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ENLAGEMENT OF MIST PARTICLES FOR WET TYPE ELECTROSTATIC PRECIPITATOR

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ABSTRACT

Gaseous SO_3 (H_2SO_4) condenses into a nucleus and becomes sulfuric acid mist in a cooling process such as the wet flue gas desulfurization system (WFGD). The relation between the temperature condition of this cooling process and particle size of mist was examined by condensation theory and experiments. In addition, the collecting efficiency and electric current density of a wet electrostatic precipitator (WESP) were examined with the mist generated by the cooling process.

Particle sizes of mist were measured at 30 ppm of SO_3 under various cooling conditions, and were measured in the case where fine particles of ammonium sulfate were supplied by spray-drying.

The particle size of the nucleus into which mist condenses depended on the speed at which the gas is cooled. At a slower cooling speed, mist did not condense into small particles. This indicates that the particle size of mist grows in the range where the gas temperature around the SO_3 condensation temperature is lowered slowly.

The electric current density of THE model ESP increased when the particle size of mist was larger, and the collecting efficiency was improved, too. This indicates that the specific collecting area of the ESP is influenced by the cooling condition.

NOMENCLATURE

a: Radius of mist particle (m)
F : Mass-transfer flux (kg/s)
t: Time (s)
ρ_p: Density of mist (kg/m^3)
D_g: Diffusion coefficient (m^2/s)
m_g: Mass of molecule (kg)
p_8 : Atmospheric vapor pressure (Pa)
p_d: Vapor pressure on surface of particle (Pa)
l_g: Mean free path of vapor molecule (m)
d_{av}: Average particle diameter (m)
k: Boltzmann's constant (J/K)
T: Temperature (K)
Y: Coefficient (1)
T_g: Gas temperature (°C)
γ: Surface tension (N/m)
M: Molecular weight (kg)
G: Average thermal velocity (m/s)
p_s: Saturated vapor pressure on plane (Pa)
d: Particle diameter (m)
s : Geometric standard deviation (–)
SCA: Specific collecting area (s/m) [Dust collection area/Volume of treated gas]

1. INTRODUCTION

Since the ban on sales of electric power by independent power producers (IPP) was lifted in 1995 in Japan, many power generation plants have been planned for wholesale power sales. Of those, many of the IPPs operating petroleum-related businesses use residue oil or petroleum coke as fuels. Since such fuels contain a high concentration of sulfur, the combustion exhaust gas contains SO_3 in concentrations of as high as several tens of ppm.

As an exhaust gas treatment system, in addition to a dry type electrostatic precipitator and WFGD, a wet type electrostatic precipitator (WESP) is newly being installed to remove SO_3 mist.

The acid dew point of the exhaust gas that contains SO_3 in concentrations of several tens of ppm is as high as one hundred and several tens of °C. Although SO_3 is in the gaseous state within the dry ESP, mist is generated when water is sprayed with wet desulfurization equipment to decrease the temperature. Since the generated SO_3 mist contains particles of very small diameter, it is almost impossible to remove them by making them collide with water sprayed from the wet desulfurization equipment, so a WESP is installed to collect such fine mist. However, a problem with the WESP is that the equipment must be large because of current control due to the space-charge effect and small mist particle diameter.

In this research, enlargement of the mist particle diameter and the dust collection efficiency of the WESP were examined to optimize exhaust gas treatment systems.

2. DETAILS OF THE STUDY

2.1 Condensation and Growth of Particles

SO_3 mist is generated by a process in which the temperature is decreased by the desulfurization equipment. According to a report by Muller, the acid dew point of sulfuric acid is approximately 140°C if the concentration is 30 ppm. Consequently, gaseous sulfuric acid of approximately 170°C at the inlet of the desulfurization equipment starts condensing using dust contained in the exhaust gas as a nucleus when the temperature decreases to approximately 140°C. When the temperature decreases further down to the water dew point, water condenses around condensed sulfuric acid mist. Consequently, the concentration of sulfuric acid in the condensed mist is high at the initial stage of condensation, and it decreases as the mist takes up water in the process of reaching the dew point.

The speed of growth of particles by vapor condensation can be generally expressed by equation (1) shown below. To find the conditions under which the mist particle diameter can be made larger, the status where mist condenses during the process of temperature decrease was simulated.

$$\frac{da}{dt} = \frac{F}{4p\, a^2\, ?_p} \qquad (1)$$

$$F = 4\, p\, a\, D_g\ \ m_g\, Y\, \frac{p_8 - p_d}{k\, T} \qquad (2)$$

$$In \left(\frac{p_d}{p_s}\right) = \frac{2\, ?\, M}{a\, ?_p\, R\, T} \qquad (3)$$

$$\gamma = 0.001 \times (75.716 - 0.1416\, T_g\ - 0.00025054\, T_g^2) \qquad (4)$$

$$D_g = \frac{G\, l_g}{3} \qquad (5)$$

$$G = \sqrt{\frac{8\, k\, T}{p\, m_g}} \qquad (6)$$

The saturated vapor pressure of a sulfuric acid solution, p_s, varies depending on the sulfuric acid concentration. In this research, the simulation was performed by applying the vapor pressure corresponding to the sulfuric acid concentration. The vapor pressure of concentrated sulfuric acid is given by equation (7), which is approximately consistent with the data for exhaust gas with a moisture concentration of 10% presented by Muller within the temperature range from 90 to 160°C [1].

$$p_s = 10^{\{21.137 - 9485.1\, /\, (273+Tg\,)\}} \times 133.322 \qquad (7)$$

The range of diameter of the particles used as condensation nuclei was set between 0.001 µm and 10 µm, which was equally divided by the logarithmic value into 40 for application.

$$f(d) = \frac{1}{\sqrt{2p}\, lns}\ \exp\ \{ -\ \frac{ln^2(d/\, d_{av}\,)}{2ln^2 s}\ \} \qquad (8)$$

2.2 Experimental Equipment

Figure 1 schematically shows the experimental equipment. The equipment consisted of a kerosene boiler, water spray cooling tower, water cooler, WESP, and a fan, with a laser particle size analyzer placed in a flue at the inlet of the model ESP. SO_2 and air were supplied to the SO_3 generator filled with catalyst for sulfuric acid generation to generate SO_3, which was fed to the flue through the boiler exit. The water spray cooling tower of 0.5 m in diameter and 3 m in height was provided with four 2-fluid nozzles from No.1 to No.4. The pattern of temperature decrease within the cooling tower was varied by changing the water volume coming out of each nozzle.

The model WESP consisted of stainless steel units of 600 mm in height, 400 mm in length, and a dust collecting electrode interval of 220 mm. The discharge wires were of a structure with 25-mm wire attached to a pipe of 21.7 mm in diameter. Three wires were placed at the pitch of 200 mm in parallel to the gas flow.

The possibility of enlarging the mist particle size was examined by changing the pattern of temperature decrease within the water spray cooling tower, with particles supplied by spray-drying. The current density and the dust collection efficiency of the model WESP were examined under different cooling temperature conditions.

3. RESULTS AND DISCUSSION

3.1 Simulation of Mist Enlarging Conditions

When the temperature decreases to the condensation temperature, the condensing component in gas starts condensing on the surface using particles as nuclei. As shown by equation (2), the volume of condensation is a function of the difference between atmospheric vapor pressure and the vapor pressure on the surface of particles ($p_8 - p_d$), which is affected by the temperature decrease. As shown by equation (3), the vapor pressure on the surface of particles is affected by the particle diameter. The smaller the particle diameter, the higher the vapor pressure. Therefore, condensation of mist is affected by the speed of temperature decrease and the distribution of particles used as nuclei for condensation. With those factors taken into consideration, the particle distribution in equation (8) was applied to condensation nuclei, and the effect of the speed of temperature decrease was simulated to find the conditions under which particles can be made larger.

Figure 2 shows the result of simulation of how the mist particle diameter changed when the exhaust gas containing sulfuric acid at a concentration of 30 ppm was cooled down. The calculation was made on the assumption that sulfuric acid condensed while the temperature decreased from 150°C to 100°C, and water condensed at a temperature lower than 100°C. That is why the simulation curves were discontinued at the point of 100°C. The diameter of particles used as nuclei varied depending on the degree of temperature decrease. When the temperature was decreased in steps of 1°C, the particle diameter was 0.02 µm or larger. When the temperature was decreased in steps of 10°C, the particle diameter was 0.03 µm or larger, and it was 0.001 µm or smaller when the temperature was decreased by 50°C. This indicates that if the cooling speed is faster, smaller particles are used as nuclei. The fact that smaller particles could be used as nuclei suggests that the number of particles used as nuclei increases. On the other hand, the absolute volume of condensation of sulfuric acid gas is determined not by the speed of temperature decrease but by the temperature after cooling. From these results, we conclude that it is effective to decrease the temperature gradually within the temperature range where condensation can occur. Figure 3 shows the particle distribution of condensed mist calculated under the same conditions as Fig. 2. The mist showed a mono-disperse tendency with uniform particle diameter, the particle diameters of both sulfuric acid condensation mist and water condensation mist became larger if the temperature was decreased by 1°C.

3.2 Mist Particle Diameter

i) Effect of maintaining cooling temperature

Since we conjectured that a gradual temperature decrease during condensation was effective for enlarging the mist particle size, the temperature within the cooling tower was maintained at a certain level temporarily.

Figure 4 shows the temperature patterns within the cooling tower expressed as A to H. With H, the temperature was decreased rapidly. The total volume of water sprayed within the water spray cooling tower was kept at a constant level, 300 mL/min., and the dew point at the exit fell within the range from 57 to 58°C in either of the patterns.

Figure 5 shows the relation between the temperature maintained within the cooling tower and the average particle diameter when the sulfuric acid concentration was 30 ppm. The mist particle size reached a peak when the temperature was maintained around 130 to 140°C. The mist particle diameter was larger within this range than at any other temperature. According to Muller, the acid dew point at the sulfuric acid concentration of 30 ppm is approximately 142°C. From this, to enlarge the mist particle diameter, it is effective to maintain the temperature approximately 10°C lower than the acid dew point. As estimated in the simulation, the mist particle diameter became larger because the temperature was decreased gradually within the condensation temperature range. With the decrease of temperature, the sulfuric acid becomes liquid. If the temperature is decreased gradually, the differential pressure of the vapor caused by the temperature difference is small. Consequently, particles smaller than a certain size cannot be used as nuclei for condensation. The number of nuclei decreased as a result, while the mist particle diameter increased.

ii) Effect of feeding particles

Figure 6 shows the change of mist particle size when ammonium sulfate solution of 0.1 to 1% concentration was sprayed from nozzle No.1 with the temperature of the water spray cooling tower kept at 130°C. With the increase of ammonium sulfate, the particle size increased. As shown by Fig. 7, the average particle diameter of ammonium sulfate dust generated by spray drying was 1 to 1.5 μm. From this, sulfuric acid and water are considered to have condensed around large particles generated by spray drying. In addition, by feeding particles, the number of particles less than 0.01 μm in size decreased. In other words, the coagulation constant of particles by Brownian movement is small among particles of the same size, while it is larger among particles of different sizes [2]. For example, the coagulation constant of particles of 0.01 μm in diameter is 6×10^{-16} m^3/s, while that of particles of 0.01 μm and 1 μm is 2×10^{-13} m^3/s, larger by more than two orders of magnitude.

If the particle size increases, the dust collecting efficiency can be improved, but feeding additional particles increases the load on the ESP. For example, if ammonium sulfate is dissolved at the concentration of 0.1% in the spray water whose temperature is decreased from 170°C to 130°C, the dust concentration in the exhaust gas increases by approximately 16 mg/m^3_N. Whether the dust concentration at the exit of the ESP can be reduced is a key point in feeding additional particles, which is described in the next section.

3.3 Performance of Wet Model ESP

i) Current density

Figure 8 shows the relation between the applied voltage and the current density when the mist generated under the spray patterns shown in Fig. 4 was introduced in the wet model ESP. The current density in Fig. 8 is the average value of three units on the upstream side, and the specific collecting area (SCA) at this time was 20 s/m. As the applied voltage was increased, the current density increased in all of the spray patterns. The increase was the lowest with spray pattern H, in which the temperature was decreased rapidly. Figure 9 summarizes the relation between the current density and the temperature when a voltage of 40 kV was applied. The figure also shows the result when ammonium sulfate solution of 0.25% concentration was sprayed from nozzle No.1. Compared with the case where the temperature was decreased rapidly, the current density increased around 130°C. The range in which the current density increased corresponded with the temperature range in which the mist particle size increased as described in section 3.2. From the above, we conclude that the current density increased mainly because the mist particle diameter increased.

When additional particles were injected, the current density reached the maximum level, which was higher than the case in which no additional particles were injected, around the temperature of 130°C. Figure 10 summarizes the effect of ammonium sulfate concentration on the current density when the temperature was maintained at 130°C. The current density increased when ammonium sulfate was fed, and the density remained almost constant even if the concentration was changed from 0.1 to 1%. From the above, we assume that spraying ammonium sulfite solution of around 0.1% concentration and keeping the temperature around 130°C are effective to increase the current density.

ii) Collection efficiency

Figure 11 shows the dust collection efficiency obtained when water only was sprayed and the temperature was decreased rapidly, and when the mist generated by spraying ammonium sulfate solution of 0 to 0.5% concentration from nozzle No.1 under the temperature kept at 130°C was fed to the model WESP. The specific collecting area was 20 s/m. The dust collection efficiency was higher when the temperature was decreased gradually to 130°C than when it was decreased rapidly. Figure 12 summarizes the exit dust concentrations. The concentration at the exit was about 50% lower when the temperature was decreased gradually than when it was decreased rapidly. The dust concentration in exhaust gas was approximately 80 mg/m^3 when ammonium sulfite solution of 0.5% concentration was sprayed. Even though the load by dust increased, the concentration at the exit decreased, which is because the synergistic effect of the increase of mist particle diameter and the current density improved the dust collection efficiency.

4. CONCLUSION

To enlarge the particle diameter of the sulfuric acid mist generated in the process of cooling exhaust gas containing sulfuric acid gas, experiments were conducted based on the theory of condensation and growth. Generated mist was injected into the wet model ESP to examine the dust collection efficiency, and the following results were obtained.

(a) When the temperature within the range where condensation of sulfuric acid can occur was decreased gradually by simulation, sulfuric acid condensed on the particles of a certain size or larger, and the mist particle diameter increased.

(b) By temporarily keeping the temperature within the cooling tower approximately 10°C lower than the acid dew point, the mist particle diameter increased, which was confirmed by experiments.

(c) If ammonium sulfate particles were supplied by spray-drying in the above cooling method, the mist particle diameter further increased.

(d) The generated mist was fed into the model ESP and the current density and the dust collection efficiency were examined. It was found that the current density increased and dust collection efficiency improved when the mist particle diameter was increased. With the method of supplying ammonium sulfate particles by spray-drying, the dust concentration at the exit decreased even though the load by dust increased at the inlet.

5. REFERENCES

1) Muller P.: Beitrag zur Frage des Einflusses der Schwefelsaure auf die Rauchgas-Taupunkttemperatur: Chemie-Ing. Techn., **31**,5, pp. 345-351 (1959)

2) Kanji Takahashi: Aerosol (Fundamental): pp. 71-76, Yohkendo ,Tokyo(1981)

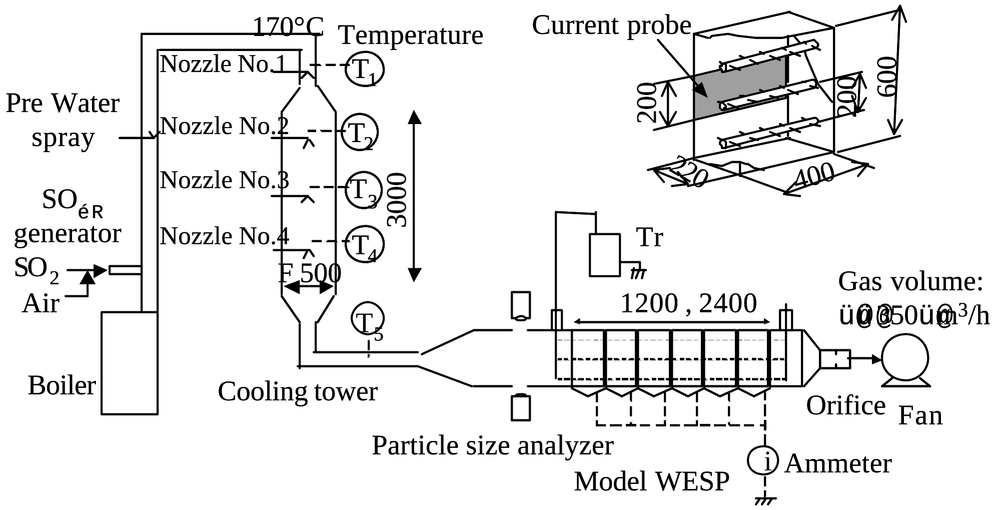
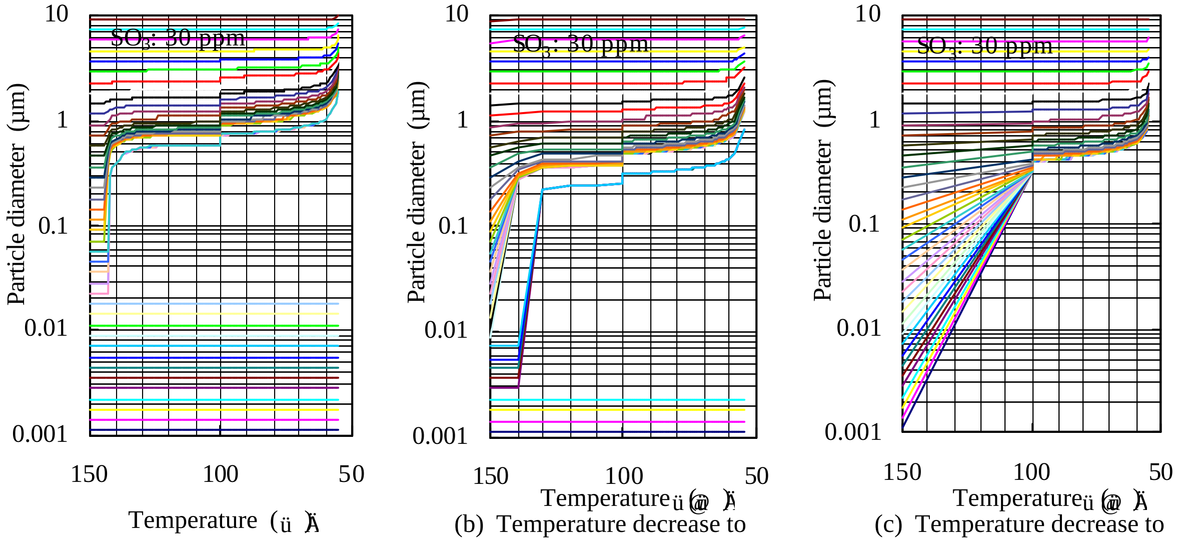


Fig.1 : Schematic diagram of experimental apparatus



(a) Temperature decrease: By 1 degree

(b) Temperature decrease to to 100 degrees: By 10 degrees

(c) Temperature decrease to to 100 degrees : By 50 degrees

Fig. 2 : Particle size change
•@@@@(by simulation)

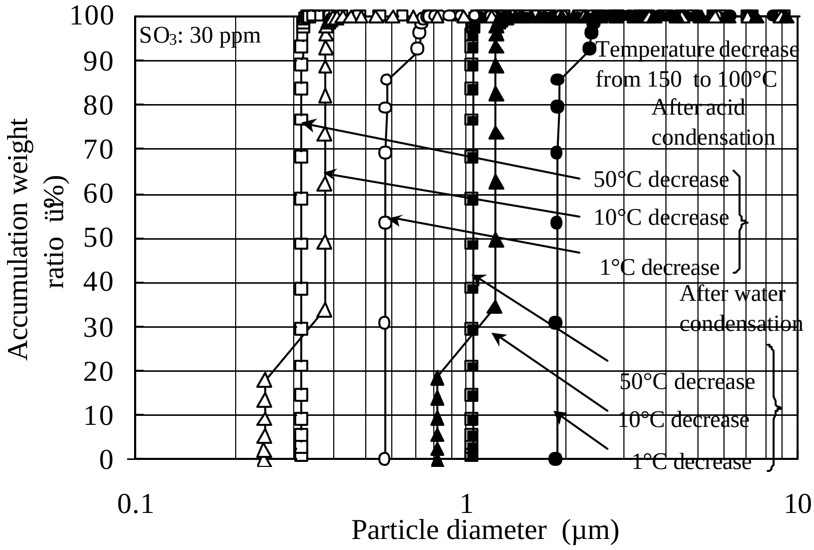


Fig. 3 : Effect of cooling rate
(by simulation)

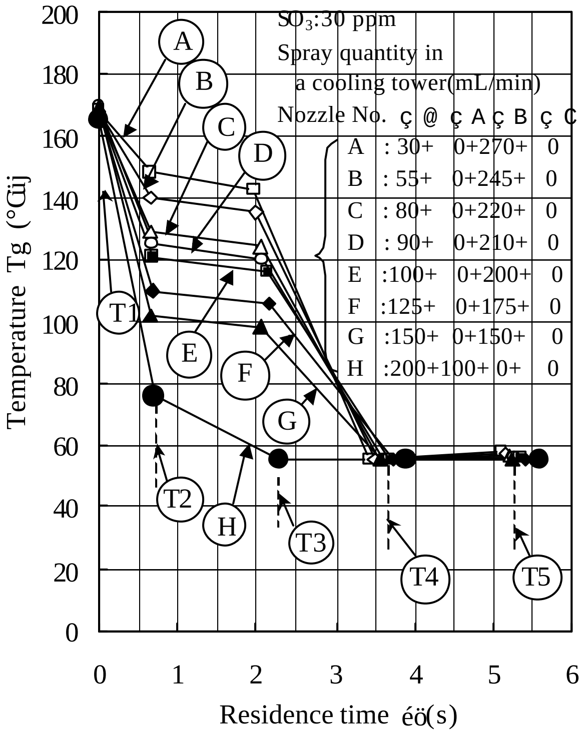


Fig. 4 : Temperature pattern in a cooling tower

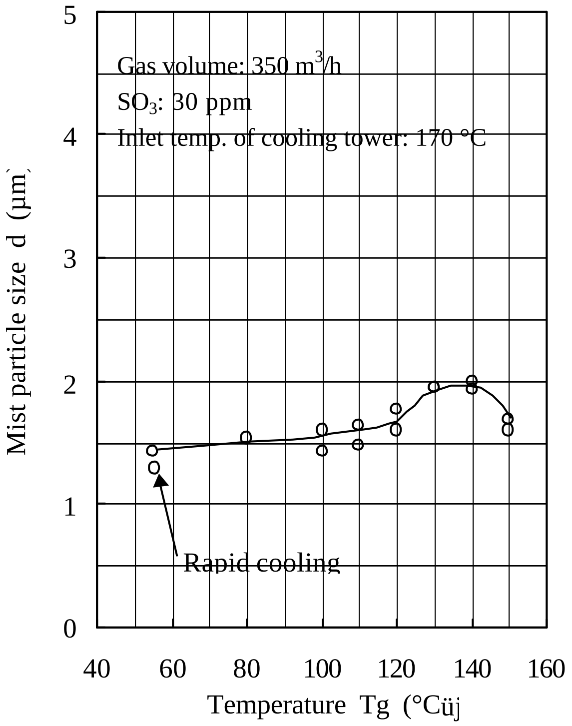


Fig. 5 : Effect of maintaining temperature on condensation particle size

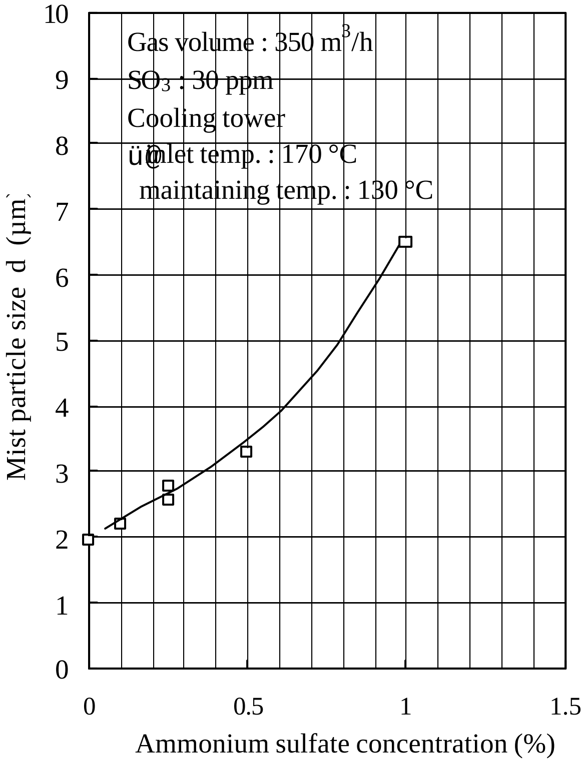


Fig. 6 : Effect of ammonium sulfate contents on mist particle size

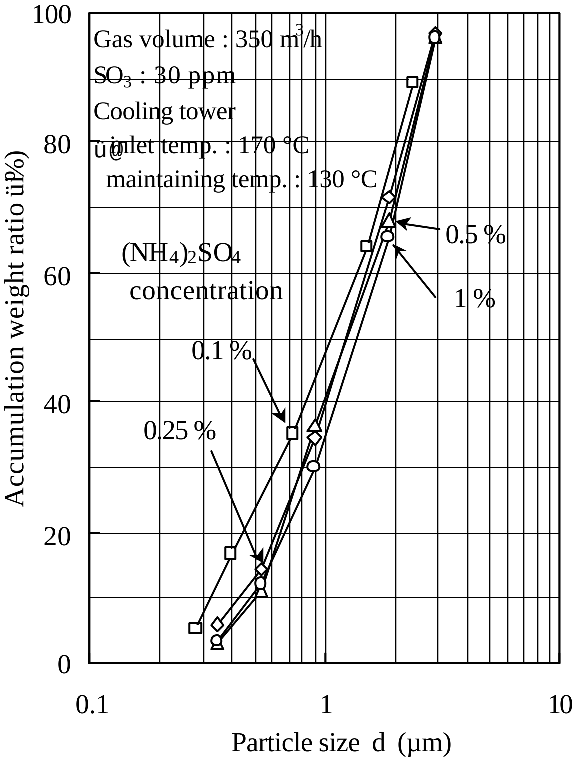


Fig. 7 : Particle size distribution generated by spray dry

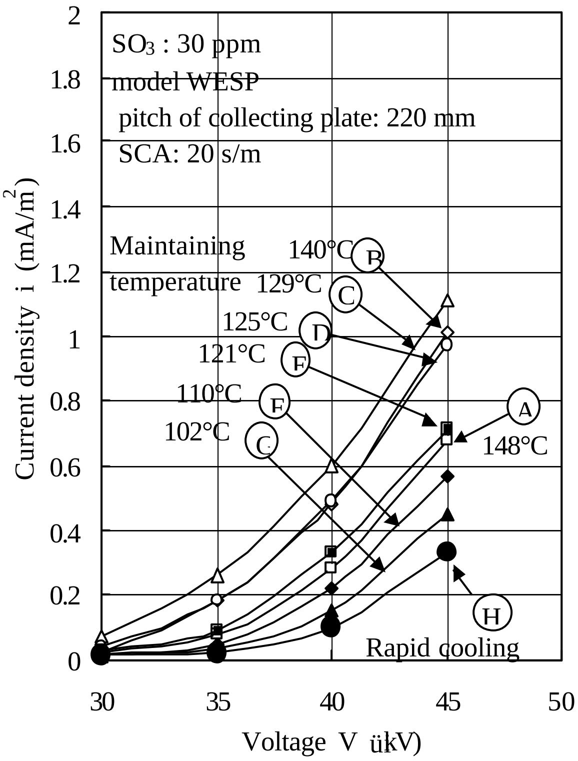


Fig. 8 : V-I curve
(water injection)

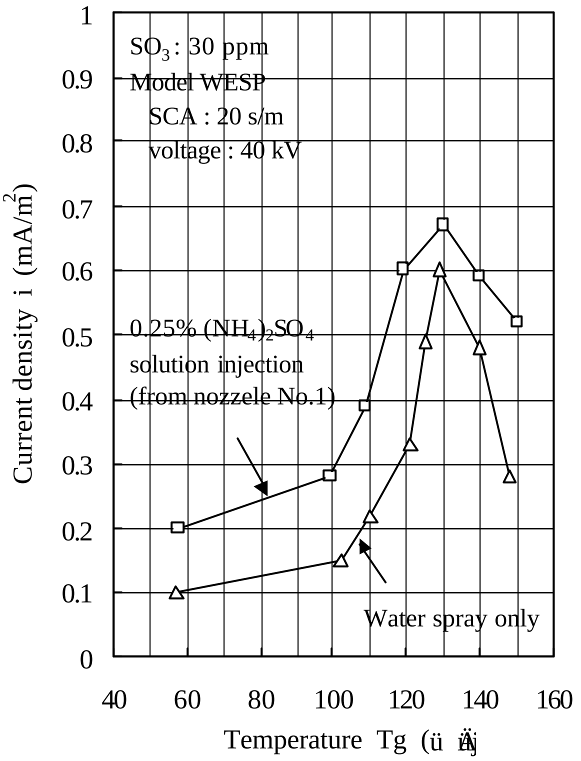


Fig. 9 : Relation between temperature and current density

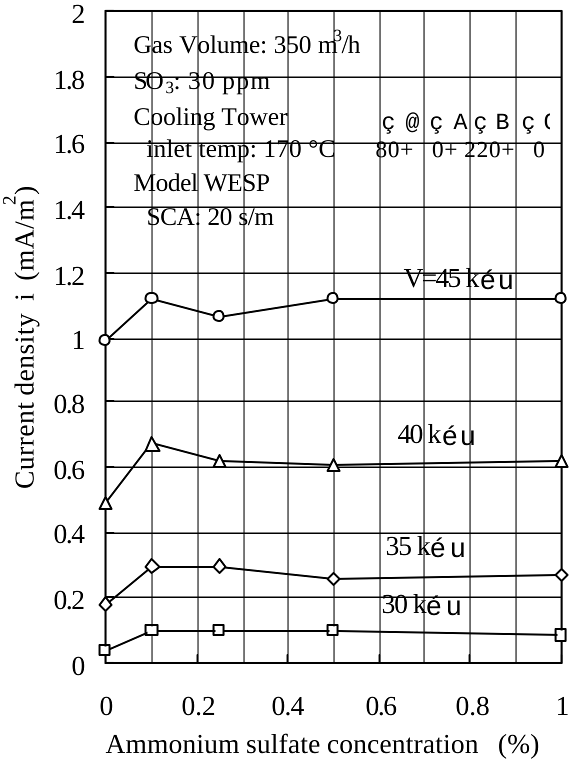


Fig.10 : Relation between content of ammonium sulfate and current density

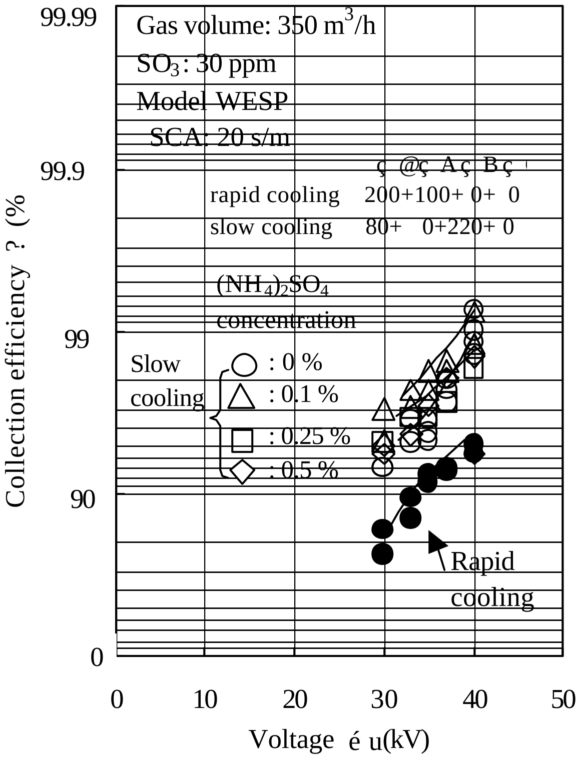


Fig. 11 : Relation between voltage and efficiency

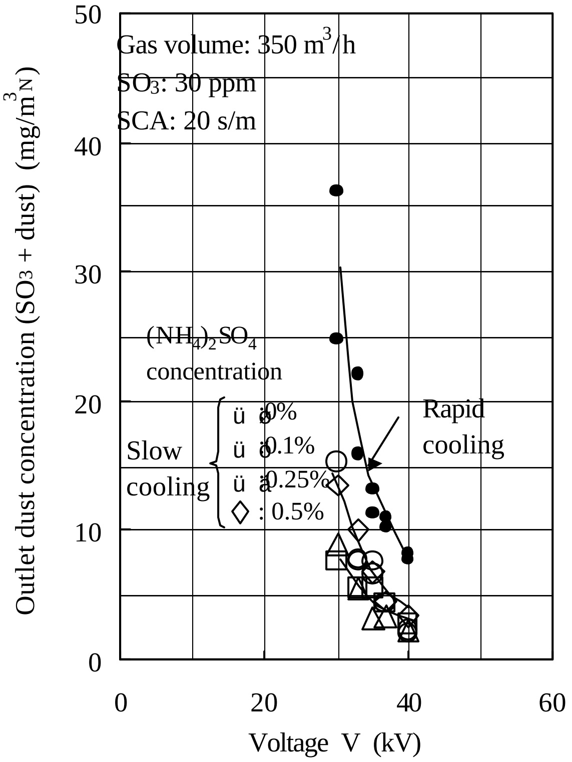


Fig. 12 : Effect of cooling method and particle injection on outlet dust concentration

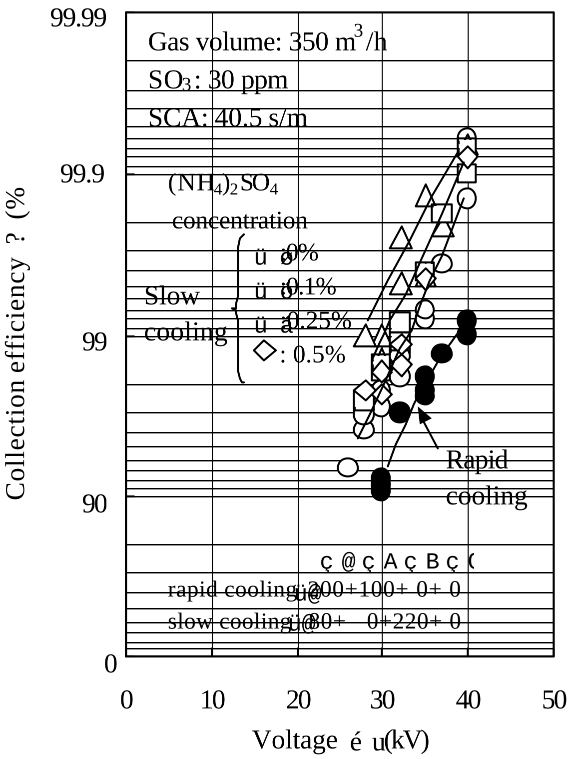


Fig. 13 : Relation between Voltage and efficiency

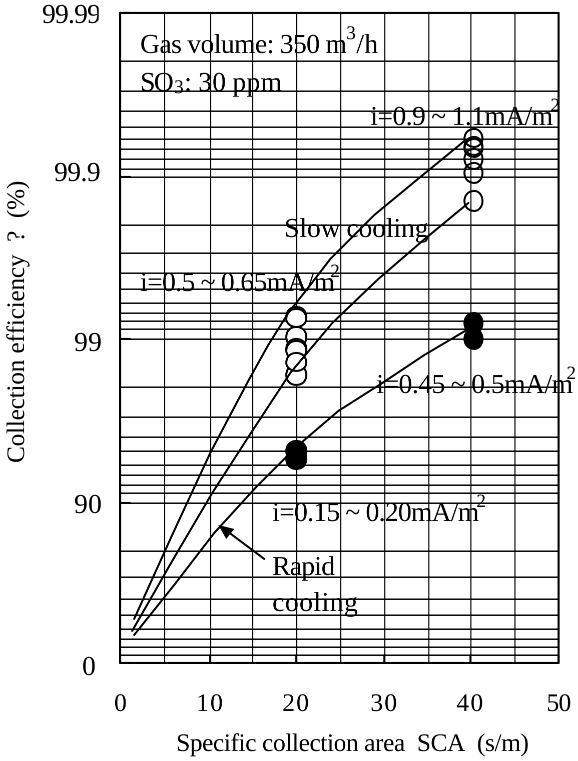


Fig. 14 : Relation between SCA and efficiency