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An Experimental Study of Ash Accumulation in Flue Gas

Yuetao Shi\textsuperscript{1,2}, Xiaojuan Wang\textsuperscript{1}, Da Chu\textsuperscript{1}, Fengzhong Sun\textsuperscript{1}, Zhixiong Guo\textsuperscript{2*}

\textsuperscript{1}School of Energy and Power Engineering, Shandong University, Jinan, China

\textsuperscript{2}Department of Mechanical and Aerospace Engineering, Rutgers University, New Jersey, USA

*Correspondence authors: Z. Guo, Professor, guo@jove.rutgers.edu

Y. Shi, Associate Professor, shieddie@sdu.edu.cn

Abstract

Accumulation of small particles is beneficial for dust removal. We have carried out experiments to investigate the influences of flue gas properties, especially temperature, humidity, sulfuric acid and dust concentrations, on ash particle accumulation. The ash used was collected from an electric precipitator of a coal-fired power station. It is found that ash accumulation is strongly influenced by the flue gas temperature in comparison with the Engineering Acid Dew Temperature (EADT). With decreasing temperature below the EADT, both sulfuric acid in the flue gas and ash humidity rise, and the detected particle distribution shifts to larger size - indicating increased particle accumulation. Therefore, the flue gas temperature can be controlled to enhance particle accumulation and improve ash collection efficiency.

Keywords: Ash; Flue gas; Temperature; Particle accumulation
Nomenclature

A  Ash
C  Concentration
EADT  Engineering acid dew temperature (°C)
K  Conversion rate
M  Molar mass (g/mol)
P₀  Local atmospheric pressure (Pa)
Q  Calorific value (kJ/kg)
R  Volume fraction
S  Sulfur
T  Temperature (°C)
Vᵢ  Actual flue gas volume (m³/kg)

Greek symbols

α  Excess air coefficient
αₐ  Fly Ash Coefficient
β  Coefficient
ρ  Density (kg/m³)

Subscripts

ld  Dew point
sld  Acid dew point
ar  As received basis
net  Low calorific
1. Introduction

The emission of industrial waste gas and aerosol especially micro/nano particles brings great threats to the health of human beings. Not only may it affect and disable organs of human body, but also interfere with the function of human immune system [1, 2]. A dust collector is thus necessary in a power plant. The collection efficiency of a dust collector is closely related to ash size. According to the study of Zhou et al. [3], a traditional dust collector was efficient to particles of diameter larger than 10 µm but inefficient to inhalable small particles of diameter between 0.1 and 10 µm. Ash accumulation is one of the most effective and economical methods for improving dust collection efficiency. Research and technical development on ash accumulation have aroused widespread interests [4].

Ultrasound was utilized to intensify the accumulation of sub-micron particles by de Sarabia et al. [5]. Others [6-9] investigated the influence of bipolar charging on the efficiency of fine particles accumulation. These studies found that the percentage of fine particles (0.1~1.0 µm) decreased by 17-19% due to particle accumulation. Watanabe [10] studied the electrostatic accumulation. Thonglek and Kiatsiriroat [11] 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 [12] and Rodriguez-Maroto et al. [13] 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.

In recent years, some researchers and engineers put forward the method of decreasing the exhaust gas temperature from 120–170°C to 90–110°C or a even lower range in order to recover waste heat from exhaust flue gas [14]. 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 [14]. Noda and Makino [15] 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. Ronsse et al. [16] 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 study, a series experiments were conducted to investigate the influence of flue gas properties such as temperature, SO₃ volume fraction, water vapor content,
and dust concentration 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. A focus is to lower the gas temperature below the EADT to increase ash accumulation in order to improve ash collection efficiency.

2. Description of Experiment and Method

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 mm². The air duct is insulated outside to minimize heat dissipation. During experiments, the air generated from the forced fan remains constant, i.e., 383 m³/h at 15 °C. Thus, the air mass flow rate is 0.137 kg/s. 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. Once a formal experiment starts, the baffles opening remains constant.

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 component 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 20~40 µm. 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 locating 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 m³/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 in the present experiments was collected from an electric precipitator of a coal-fired power station in China. Now the air in the duct is changed into 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 in the experiments 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 Measuring instruments

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 [17], the sedimentation methods [17], and the microscope method [18]. In this study, an LS13320 laser particle analyzer [19] 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 17 nm~2000 µm 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%. According to the listed instrument specifications, the measuring precision is 4.25% and 1.52% for dust humidity and particle diameter distribution, respectively. The parameters to be measured and the instruments used are summarized in Table 1.

### 2.3 Experimental Conditions

The purpose of this study is to analyze the influence of different gas parameters on ash particle accumulation. These parameters include SO₃ volume fraction, water vapor volume content, dust concentration, and temperature of flue gas.
The SO$_3$ volume content usually varies within the range of 20–50ppm in industrial flue gas of coal-fired boilers [20]. However, it is difficult to keep SO$_3$ volume content at very low values steadily and precisely during experiment. Therefore, the SO$_3$ volume portion is preset to four values in the present experiments, i.e., 30, 40, 50 and 60ppm. The conversion between ppm and common unit in practice, kg/m$^3$, is as follows:

$$\frac{kg}{m^3} = \left( ppm + \frac{M_{H_2SO_4}}{22.4} \right) \times \frac{273.15}{273.15 + T} \times \frac{P}{101325}$$

(1)

where, $M_{H_2SO_4}$ is the molar mass of H$_2$SO$_4$, 98g/mol; $T$ is the temperature in the duct, 130°C; and $P$ is the absolute pressure in the duct measured by a barometer, 103,220 Pa. Thus, the four preset ppm values correspond to 0.092, 0.121, 0.151 and 0.181 kg/m$^3$, respectively.

In practical processes, water vapor volume content in flue gas is usually between 6–15% [21]. In the current experiments, the water vapor volume content is set to four values, i.e., 6, 8, 10 and 12%, corresponding to 3.3272×10$^{-2}$, 4.4363×10$^{-2}$, 5.5454×10$^{-2}$ and 6.6545×10$^{-2}$ kg/m$^3$, respectively. 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%, i.e., 4.48×10$^{-3}$ kg/m$^3$. According to the above data with 0.106 m$^3$/s air volume flow rate from the forced fan, the sprayed water flow rate corresponding to the four preset water vapor contents is calculated as 1.104×10$^{-2}$, 1.53×10$^{-2}$, 1.95×10$^{-2}$ and 2.376×10$^{-2}$ m$^3$/h, respectively. And the corresponding mass flow rate is 3.067×10$^{-3}$, 3.75×10$^{-3}$, 5.42×10$^{-3}$ and 6.6×10$^{-3}$ kg/s, respectively.
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, which is converted into a mass/volume proportion of 588kg/m³. 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 0.02 kg/m³ [22]. 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 [23]. The ash concentration is preset to four values, i.e., 4.26×10⁻³, 6.67×10⁻³, 10.54×10⁻³ and 17.05×10⁻³ kg/m³, respectively.

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 [24]. Since low-temperature was found to be helpful for dust removal in electrical agglomeration of aerosols [14], 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.

After careful calibration with control valves, the flue gas temperature, water vapor contents, and other important experimental conditions are summarized in Table 2. For comparison, a standard condition is set as follows: SO₃ volume portion at 40ppm, water vapor content at 10%, dust concentration at 10.54×10⁻³ kg/m³, and gas
temperature at 70°C. To study the effect of one parameter, we will vary the parameter at the predefined values while keep other three factors at the standard condition.

3. Results and Discussion

3.1 Engineering acid dew temperature (EADT)

The simulated flue gas in the present experiments was consisted of air, SO₃, water vapor, and ash. During the experimental process, H₂SO₄ gas was produced because of SO₃ 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 H₂SO₄ 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 – 110°C) was generally below the ADT in this study. On the other side, the exhaust flue gas temperature in industry could reach to 115~130°C. It is costly and impractical to further lower the gas temperature to below 50°C.
The present first author proposed a new concept of Engineering ADT (EADT) [25]. 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 clear; and no corrosion was observed [26]. 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. The EADT was calculated as about 32~35°C less than the ADT value [25], i.e.,

\[
EADT = T_{\text{sld}} - (32 \sim 35)
\]  

(2)

In which \( T_{\text{sld}} \) is the ADT, calculated by the Soviet correlation [26] as

\[
T_{\text{sld}} = T_{\text{ld}} + \frac{\beta \times \sqrt[3]{S^X}}{1.05 \times h \times d^4}
\]  

(3)

where \( T_{\text{ld}} \) is water dew point, \( S^X \) is the converted sulfur mass content of the fired coal, \( A^X \) is the converted ash mass content of the fire coal, \( h \) is fly ash coefficient, and \( \beta \) is a coefficient relevant to excess air coefficient. For a pulverized coal boiler, \( h = 0.9 \), which means 90% ash leaves the boiler through flue gas; and \( \beta \) is calculated as 125. In Eq. (3), \( T_{\text{ld}}, S^X \) and \( A^X \) are to be calculated according to the fired coal quality and industry scale experimental conditions in the following.

The converted sulfur mass fraction \( S^X \) and ash mass fraction \( A^X \) are calculated by:

12
\[ S^X = 4190 \frac{S_{ar}}{Q_{net,ar}} \]  \hspace{1cm} (4a) \\
\[ A^X = 4190 \frac{A_{ar}}{Q_{net,ar}} \]  \hspace{1cm} (4b)

In which \( S_{ar} \) and \( A_{ar} \) are mass fraction of sulfur and ash, respectively, in coal of As Received basis. The term ‘As Received basis’ means coal in the condition as received by the consumer without processing (i.e., when the coal is received by a power plant in ambient environmental conditions). The low calorific value of As Received basis \( Q_{net,ar} \) [27] is

\[ Q_{net,ar} = 4.1816 \times (1 - M_{ar}) \times \left[ 8200 - 900 \left( \frac{A_{ar}}{1 - M_{ar}} \right) \right] - 420 \]  \hspace{1cm} (5)

In which, \( M_{ar} \) and \( A_{ar} \) are water and ash mass fractions in coal of As Received basis.

The actual flue gas volume, \( V_y \), generated when burning 1kg coal is calculated as:

\[ V_y = \left( 0.249 \times Q_{net,ar} + 0.77 + (\alpha - 1) \times \frac{Q_{net,ar} \times 1000}{3704} \right) \times \left( 1 + \frac{T}{273.15} \right) \text{[m}^3\text{/[kg]} \]  \hspace{1cm} (6)

where \( \alpha \) is the excess air coefficient; and \( \alpha = 1.3 \) for flue gas exhausted from industrial boilers [28]. \( T \) is the gas temperature in the accumulation section of the present experiment.

The SO\textsubscript{3} volume fraction, \( R_{SO_3} \), and water vapor volume fraction, \( R_{H_2O} \), and ash concentration, \( C_A \), in the simulated flue gas are calculated as follows:

\[ R_{SO_3} = K \times \frac{S_{ar}}{2 \times \rho_{SO_2} \times V_y} \times 10^6 \]  \hspace{1cm} (7)
\[ R_{H_2O} = \left[ \frac{16.1(\alpha-1)Q_{net,ar}}{3704} + \left(1.24M_{ar} + 11.1H_{ar} + \frac{16.1Q_{net,ar}}{3704}\right) \right] / V_y \]  
\[ C_A = \frac{10\alpha^b \times A_{ar}}{V_y} \]

where \( K \) is the conversion rate from \( \text{SO}_2 \) to \( \text{SO}_3 \), \( K=0.03\sim0.08 \) [29]. \( \rho_{\text{SO}_2} \) is the density of \( \text{SO}_2 \) at the standard condition, \( \rho_{\text{SO}_2} = 2.86 \text{ kg} / \text{Nm}^3 \). \( H_{ar} \) is the hydrogen mass fraction in coal of As Received basis, which has little influence on the ADT. In the present study, \( H_{ar} \) is set as 1% according to the industrial process.

The water dew point \( T_{ld} \) is now calculated as:
\[ T_{ld} = 42.4332 \times \left( R_{H_2O} \times P_0 \right)^{0.13434} - 100.35 \]

In which, \( P_0 \) is the local atmospheric pressure, \( P_0=103,220 \) Pa.

With assumed values of \( A_{ar} \), \( M_{ar} \), \( S_{ar} \), \( H_{ar} \), and \( K \), the \( \text{SO}_3 \) volume fraction \( R_{\text{SO}_3} \), water vapor volume fraction \( R_{H_2O} \), and fly ash concentration \( C_A \) in the flue gas can be calculated. If the calculated values equal to the experimental conditions, the assumed values can be used to derive the acid dew point and the EADT. The flow chart for calculating the EADT is shown in Fig. 2.

According to the present experimental conditions, the maximum ADT obtained from the Soviet correlation is about 133\(^\circ\)C, and the maximum EADT is in the range of 93\sim98\(^\circ\)C.

3.2 Influence of gas temperature

First we kept the water vapor content, \( \text{SO}_3 \) volume fraction and dust concentration at the standard condition, and varied the gas temperature in the accumulation section according to the four preset values. Ash was collected from the ash collector every 20
min for sample analysis. The curves of the collected ash mass and the dust humidity against the flue gas temperature are shown in Fig. 3. It is seen that the collected ash at 90°C is more than that at 110°C. But when the gas temperature drops to 70°C and 50°C, the collected ashes increase dramatically. The calculated EADT showing between the two dashed vertical lines in the figure is in a range of 92~97°C. This EADT range is wider than the EADT range as defined in Eq. (3) because the conversion rate from SO₂ to SO₃ in the coal has a range from 3% to 8% and thus the ADT varies in a small range as well. When the gas temperature in the accumulate section drops from 110°C to 90, 70, and 50°C, it represents four distinct stages: gas temperature above the EADT, near the EADT, about 22~27°C below the EADT, and 42~47°C below the EADT. The lower the gas temperature, the more the collected ash. The dust humidity showing in Fig. 3 also increases as the flue gas temperature drops. Its increasing tendency is consistent with the increase of the ash collection.

Fig. 4a shows the size distributions of collected particles under the four different gas temperatures, in which the vertical coordinate is volume fraction, defined as the volume of a given diameter divided by the overall volume. It is seen that there are basically two profile shapes. The profiles for 110°C and 90°C are very similar because both temperatures are either above or slightly below the EADT. In the zone of larger ash particle (> 25µm), the volume fraction for 90°C is slightly greater than that at 110°C. The profiles for 70°C and 50°C represent another shape, though they are different in the region > 30µm. There are no fine particles at all in these two cases. At 70°C, there are no particles smaller than 11µm; and at 50°C, no particles smaller
than 17µm. The volume fractions of larger particles in these two cases are twice or more of those at 110°C and 90°C.

Fig. 4b shows curves of cumulative volume fraction of the collected particles under different temperatures. It should be mentioned that the dust used in the present experiments was obtained from a power plant and the particles in the dust were generally very small. The collector used is inefficient for collecting fine particles of diameter < 20µm. Fig. 4b shows that about 40% of the collected particles is smaller than 20µm at 90°C and about 46% at 110°C. However, such a value drops to 10% at 70°C and 5% at 50°C. This explains the improved collection efficiency for these two lower-temperature cases as seen in Fig. 3.

When the temperature (110°C) is above the EADT, the condensed sulfuric acid is rare and the dust humidity is low. When the temperature (90°C) is slightly under the EADT, the condensed sulfuric acid starts to increase, the dust humidity rises and particles become sticky. When two sticky ash particles collide, they tend to accumulate and form a larger particle that is easy to collect. When the temperature dropped to 20°C and even 40°C below the EADT, the sulfuric acid and humidity increased dramatically such that all fine particles (< 10µm) disappeared in these two cases as shown in Figs. 4a and 4b.

3.3 Influence of SO₃

Fig. 5 shows the collected ash amount, dust humidity, and EADT variations against SO₃ volume fraction in the accumulation section. Fig. 6 examines the particle sizes of the collected ash for four different SO₃ concentrations. It is seen from Fig. 5
that the collected dust particles increase with increase of the SO$_3$ content. In particular, there is a dramatic jump on the collected ash when the SO$_3$ concentration increases from 30 to 40ppm. The humidity also increases as SO$_3$ volume fraction increases, but a larger increase occurs at 60ppm. As shown in Fig. 6a, no particles under 20µm exist at 60ppm because of strong particle accumulation effect. When the SO$_3$ concentration is low (30ppm), the temperature in the accumulation section is just in the EADT range as shown in Fig. 5. There are little sulfuric acid and little water in the gas. Thus, the volume fraction of small particles (<20µm) at 30ppm shown in Fig. 6b is the largest among the four SO$_3$ concentrations. From Fig. 6b shows that the cumulative volume fraction at 20µm is about 20% at 30ppm, 12% at 40ppm, 10% at 50ppm, and 0 at 60ppm.

3.4 Influence of water vapor

Figs. 7 and 8 display the influences of water vapor content on the collected ash, dust humidity and ash diameter distribution. As shown in Fig. 7, both the collected ash and dust humidity increase as the water vapor content increases. The ash collected amount increases nearly linearly with the water vapor content. There is a sharp increase in humidity when the water content increases from 10% to 12%. From Fig. 8a, it is seen that when the water vapor content reaches 12%, there is no particles under 14µm; and Fig. 8b shows that the cumulative volume fraction for particles larger than 20µm is about 55% at 6% water vapor, 70% at 8% water vapor, 85% at 10% water vapor and 95% at 12% water vapor, respectively. This variation is nearly linear just like the collected ash curve shown in Fig. 7. Furthermore, Fig. 8a shows that the
amount of larger particles (>25μm) at 10% and 12% water contents is much greater than that at 6% and 8% water contents, which leads to high collection efficiency at 10% and 12% water contents. The above two factors explains why the collected ash changes almost linearly with the water vapor content.

### 3.5 Influence of dust concentration

The influences of dust concentration on collected ash, dust humidity, and ash diameter distribution are illustrated in Figs. 9 and 10. The collection efficiency, defined as the ratio of collected ash to the ash passing through the accumulation section within 20 min, is also plotted in Fig. 9. It is seen that the collected ash, dust humidity, and collection efficiency all increase as the dust concentration increases. However, the collected ash amount varies almost linearly with the dust concentration; while the collection efficiency and humidity are not, and their variations are very similar. The particle size distribution also shifts to large particle with increasing dust concentration as shown in Fig. 10.

Dust concentration has two opposite effects on particle accumulation. On one side, particles tend to accumulate because of the increased collision probability with the increase of dust concentration. This is why the collected ash amount is nearly linear to the dust concentration. When the dust concentration is 4.26 g/m³, the flue gas temperature is about 20°C below the EADT. Nevertheless, the collected ash amount is the least for this case because of the low collision probability at low dust concentration. On the other hand, the average sulfuric acid absorbed per unit ash area decreases with the increase of dust concentration, which is unfavorable to particle
accumulation. Further, the EADT decreases with increasing dust concentration. These lead to the nonlinear change of humidity and collection efficiency. For example, when the dust concentration increases from 4.26 g/m$^3$ to 6.67 g/m$^3$, the collision probability between particles increases significantly, resulting in strong particle accumulation and a jump in collection efficiency. With further increase of the dust concentration to over 12 g/m$^3$, the EADT drops such that the flue gas temperature is higher than the EADT. Even though collisions increase, the water vapor is hard to be absorbed by the ash particles because of higher flue gas temperature than the EADT. This is unhelpful for particles accumulation.

4. Conclusion

Experimental studies are conducted to investigate ash particle accumulation under different flue gas conditions. It is found that the EADT is an important parameter. When the gas temperature was above or near the local EADT, the sulfuric acid in flue gas was rare and the dust humidity was low. The ash diameter distribution was nearly unchanged. When the gas temperature dropped to 20 to 40°C below the local EADT, the sulfuric acid in the flue gas and the dust humidity rised significantly. The collected ash shifts to larger particle profile, indicating accumulation of small particles. The lower the gas temperature is as compared to the EDAT, the better is the particle accumulation, and the higher is the dust collection efficiency.

The EADT increases with increasing SO$_3$ concentration and water vapor content, but decreases with increasing ash concentration. These three gas properties, together
with the gas temperature will determine the overall efficiency of particle accumulation. Through this study it is suggested that the flue gas temperature should be lowered to 20 to 40°C below the EADT such that the small particles in flue gas can be accumulated to larger particles of size > 20 μm. This will improve ash collection efficiency substantially.

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[18] H. Yoshida, H. Masuda, K. Fukui, Particle size measurement with an improved sedimentation balance method and microscopic method together with computer


Fig. 1 Schematic diagram of the experimental system.

1-forced fan; 2-baffles; 3-pitot tube; 4-micromanometer; 5-electric heating pipes; 6-solid state relay; 7-intelligent temperature controller; 8-atomizing nozzle; 9 anti-corrosion flowmeter; 10-speed regulator; 11-mirco high-pressure pump; 12-valve; 13-sulfric acid tank; 14-thermocouple; 15-screw feeder; 16-ash bunker; 17-frequency converter; 18-electromoter; 19-drainage; 20-heat exchanger; 21-valve; 22-circulating water pump; 23-water tank; 24-make up water valve; 25 thermocouple; 26-digital temperature indicator; 27-cyclone separator.
Fig. 2 The flow chart for calculating EADT.
Fig. 3 Ash collected and dust humidity vs. gas temperature.
Fig. 4 (a) Particle size distribution and (b) cumulative particle volume fraction at different gas temperatures.
Fig. 5 Ash collected and dust humidity vs. SO$_3$ volume fraction.
Fig. 6 (a) Particle size distribution and (b) cumulative particle volume fraction at different SO₃ volume portions.
Fig. 7 Ash collected and dust humidity vs. water vapor content.
Fig. 8 (a) Particle size distribution and (b) cumulative particle volume fraction at different water contents.
Fig. 9 Ash collected and dust humidity vs. dust concentration.
Fig. 10 Particle size distribution for different dust concentrations.
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Instruments</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient temperature and moisture</td>
<td>TY-3827 hygrothermograph</td>
<td>0.01°C; 0.01%</td>
</tr>
<tr>
<td>Barometric pressure</td>
<td>DYM3 barometer</td>
<td>10Pa</td>
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<tr>
<td>Air velocity</td>
<td>Pitot tube</td>
<td>0.1m/s</td>
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<tr>
<td></td>
<td>Testo512 micro manometer</td>
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<tr>
<td>Spray quantity</td>
<td>Glass rotameter</td>
<td>0.278m³/s</td>
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<tr>
<td>Air temperature</td>
<td>TES1310 digital temperature</td>
<td>0.1°C</td>
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<tr>
<td></td>
<td>indicator</td>
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<tr>
<td>Particle diameter</td>
<td>LS13320 laser particle analyzer</td>
<td>0.001µm</td>
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<tr>
<td>Sample weight</td>
<td>BSM120.4 electronic scale</td>
<td>1×10⁻⁴kg</td>
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</table>
Table 2. Experimental Conditions

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Data</th>
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<tbody>
<tr>
<td>SO\textsubscript{3} content</td>
<td>ppm</td>
<td>30 40 50 60</td>
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<tr>
<td>Water vapor content</td>
<td>%</td>
<td>6 8 10 12</td>
</tr>
<tr>
<td>Ash concentration</td>
<td>\textit{10}\textsuperscript{-3}kg/m\textsuperscript{3}</td>
<td>4.26 6.67 10.54 17.05</td>
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<tr>
<td>Flue gas temperature</td>
<td>°C</td>
<td>110 90 70 50</td>
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<tr>
<td>Water flux</td>
<td>\textit{10}\textsuperscript{-3}m\textsuperscript{3}/s</td>
<td>0.125 0.083 0.066 0.05</td>
</tr>
</tbody>
</table>