the electrostatic field. Coupled with the Brownian effect, the accumulated displacement of particles increased,³⁶ which made them more likely to collide with the water film on the tube wall and subsequently be intercepted. The condensate on the tube surfaces will carry the captured particles to the water tank, thereby achieving self-cleaning and avoiding fouling.

It is considered an effective method to improve the removal efficiency of WESP by increasing the applied voltage.³⁷ As the voltage increases, the process of particle charging can be sustainable, resulting in more particles deposited on the collecting plate. Moreover, the external electrical field could

also accelerate the particle growth, thereby enhancing the particle-removal efficiency in the CHE. This process was verified, as shown in Figure 4(b). With no applied voltage, the particle deposition only occurred in the CHE, and the outlet concentration reached 3.78 mg/m^3 , which was inferior to the effect with the corona discharge (1.09 mg/m^3). The collection efficiencies of the CHE and WESP+CHE are shown in Figure 4(c). The removal efficiencies of both WESP and CHE increased with increasing voltage. Further, compared with the removal efficiency peaked at 88.3%. Notably, WESP reduced the concentration of particles entering the CHE, which reduced the collection efficiency of the CHE. However, the removal efficiency still increased with the voltage.



Figure 6. (a) Ion components of different samples, (b) appearance of different samples, (c) recovered water amount, and (d) comparison of the water quality with the national standards.

Previous studies have highlighted that particle growth can be enhanced by increasing the temperature difference of flue gas, promoting its trapping. A large temperature gradient will promote the thermophoretic deposition of particles, leading to further particle concentration reduction. Figure 4(d) confirms that the particle collection efficiency can be increased from 85.32% to 89.43% by reducing the flue gas temperature. Furthermore, the minimum-particle concentration can be lower than 1 mg/m³ when the temperature difference reaches 5 K. The test results show good reliability for particle-removal in the WESP+CHE.

Synergetic Removal of Hg and SO₃. The enhancement in the flue gas phase transition also increases the removal efficiency of some water-soluble pollutants and pollutants adsorbed on fine particles, such as SO₃ and Hg (mainly Hg²⁺ and Hg^P). Herein, the changes in the mass concentration of SO₃ and Hg in the flue gas-treatment device were explored to verify the performance of the proposed flue gas treatment method for the synergistic removal of pollutants under the phase transition enhancement. Further, the mass balance is described in the SI.

Hg mainly occurs in the form of gaseous mercury (Hg⁰, Hg^{2+}) and particulate-bound mercury (Hg^{p}) in flue gas. During the flue gas treatment, Hg^{2+} can be easily captured by WFGD because of its high solubility in water,³⁸ and Hg^p can be effectively removed using PM-control devices (i.e., ESP, WESP, etc.). Some of the Hg⁰ species can be oxidized to Hg²⁺ by free radicals generated from the corona discharge in the WESP, after which they are captured.³⁹ Therefore, based on the Hg balance, the Hg concentration at the inlet of the WFGD was set to 100% (4.20 μ g/m³), and 38.02% of the Hg was captured during the desulfurization process (as shown in Figure 5(a). This arises because the dissolved Hg^{2+} in the slurry can react with sulfide or sulfur oxides in the flue gas to form insoluble mercury sulfide or sulfate. In the WESP and CHE, 25.50% of the Hg entered the water and slag because of the dissolution of Hg^{2+} and adsorption of Hg^{p} by the particles. Finally, 26.23% of the Hg was released to the atmosphere (1.10 $\mu g/m^3$).

For SO₃, it exists in the form of sulfuric acid aerosol in highhumidity flue gas because of the phase transition, and it can be considered to comprise ultrafine particles. WESP is considered the most effective aerosol collector. Thus, as shown in Figure 5(b), setting the SO₃ concentration at the outlet of WFGD as 100% (8.52 mg/m³), WESP removed 76.8% of sulfuric acid aerosol by corona discharge, which was similar to the particle-removal process. Most of the SO₃ species entered the wastewater as SO₄²⁻. Under the effect of phase transition enhancement by corona discharge, the escaping sulfuric acid aerosol entering the CHE grew with the decrease in the flue gas temperature, after which it was captured by the water film on the tube wall. Finally, only 1.56% of SO₃ was emitted to the atmosphere (0.13 mg/m³). Therefore, the removal efficiency of the WESP+CHE for SO₃ can reach 98.44%.

High-Quality Water Recovery with High Efficiency. Recovering more water with a low PM and salt concentration is imperative for improve the water quality. Therefore, in this section, in addition to obtaining more condensed water by corona discharge-enhanced phase transition, we improve the quality of recovered water by removing particles and saltcontaining droplets from flue gas by corona discharge. The ion components of the samples and the water recovery rate were tested to investigate the water recovery performance of the proposed novel device.

As shown in Figure 6(a), the total concentration of ions in the liquid sample decreased significantly with the flue gas treatment process. Correspondingly, the turbidity of the water sample was substantially reduced (Figure 6(b)); that is, the amount of impurities in the water was reduced, as ascertained by the pollutant concentration of the flue gas in the devices. Additionally, Ca^{2+} , Cl^- , and SO_4^{2-} were found to be the main ions in the water sample, and the proportion of Cl^- in the flue gas after desulfurization was significantly reduced. This indicated that the chlorine-containing pollutants were mainly removed through the desulfurization device. The proportion of SO_4^{2-} in the wastewater increased significantly, which proves that a high proportion of SO_3 was removed by the WESP.

The condensation of water vapor is directly related to the temperature drop of the desulfurized flue gas, which is mainly controlled by the flow rate of the cooling water. Meanwhile, due to the enhancement of the water vapor condensation and droplet deposition by corona discharge, the amount of recovered water increased further. As presented in Figure 6(c), as the cooling water flow rate increased, the flue gas



Figure 7. (a) Heat recovery enhanced by the combined effects of corona discharge and temperature management, and (b) comparison of heat recovery rates.

Table 1. Comparison of the Water and Heat Recoveries

	average recovered heat (kW)			recovered wa		
temperature difference (K)	0 kV	39–40 kV	increase rate	0 kV	39–40 kV	increase rate
4	1203.79	1684.85	39.96%	2.12	2.55	20.28%
4.5	1340.96	1900.10	41.70%	2.25	2.84	26.22%
5	1497.14	2115.34	41.29%	2.61	3.26	24.90%

temperature difference increased, and the maximum water recovery rate reached 2.61 t/h from the 200 000 m³ flue gas. When the applied voltage was 39-40 kV, the maximum water recovery rate increased to 3.26 t/h, which proved the effectiveness of this method for water recovery.

The quality of the recovered water influences its reuse, and corresponding national standards for industrial water have been tightened. Figure 6(d) depicts the comparison between the recovered water sample and the standard requirement. Due to the removal of particles and salt droplets by WESP, the ion concentration of the recovered water in the CHE was significantly reduced, thus improving the water quality. The results showed that the recovered water met the water standard in terms of total water hardness (Figure 6(d1)), sulfate content (Figure 6(d2)), and chloride-ion content (Figure 6(d3)). Moreover, the water can potentially be used without treatment, which can reduce the material and energy consumptions of the water-treatment system in the power plant. However, when WESP was turned off, the concentration of pollutants at the entrance of the CHE increased, which deteriorated the quality of the recovered water. The results also illustrated the important role of WESP in obtaining clean water.

Heat Recovery and CO_2 Reduction. The heat-exchange efficiency of the CHE is affected by many factors, such as the composition of the flue gas, humidity, flow, and the temperature of the cooling water. Therefore, the heat-exchange will fluctuate as multiple parameters are varied during the operation. The heat emitted from the temperature-decreased flue gas is described as

$$Q = Q_s + Q_1 \tag{6}$$

where Q_s is the sensible heat emitted from flue gas because of the temperature decrease, and Q_1 is the latent heat from the condensation of the water vapor.

The change in the heat recovery rate under different flue gas temperature differences during the operation of the unit is displayed in Figure 7. The sensible heat increased with the expansion of the flue gas temperature difference. Furthermore, the latent heat released from flue gas phase change increased with the water vapor condensation enhanced by the temperature drop. Thus, the recovered heat was increased. Moreover, according to the results in the water recovery analysis, the corona discharge also promotes the condensation of moisture in the flue gas, which would also increase the latent heat released from the gas. The results showed that the increase in the applied voltage would enhance the heat recovery rate. When the voltage reached the high stage (at about 40–47 kV), the heat recovery could reach up to approximately 2500 kW for a 220 t/h CFB. Additionally, through corona discharge, the heat transfer between the flue gas and cooling water changed more obviously with the flue gas temperature difference, that is, the slope of the fitting curve increased.

However, as shown in Table 1, the increased recovery rate of water was always lower than that for heat, which indicated that the condensed water was not collected completely. This phenomenon could also be observed in the difference between the theoretical value and test value in Figure 6(c). Therefore, the method of improving the collection efficiency of condensed water should also be further studied.

After the cooling water absorbed the heat released by the flue gas, it was added to the boiler feedwater system after passing through the economizer. The heat absorbed in the CHE reduced the fuel consumption that released the same heat while reducing carbon emission from fuel combustion. The calculation process is described in the SI.

The calculation results are listed in Table 2. By applying the flue gas treatment methods mentioned in this research, up to 0.3 t/h (2628 t/y) of standard coal could be saved. Moreover, 0.8 t/h (7008 t/y) of CO_2 emission could be reduced as well. According to the power plant annual statistics, the unit consumes an average of 173 070 tons of fuel per year. Thus, the annual carbon emission of the unit could be reduced by 2.02% with this method, promoting the realization of carbon neutrality without compromising the unit operation.

Table 2. Estimated annual carbon emission reductions with the device

items	unit	value
recovered heat per hour	kJ/h	[4631364, 8668224]
fuel saving	t/h (standard coal)	[0.16, 0.30]
	t/h (fuel for this unit)	[0.21, 0.40]
CO ₂ emission reduction	t/h	[0.43. 0.80]

Although the device exhibits good water and heat recovery performances, it consumes additional power, which cannot be ignored. The energy consumption of the device mainly comes from the corona discharge and the pressure loss of the flue gas during the device operation. During the industrial demonstration, the average power consumption caused by the corona discharge was 22.43 kW, while the average additional power consumption caused by pressure loss was 44.4 kW. Evidently, the additional power cost is low compared to the total power consumption cost of the ultralow emission system (636.15 kW).

In summary, these engineering practices are all achieved through phase transition enhanced by corona discharge. The corona discharge not only promoted the removal of pollutants but also reduced the maintenance expenses of CHE by removing slurry droplets in advance. The phase transition enhanced by corona discharge increased the number of condensed droplets captured by the tube wall of the CHE, which led to an increase in the water and heat recovery rates. For further application, strategies to improve the economic benefit of this method should be considered. Thus, a flue gas treatment method that combines a precharger, CHE, and WESP could be considered to face the complex operating conditions in the future.

ASSOCIATED CONTENT

1 Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.2c00917.

Details of laboratory-scale experiment; schematic of the experimental setup and configuration of sampling position along with the growth tube (Figure S1); comparison between the simulation and actual measurement of the flue gas temperature distribution in the growth tube (Figure S2.); basic parameters of the fuel (Table S1); original particle-size distribution under different flue gas temperature differences and applied voltages (Figure S3); details of mass balance; theoretical condensation mass of water vapor; calculation of fuel saving and carbon emission reduction (PDF)

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Notes

The authors declare no competing financial interest.

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