EXPERIMENTAL MEASUREMENT OF FLUE GAS TEMPERATURE VERSUS ASH ACCUMULATION

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ABSTRACT
It is known that particle accumulation is beneficial for dust removal in industry. In order to understand better particle accumulation mechanism, experiments were carried out to analyze the influence of flue gas temperature and humidity on ash accumulation. It is found that the Engineering Acid Dew Temperature (EADT) of flue gas is an important parameter that determines the efficiency of particle accumulation. When the gas temperature is lower than the EADT, the sulfuric acid in the flue gas and ash humidity rise dramatically, which leads to particle accumulation. In order to improve the collection efficiency, the flue gas temperature can be controlled to trigger particle accumulation.

1 INTRODUCTION
Direct emission of industrial waste gas and aerosol threatens human health [1]. It is necessary to install dust collectors in power plants. The collection efficiency of a dust collector is closely related to ash size. Traditional dust collectors were efficient to particles of diameter larger than 10 µm but inefficient to inhalable small particles of diameter between 0.1 and 10 µm [2]. Ash accumulation is an effective and economical method for improving dust collection efficiency.

Ultrasound was utilized to intensify the accumulation of sub-micron particles [3]. The influence of bipolar charging on the efficiency of fine particles accumulation was investigated [4, 5]. These studies found that the percentage of fine particles (0.1~1.0 µm) decreased by 17-19% due to particle accumulation. Watanabe [6] studied the electrostatic accumulation. Thonglek and Kiatsiriroat [7] observed the accumulation of sub-micron particles by a non-thermal plasma electrostatic precipitator and noted that the efficiency increased when the gas velocity was increased from 0.5 to 1 m/s at 45 kVp voltage and 20 kHz frequency. Tiwary and Reethof [8] and Rodriguez-Maroto et al. [9] studied the method of acoustic accumulation. Their results revealed that the accumulation caused a 20% concentration reduction for particles of diameter smaller than 1 µm. The above-mentioned studies considered particle accumulation via adjusting the operation parameters of dust collectors, such as gas velocity, voltage, and current frequency.

Recently some researchers and engineers put forward the method of decreasing the exhaust gas temperature from 120~170°C to 90~110°C or an even lower range in order to recover waste heat from exhaust flue gas [10]. Low-temperature dust removal technology can prevent the corona effect of an electrostatic precipitator effectively and reduce the dust emission, because the flue gas velocity declines with decreasing temperature, and the flue gas would stay in the precipitator for a longer time, which is
helpful for dust removal [10]. Noda and Makino [11] investigated the influence of operating temperature on the performance of an electrostatic precipitator, and pointed out that the collection efficiency of a low-temperature electrostatic precipitator is related with Na and K contents. Ronisse et al. [12] discovered the effect of particle surface moisture on accumulation growth rate in fluidized beds through population balance modeling. As a matter of fact, flue gas properties vary with temperature. To authors’ knowledge, the gas temperature effects on a wide range of flue gas properties affecting ash accumulation is not yet available in the literature.

In this paper, experiments were conducted to investigate the influence of flue gas properties such as temperature, SO$_2$ volume fraction, and water vapor content on ash particle accumulation. The collected ash particle size distribution was analyzed. The Engineering Acid Dew Temperature (EADT) for the flue gas was calculated and compared with the actual gas temperature during dust collection.

2 EXPERIMENT DESCRIPTION
2.1 Experimental System

The experimental system used for ash collection is shown in Fig. 1. The major part is a small wind tunnel of about 8m long with a cross section of 300×280 mm$^2$. The air duct is insulated outside to minimize heat dissipation. During experiments, the air generated from the forced fan remains constant, i.e., 383 m$^3$/h at 15 °C. The air flows through the baffles, electric heating system, spraying system, feeding system, cooling system, accumulation section, and dust samples collector in turn. The baffles are used to adjust the air velocity in the accumulation section during pre-experiments.

The heating system is to heat up the air from the fan. It is composed of a 380V three-phase power supply, a solid-stay relay, an intelligent temperature controller, 6 electric heating pipes, and a thermocouple. The temperature controller receives the signal from the thermocouple. When the air temperature at the measuring point is higher/lower than 130°C, the controller will actuate the relay to power off/on the power supply of the heating pipes to keep the air temperature constant (130°C).

The spraying system sprays atomized water and sulfuric acid into the heated air to adjust the air temperature precisely. It is composed of an anti-corrosion flowmeter, a low-pressure superfine atomizing nozzle, a speed regulator, a micro high-pressure pump, and a tank. The prepared dilute sulfuric acid is sprayed into the air with average drop diameter about 20–40µm. The flux of sulfuric acid is adjusted by the speed regulator, which can control the rotating speed of the pump. The thermocouple in the heating system located in the downstream of the spraying system monitors the temperature and ensures that the sprayed water and sulfuric acid turn into vapor at the temperature of 130°C. The air volume flow rate after the spray system is 535.9 m$^3$/h after temperature correction. Thus, the duct air velocity is about 1.77 m/s.

The feeding system feeds ash into the air. It is composed of an ash bunker, a screw feeder, a frequency converter, and an electromotor. The ash used was collected from an electric precipitator of a

![Figure 1. THE SCHEMATIC DIAGRAM OF EXPERIMENTAL SYSTEM](image-url)
coal-fired power station in China. Now the air in the duct became flue gas with the additions of water vapor, ash, and sulfuric acid vapor after flowing through the heating system, the spraying system, and the feeding system. The created gas is similar to flue gas exhausted from coal-fired boilers.

The cooling system in the experimental setup is to cool down the flue gas to a preset temperature to investigate the effect of temperature on particle accumulation. It is composed of a water tank, a circulating water pump, valves, and a heat exchanger. The heat is transferred from the hot flue gas to the circulating water. There is another thermocouple at the accumulation section to measure the flue gas temperature. This gas temperature is variable by adjusting the circulating water valve, and it is a key parameter in this study.

The cooled flue gas flows into the accumulation section with a cross section of 600×280 mm², which is larger than that of the wind tunnel duct. Here the flue gas slows down to about 0.8 m/s, which is similar to the velocity in practical processes designed by Chinese standard General Technical Specifications for Electrostatic Precipitation Engineering (HJ2028-2013). A reduced velocity increases collisions between ash particles and thus promotes particle accumulation. It takes about 2 seconds for the flue gas to flow through the accumulation section. At the side of the section, a transparent acrylic board is installed to observe particle deposit in the accumulation section. The current experimental design prevents particles from deposit in the accumulation section before entering into the dust collector. The dust collector is actually a cyclone separator, through which ash particles are collected for sampling analysis.

2.2 Measurement

The particle size distribution obtained in sampling analysis can be used to assess directly ash accumulation effect. Particle accumulation is also affected by the humidity in the flue gas as later pointed out. Therefore, we measured both particle size distribution and humidity in this study.

There are many means to measure the distribution of particle diameter, such as the vibration methods [13], the sedimentation methods [13], and the microscope method [14]. In this study, an LS13320 laser particle analyzer was used to measure the size distribution of the collected particles because of its wide measuring range, faster measuring response, better reproducibility, and easiness to operate. The measuring range of the analyzer is 17nm–2000μm with a measuring accuracy of 0.001 μm.

The drying method was adopted to measure the dust humidity according to Chinese National Standard - Methods of Dust Characters Test (GB/T 16913-2008). The dust humidity is defined as the ratio of the lost weight to the total weight of the collected sample after it is dried in the electrically heated drying oven. A 9037A drying oven having a temperature range from 15 to 300°C was used in the present study.

The flow injection of the sprayed sulfuric acid was calibrated by a 100 ml measuring cylinder. The relative error of the measured flow is about ±1%.

2.3 Experiments

The purpose of this study is to analyze the influence of different gas parameters on ash particle accumulation. These parameters include SO₂ volume fraction, water vapor volume content, dust concentration, and temperature of flue gas.

The SO₂ volume content usually varies within the range of 20–50ppm in industrial flue gas of coal-fired boilers [15]. However, it is difficult to keep SO₂ volume content at very low values steadily and precisely during experiment. Therefore, the SO₂ volume portion is preset to four values in the present experiments, i.e., 30, 40, 50 and 60ppm.

In practical processes, water vapor volume content in flue gas is usually between 6–15% [16]. In the current experiments, the water vapor volume content is set to four values, i.e., 6, 8, 10 and 12%. In the testing process, the environmental temperature was maintained at about 15°C. The relative water vapor volume content in the air is about 35%.

In order to ensure high accuracy, the sprayed water and sulfuric acid should be added into the test system simultaneously. To this purpose, we used 6mol/L sulfuric acid solution. The capacity of the sulfuric acid tank is 0.025m³. The sprayed flux of the sulfuric acid was calculated in advance and adjusted by the spraying system.

The ash concentration in industrial flue gas is about 20 g/m³ [17]. In this study, ash concentration could be adjusted by the feeding system. The output of the screw feeder is proportional to its rotational speed in the calibration test, which can be adjusted by a frequency converter [18]. The ash concentration is set at 10.54 g/m³.

The temperature of the flue gas is a critical parameter that influences the ash accumulation. The exhaust flue gas temperature in practical coal-fired boilers varies in 115–130°C, about 20°C above the calculated acid dew point [19]. Since low-temperature was found to be helpful for dust removal in electrical agglomeration of aerosols [10], we would focus on the influence of low-temperature on ash accumulation in the present system. The gas temperature in the accumulation section could be adjusted by the control valve from the water tank and was preset to four values as well, i.e., 110, 90, 70, and 50°C, all below the acid dew point.

3 RESULTS AND DISCUSSION

3.1 EADT

The flue gas in the present experiments was consisted of air, SO₂, water vapor, and ash. During the experimental process, H₂SO₄ gas was produced because of SO₂ and water vapor chemical reaction. H₂SO₄ vapor condensates when the flue gas temperature is below the Acid Dew Point (ADT), which is the temperature when H₂SO₄ vapor begins to condensate. ADT is a function of the partial pressure of H₂SO₄ vapor.

When the flue gas temperature is slightly lower than the local ADT, the partial pressure of H₂SO₄ vapor decreases because part of the H₂SO₄ vapor condensates into liquid acid, leading to a decrease of the local ADT. Thus, the condensation may not continue and the condensed sulfuric acid is so rare that
it has little influence on particle accumulation. As the flue gas temperature drops much below the ADT, however, the $\text{H}_2\text{SO}_4$ vapor condensation produces a large amount of liquid acid. The ash absorbs the liquid acid, which makes the ash particles sticky and easy to accumulate. This was why the preset gas temperature range ($50 \sim 110^\circ C$) was generally below the ADT in this study. On the other side, the exhaust flue gas temperature in practical industry could reach to $115\sim130^\circ C$. Therefore, it could be very costly and impractical to further lower the gas temperature to below $50^\circ C$.

Shi et al. [20] proposed a new concept of Engineering ADT (EADT). The EADT was defined as the critical turning temperature point or a range, at which the heat transfer performance of waste heat recovery system in low-temperature flue gas changes dramatically. It was found that, when the wall temperature was greater than the EADT, the deposited ash on the heat transfer surface was loose and easy to clean; and no corrosion was observed. When the wall temperature was lower than the EADT, the deposited ash was sticky and hard to blow away; and wall corrosion was obvious and the heat transfer performance became worse dramatically. Thus, we believe that the EADT is more relevant to ash particle traits, especially to particle accumulation.

3.2 Influence of Gas Temperature

Keep the water vapor content, $\text{SO}_3$ volume fraction and dust concentration at standard condition. Keep the temperature in the accumulation section at different temperatures. Ash was collected from the ash collector every 20 minutes for further analysis. The curves of collected ash, ash diameter distribution and ash humidity under different temperatures are shown in Figs. 2, 3, and 4. From these figures, the following phenomenon can be observed.

In Fig. 2, the amount of collected ash in 20 minutes increases dramatically as the gas temperatures goes down. The collected ash at $90^\circ C$ is slightly more than that at $110^\circ C$. But when the temperature is under $90^\circ C$, the collected ash rises dramatically. In Fig. 3, collected ash humidity increases with flue gas temperature drops. In Fig. 4, the vertical coordinate is volume fraction, which is defined as the volume of a given diameter divided by the overall volume. The profiles of volume fraction under different temperatures are of two shapes. The profiles under $110$ and $90^\circ C$ are almost same. In large ash particle zone (about $>18\mu m$), the volume fraction under $383K$ is slightly larger than that at $90^\circ C$. But in small particle zone (about $<18\mu m$), the volume fraction at $110^\circ C$ is slightly smaller than that of $90^\circ C$. The profiles at $70$ and $50^\circ C$ are of another shape. There are no small particles at all. There are no particles smaller than $11\mu m$ at $70^\circ C$ and no particles smaller than $17\mu m$ at $50^\circ C$. But the volume fraction of large particles is quite high.

The reasons for the above curves are closely related to the gas temperature. The calculated the EADT is about $92\sim97^\circ C$. When the temperature in the accumulate section drops from $110$ to $50^\circ C$, it drops through the EADT to lower temperature.

When the temperature is above the EADT($110^\circ C$), the condensed sulfuric acid is rare and the dust humidity is low. The dust used in the experiments is obtained from power plant, it is so tiny that most of them cannot be collected by ash collector. So the collected ash in 20 minutes is the least and the volume fraction of small particles is smaller than that of large particles. When the temperature is slightly under the EADT($90^\circ C$), the condensed sulfuric acid increases, the ash humidity rises and particles become more sticky. When two sticky ash particles collide, they will accumulate and because larger. So the collected ash at $90^\circ C$ is more than that under $110^\circ C$. The volume fraction of larger particle at $90^\circ C$ is more than that at $110^\circ C$. When the temperature goes down to $70^\circ C$ and $50^\circ C$, it is far below the EADT and almost approaches the water dew point. There are much sulfuric acid and water in the gas, and the humidity rises dramatically. Ash particles collide with each other and accumulation goes on. So the collected ash increases and the particle size distribution changes. That is, there are no small particles at all.
3.2 Influence of SO$_3$ Content

The curves of collected ash, ash humidity and ash diameter distribution at different SO$_3$ volume content are shown in Figs. 5, 6, and 7. From these figures, the following phenomenon can be observed. In Fig. 5, with the SO$_3$ concentration rises, more and more dust particles are collected. At the same time, there is a dramatic jump when the SO$_3$ concentration increases from 30ppm to 40ppm. Fig. 6 shows that the humidity also increases with it and the dramatic increase occurs at 50 to 60ppm. In Fig. 7, when the SO$_3$ concentration rises, the small particles vanish gradually and larger particles become more and more. At 60ppm, no particles under 20µm exist.

The reasons for the above curves are closely related to the local gas temperature and EADT. The EADT increases, with the SO$_3$ concentration in the accumulation section rises from 30ppm to 60ppm. When the SO$_3$ concentration is low, the EADT is relatively high. Thus the temperature in the accumulation section is slight lower than EADT. There are little sulfuric acid or water in the gas. So the collected ash is the least and the humidity is the lowest at 30ppm. With the SO$_3$ concentration rises, the EADT goes up, which leads to more and more sulfuric acid vapor condensate. Thus the ash humidity rises and becomes stickier. When two sticky ash particles collide, they will accumulate and become larger. So the collected ash increases with the rise of the SO$_3$ concentration. The volume fraction of larger particle at 30ppm SO$_3$ concentration is less than other conditions. When the SO$_3$ concentration reaches 50ppm or 60ppm, the EADT is so high that the gas temperature in the accumulation section is far below the EADT.

3.3 Influence of Water Vapor

The curves of collected ash, ash humidity and ash diameter distribution under different water vapor contents can be drawn in Figs. 8, 9, and 10. The variation can be summarized as follows.
With the increasing water vapor content, both the collected ash and humidity increase with it. The ash collected amount increases with the water vapor content almost in linearly. While there is sharp increase in humidity when the water content increases from 10% to 12%. The accumulation occurs and dust removal efficiency rises. When the water vapor content reaches 10%, there is no little particle under 10µm.

More sulfuric acid and water vapor condense, which leads to a dramatically increase in humidity. Collisions among particles get tempestuously and particles get larger. So the collected ash increases and the particle size distribution changes. That is, there are no small particles (10µm) when the water content is over 10%.

The variation is also connected with the EADT closely. The EADT increases with the water content rises from 6% to 12%. The EADT is low when the water content is 6%. So the temperature in the accumulation section is slight lower than EADT. Little water exists in the gas. Little ash particles are collected when the water vapor content is 6%. The EADT increases with the rising water vapor content, which leads to more and more sulfuric acid vapor condensate. Thus the ash humidity rises and becomes stickier, which is same as the variation with SO₃ volume fraction. As a result of that, the collected ash increases with the water content. When the water content reaches 12%, the EADT is so high that the gas temperature in the accumulation section is far below the EADT.

3 CONCLUSION
Experiments were carried out to investigate the mechanism of particle accumulation under different conditions. The result shows it is closely related to flue gas properties. It is found that the EADT of flue gas is an important temperature, which influences particle accumulation. When the gas temperature is above the EADT, the sulfuric acid in flue gas is rare and the ash humidity is low. Ash diameter distribution is the same as its original like. All these show that there is no particle accumulation occurs. When the temperature goes below the EADT, the sulfuric acid in flue gas and ash humidity rise. More and more large particles can be detected, which indicate that particle accumulation occurs. The EADT of flue gas is influenced by SO₃ concentration and water vapor content. These properties, together with gas temperature will determine whether particle accumulation will occur. The flue gas temperature can be changed to trigger particle accumulation.

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