

# Environmental Study through combustion test of Indian coal

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JAPAN COAL ENERGY CENTER

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## **Executive Summary**

CEA and JCOAL embarked on their cooperation officially as of April 30, 2010, when they signed the first Memorandum of Understanding (MOU) on Japan-India Cooperation for Pre-primary Study of Efficiency and Environmental Improvement of Coal Fired Power Stations. During 5 years of cooperation, 8 units out of 7 power stations owned by both NTPC and state utilities have been diagnosed and benefited through the joint activities and the proposals by Japanese experts. On January 22nd, 3rd MOU has been revised. The effect of this cooperation, has been enhanced by associated activities with focus on sharing of knowledge and experiences as well as capacity building such as an annual workshop; CEA-JCOAL Workshop, and also CCT Training Program, to establish a great network.

Although Indian thermal power plants (TPPs) are responsible for about 50% of the country's greenhouse gas emissions, its air emission norms for coal-based TPPs do not cover SO<sub>2</sub> and NO<sub>x</sub>, and its norms for particulate matter (PM) had been relaxed until recently. December 2015, new environmental norms has been introduced by MOEFCC to control emission by coal fired power station in India. Power utilities have to consider measures to meet their emission level by installing additional environmental facilities. In this point of view, combustion test on Indian coal at the integrated combustion and emissions control system has been conducted.

25 tonnes of G12 grade test coal has been provided by Talcher coal mine, thanks to kind cooperation by MCL under supervision by MOC and CEA as a part of India-Japan bilateral cooperation activities in power sector. Combustion test has been conducted in 3Q and 4Q in FY2015 by the integrated combustion and emissions control system in Akitsu Works, MHPS, Japan.

Indian coal contains a lot of ash, which leads to high load of smoke dust to flue gas treatment facilities with possible negative influence on dust removal/desulfurization

performance. Comparative evaluation of conventional systems and the high-performance smoke dust removal system was performed by using the Combustion-AQCS Integrated Test device and basic test devices in a laboratory.

Stable charging and possibility of highly efficient dust removal were confirmed for very low temperature EP (the high-performance smoke dust removal system). On the contrary, for low temperature EP (conventional systems), applying high voltage was impossible and dry EP (DEP) outlet smoke dust concentration was higher than that of very low temperature EP. This is seemingly because high electrical resistivity of ash resulted in the occurrence of inversive ionization phenomenon. In addition, for both low temperature EP and very low temperature EP, smoke dust concentration at the outlet of FGD was controlled to low concentration of 15mg/m<sup>3</sup>N or below. In particular, when inlet smoke dust concentration was decreased by very low temperature EP, 5mg/m<sup>3</sup>N of outlet concentration or less is achievable.

#### Smoke dust removal performance

For low temperature EP (conventional systems) and very low temperature EP (the high-performance smoke dust removal system), smoke dust concentration at the inlet of FGD was 30mg/m<sup>3</sup>N and 90mg/m<sup>3</sup>N, respectively. However, under the same condition (L/G, CaCO<sub>3</sub> concentration), desulfurization rate of both systems was equal and influence of smoke dust concentration was not found.

#### Overall heat transfer coefficient in GGH

Overall heat transfer coefficient of GGH in conventional systems and the high-performance smoke dust removal system was equal. In the high-performance smoke dust removal system, the amount of ash deposit on fin tubes was larger and decrease rate of heat transfer coefficient over time was higher than the case of conventional systems, and the heat transfer coefficient recovered to the initial value by regular soot blower operation every 2 to 3 hours. This result suggests that operation under the condition of high smoke dust concentration has no problem.

Abrasion speed in both systems was studied by using test pieces made of carbon steel and sulfuric acid resistant steel. Difference in both systems was not found and in terms of abrasion characteristics, operation of the high-performance smoke dust removal system is assumed to cause no problem even under the condition of high ash content.

#### Evaluation of economic efficiency

Based on relation between smoke dust removal performance and charge conditions, under the condition where charge is 45kV and DEP outlet smoke dust concentration is 30mg/m<sup>3</sup>N, very low temperature EP is estimated to reduce dust collection area (EP volume) by approx. 25% compared to the case of low temperature EP.

#### Mercury behavior and removal characteristics

In this research, mercury behavior and removal characteristics were evaluated with the Combustion-AQCS Integrated Facility and the basic test device in laboratory. Although Hg oxidization rate in denitrification catalyst (high mercury oxidation-type catalyst manufactured by MHPS) was rather low of 70% at around 350°C of the temperature at catalyst inlet and 63% at around 380°C of that, considering Talcher coal contains low concentration of HCl, it is considered as reasonable oxidation performance by comparing with other types of coal. Hg removal rate in DEP was 70% in the high-performance smoke dust removal system (using very low temperature EP and catalyst) and 35% in the conventional system (using low temperature EP and catalyst). It was confirmed that very low temperature EP is also effective on Hg removal. Mercury removal performance in the case of activated carbon addition, catalyst had more Hg removal effect than addition of activated carbon.

Flue gas treatment technologies used in thermal power plants, especially in coal-fired power plants are classified into “wet treatment” and “dry treatment”. Especially the smoke dust causes blocking and pressure loss by adhesion to the inside wall or

deposit. It is therefore required to construct a system and design each facility by addressing them. In this point of view, technical information regarding desulphurization and denitrification are described.

# 1. INTRODUCTION

## 1.1 Background and Objective

In India, the number of coal-fired power plants is increasing, and strengthening of regulations against exhaust gas has been expected. In December 2015, the Ministry of Environment of India announced a new regulation<sup>1</sup>. As flue gas treatment devices in India, desulfurization/dust removal devices are required in many cases. However, coal from India generally contains a lot of ash, which leads to high load of smoke dust to flue gas treatment facilities with possible negative influence on dust removal/desulfurization performance. A promising technology to address this problem is the “high-performance smoke dust removal system” originally developed by MITSUBISHI HITACHI POWER SYSTEMS, LTD. (hereinafter referred to as MHPS). In this system, a Gas-Gas Heat exchanger (GGH) is installed before an electrostatic precipitator for heat recovery, the temperature of exhaust gas at the electrostatic precipitator is lowered to improve dust collection efficiency, and smoke dust concentration emitted from stacks is reduced.

The limit of smoke dust in India specified in the regulation announced this time is 30mg/m<sup>3</sup>N which is applied to units newly established from January 2017. This limit is significantly high compared with the value required for Japanese power plants (5 to 10mg/m<sup>3</sup>N) and the regulation of the US MATS (Mercury and Air Toxics Standards) (9.0 x 10<sup>-2</sup> lb/MWh ≈ 13.5mg/m<sup>3</sup>N for newly established unit/ not low rank virgin coal). However, ash content of coal from India is around 30 to 45% in many cases, and is remarkably higher than that of coal generally used in Japan, Europe and the United States (around 10% of ash content). Accordingly, high performance of dust removal is required.

GGH of the system uses tubes with special fins and has been used at many coal-fired power plants in Japan. However, the system has not been used for Indian coal and other high-ash coal (30% ash content or more). Consequently, consideration was made from various viewpoints aiming to verify dust collection performance and operation conditions of GGH at

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<sup>1</sup> Ministry of Environment, Forest and Climate Change Notification: The Gazette of India: EXTRAORDINARY [PART II—SEC. 3(ii)], New Delhi, the 7<sup>th</sup> December, 2015



the large test facility owned by MHPS in advance. Successful application of the “high-performance smoke dust removal system” to high-ash coal achieves differentiation from foreign companies and ensures advantage in business for environmental devices in India in the future.

### 1.2 Characteristics of high-performance smoke dust removal system

Figure 1-1 shows the flow of the high-performance smoke dust removal system and Figure 1-2 shows the flow of conventional systems. In conventional systems, a GGH heat recovery device is installed between an electrostatic precipitator and a flue gas desulfurization (FGD), which results in the exhaust gas of around 140°C at the electrostatic precipitator (low temperature EP). On the contrary, in the high-performance smoke dust removal system, installing a GGH heat recovery device before an electrostatic precipitator lowers the temperature of exhaust gas at the electrostatic precipitator to around 90°C (very low temperature EP).

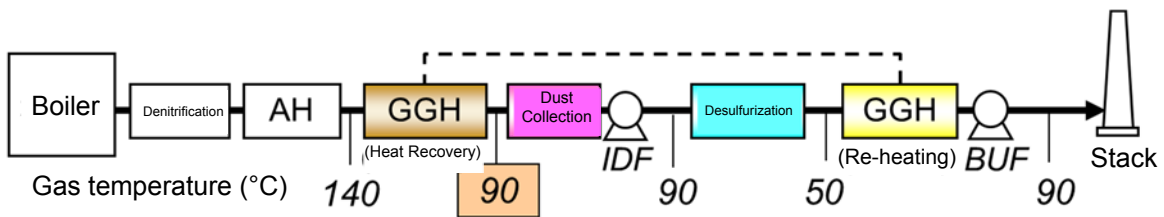


Figure 1-1 Flow of high-performance smoke dust removal system

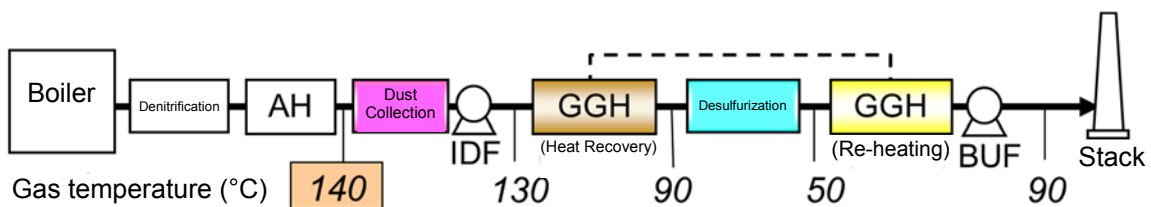


Figure 1-2 Flow of conventional systems

The high-performance smoke dust removal system has advantages as described in the

references<sup>2,3</sup>.

With regard to dry electrostatic precipitators (DEP), when electric resistance of smoke dust is low, dust collection efficiency improves in general. Figure 1-3 shows the relation between temperature of exhaust gas and electric resistance of coal ash (smoke dust). Conventional systems show low dust collection efficiency when DEP operation temperature is around 140°C which is the high electric resistance area of coal ash. On the contrary, since DEP is operated at 100°C or lower in the high-performance smoke dust removal system, the electric resistance of coal ash decreases and dust collection efficiency improves. At the same time, lower temperature of processed gas achieves smaller DEP facilities.

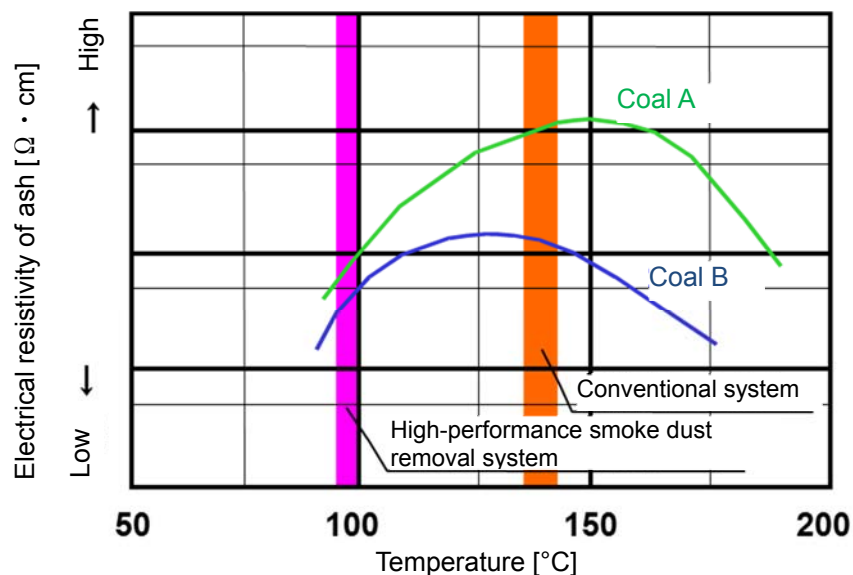


Figure 1-3 Relation between temperature of exhaust gas and electric resistance of coal ash (smoke dust)

In addition, with regard to very low temperature EP, both dust removal performance and SO<sub>3</sub> removal performance dramatically improves. Figure 1-4 shows past results of the Combustion-AQCS Integrated Facility test. Since sulfuric acid dew point of SO<sub>3</sub> in boiler exhaust gas is

<sup>2</sup> Kikkawa et al.: Highly-Efficient Removal of Toxic Trace Elements and Particulate Matter in Flue Gas Emitted from Coal-fired Power Plants by Air Quality Control System (AQCS): Mitsubishi Heavy Industries Technical Review Vol. 52 No. 2, 2015

<sup>3</sup> T. Nakamoto et al.: Advanced AQCS technology for future emission control: VGB PowerTech, 11, 2014

around 170°C, the most part of gaseous SO<sub>3</sub> condenses into smoke dust and is removed by DEP under the DEP temperature of 90°C, resulting in significant decrease of SO<sub>3</sub> concentration in exhaust gas. Since the SO<sub>3</sub> removal level of wet FGD is low, removal by dry EP achieves dramatic reduction of SO<sub>3</sub> emitted from stacks without using large high-cost wet EP.

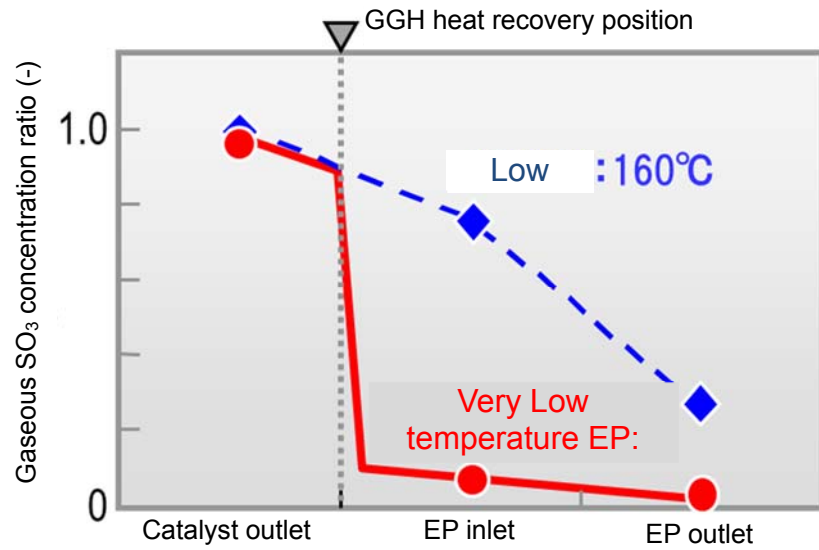


Figure 1-4 SO<sub>3</sub> reduction effect by very low temperature EP

## 2. IMPLEMENTATION DETAILS

### 2.1 Test at the Combustion-AQCS Integrated Facility

#### 2.1.1 Details of test

Coal from India (approx. 25 ton) provided by JCOAL was burned under the condition close to actual pulverized coal fired boilers (approx. 200 kg of coal was fed per hour) for one week (from Monday to Saturday) by using the “Combustion-AQCS Integrated Test Facility” of MHPS to conduct test operation of exhaust gas treatment. The components of coal, combustion flue gas, etc. were analyzed to evaluate performance of electrostatic precipitators and FGDs in conventional systems and the high-performance smoke dust removal system. In addition, the degree of heat exchange performance of an exhaust gas cooler (GGH heat recovery device) used in the high-performance smoke dust removal system was evaluated under the condition of high dust concentration. Detailed considerations are as follows:

- (1) To understand heat-transfer performance, dust removal and desulfurization performance when the high-performance smoke dust removal system is used under high smoke dust concentration
- (2) To understand heat-transfer performance, dust removal and desulfurization performance when conventional systems are used under high smoke dust concentration
- (3) To compare and evaluate economic efficiency based on test results of the both systems
- (4) To propose verification tests using Indian actual devices based on this test

#### 2.1.2 Main test operation conditions (plan)

- (1) Combustion amount of coal: 185kg/h (ash content 40%)
- (2) Gas temperature at the inlet of electrostatic precipitator:  
90-100°C (high-performance smoke dust removal system), 140-150°C  
(conventional systems)
- (3) Electrostatic precipitator charge voltage: 25 to 45kV (3 conditions)
- (4) Denitrification device: denitrification rate 90%
- (5) Flue gas desulfurization: desulfurization rate 95%

## 2.2 Basic test

In order to support the result of desulfurization performance test conducted in the integrated facility (influence of dust concentration), laboratory basic test was also conducted and the result was closely reviewed.

## 2.3 Overall process

Table 2-1 shows the overall process of this operation. Test plan was developed in the first half of FY2015, based on which coal was delivered and prepared in late September 2015. The test was conducted for the continuous one week in early October by using the Combustion-AQCS Integrated test device. After that, basic test as well as various kinds of research was conducted to underpin the obtained results, outcomes of which constitutes the essence of this report.

Table 2-1 FY 2015 overall process

Implementation items	1Q (Apr. to Jun)	2Q (Jul. to Sep.)	3Q (Oct. to Dec.)	4Q (Jan. to Mar.)
1. Test planning/contract	Plan ■■■■■	▼ Sep. 4th Contract		
2. Import of coal		■■■■■ ▼ Sep. 19th Delivery to MHPS Akitsu		
3. Preparation of test (crushing coal, etc.)		■■■		
4. Dust removal performance test (including analysis)		Integrated test device	■■■■■ Basic	
5. Various research and preparation of reports			Feb. 29th Test reports submission ▼	■■■■■

### 3. TEST METHOD

#### 3.1 Overall test at the Combustion-AQCS Integrated Facility

##### 3.1.1 Overview of the facility

Figure 3.1-1 shows the appearance of the Combustion-AQCS Integrated Facility built in Katsu Area of MHPS Kure Works, and Figure 3.1-2 shows the system flow. The facility uses pulverized coal fired furnace whose capacity is 1.5MWth and is equipped with one low NO<sub>x</sub> burner and one pair of after-air port to perform two-staged combustion. The flue gas treatment facility includes a full set of denitrification catalyst device, GGH and others (air preheater, water tube gas cooler, GGH), dry electrostatic precipitator (DEP) and wet FGD (spray type).

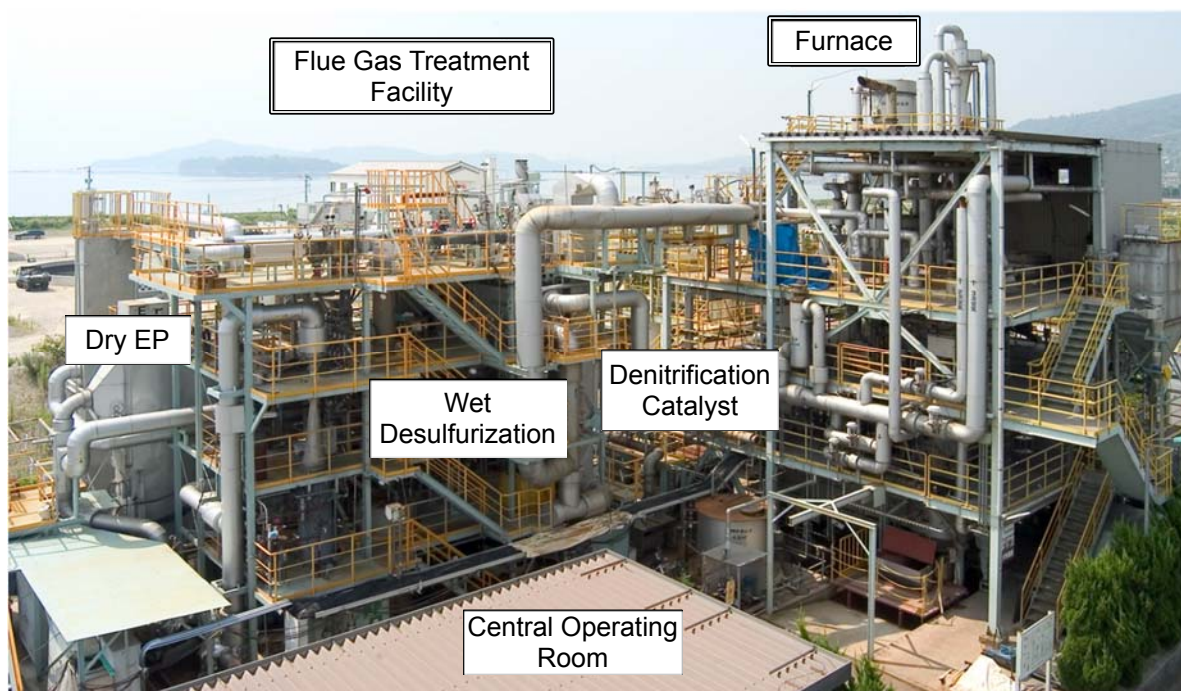
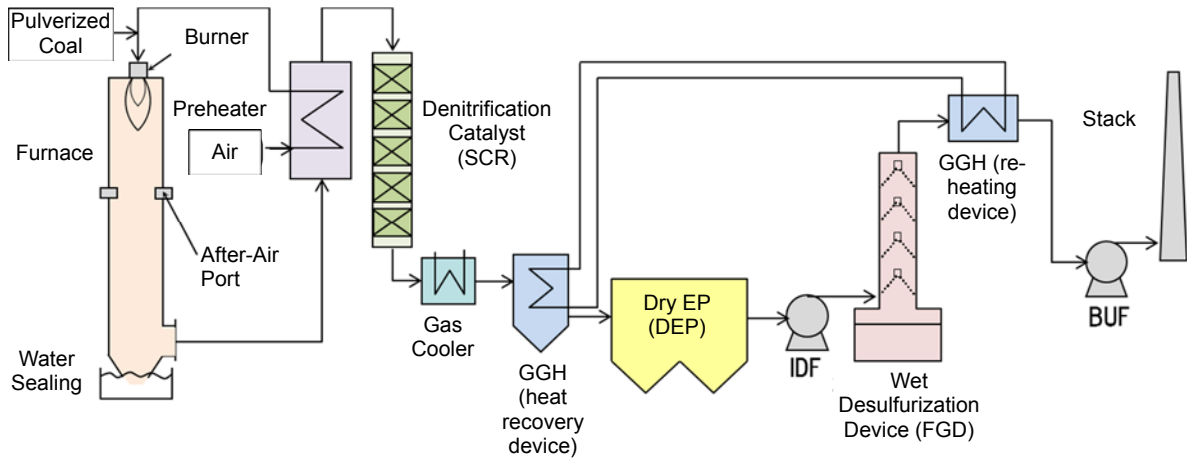
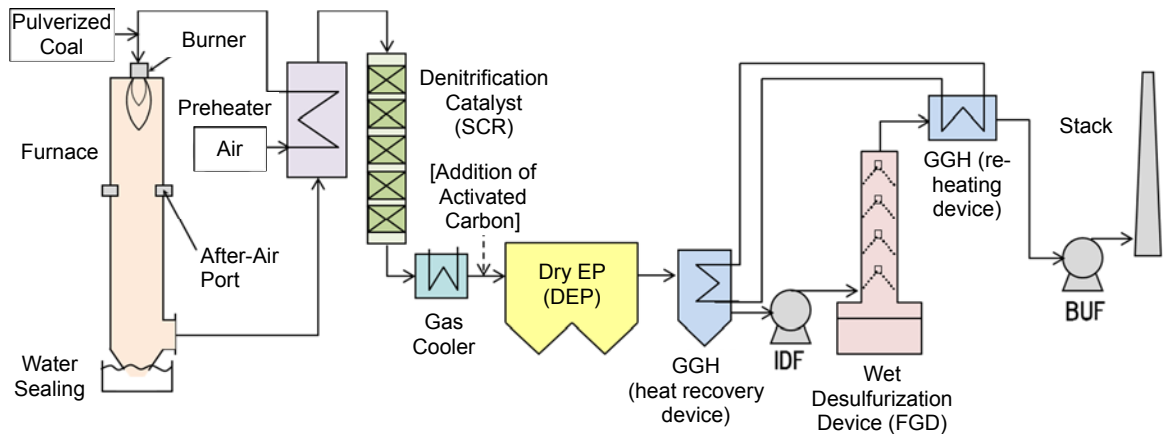


Figure 3.1-1 Appearance of the Combustion-AQCS Integrated Facility

The high-performance smoke dust removal system (a) using a very low temperature EP and conventional systems (b) using a low temperature EP were tested by switching exhaust gas ducts. In addition, another test was conducted by adding powdered activated carbon for mercury removal in exhaust gas at the inlet of DEP.



(a) High-performance smoke dust removal system (very low temperature EP)



(b) Conventional systems (low temperature EP)

Figure 3.1-2 System flow of the Combustion-AQCS Integrated Test device

### 3.1.2 Coal for the test

Talcher coal from Odisha, India provided by JCOAL was used for the test. The coal was delivered to Akitsu Area on September 19, 2015. The delivered quantity was approx. 25 tons (522 jute bags, each bag contains 50kg coal). At the time of delivery, Talcher coal was in a shape of block about several to tens of centimeters as shown in Figure 3.1-3. The block coal was roughly crushed and dried. Then, the coal was finely milled to approx. 90% of 200 mesh-pass before combustion.

Table 3.1-1 shows analysis values of coal under test. Approx. 5kg of sample of each was taken

at ten points randomly selected from the whole coal delivered to the facility. After the adjustment of reduction and pulverizing of samples, the obtained representative samples were analyzed. Analysis of the representative samples except Hg analysis was performed by MITSUBISHI HITACHI POWER SYSTEMS, LTD. and Chugoku Kankyou Bunseki Center Co., Ltd. Hg analysis was performed by MHPS for pulverized coal samples collected from the pulverized coal bin from time to time (around once a day) during the test operation by using an atomic absorption-type Hg analyzer discussed later.

India has a lot of coal fields in its eastern area (including Odisha). In general, coal from this area has high-ash content, low calorific values and low S content, and the melting point of ash is high. Coal assumed in advance had similar nature. Talcher coal for test also has high ash content of 34.5% resulting in low calorific values. The S content was 0.47% which was relatively low, and the melting point of ash was 1,550°C or more which was relatively high. The coal under test had high Hg concentration of 220µg/kg and low Cl concentration of 100mg/kg or less (reference value: 30mg/kg). Characteristics analysis of coal under test is detailed later in Chapter 4.



Figure 3.1-3 Talcher coal at the time of delivery



Table 3.1-1 Characteristics of coal under test

Analysis item		Coal name		Talcher coal (coal under test this time)	Coal assumed in advance	
		Base	Unit			
Higher calorific value		air-dried	kJ/kg	19,530	18,090	
Total water content		arrival	%	12.3	11	
Industrial analysis	Water content of air-dried sample	air-dried	%	6.51	4.7	
	Volatile content	anhydrous	%	30.03	33.3	
	Fixed carbon	anhydrous	%	35.45	24.1	
	Ash content	anhydrous	%	34.52	37.9	
Elemental analysis	C	anhydrous	%	51.2	44.96	
	H	anhydrous	%	3.68	4.11	
	O	anhydrous	%	9.12	10.39	
	N	anhydrous	%	1.06	0.75	
	Total S	anhydrous	%	0.46	0.17	
	S in ash	anhydrous	%	0.04	0.12	
	Combustible S	anhydrous	%	0.42	0.05	
	Cl	anhydrous	mg/kg	<100 (30)	-	
	F	anhydrous	mg/kg	200	-	
	B	anhydrous	mg/kg	8 (8.7)	-	
	Se	anhydrous	mg/kg	2 (2.1)	-	
Hg	anhydrous	µg/kg	220*	-		
Ash composition analysis	SiO <sub>2</sub>	ashing	%	60.8	63.48	
	Al <sub>2</sub> O <sub>3</sub>	ashing	%	28.1	24.01	
	Fe <sub>2</sub> O <sub>3</sub>	ashing	%	3.89	2.34	
	CaO	ashing	%	0.82	3.73	
	MgO	ashing	%	0.28	0.80	
	TiO <sub>2</sub>	ashing	%	2.01	1.14	
	SO <sub>3</sub>	ashing	%	0.14	0.76	
	Na <sub>2</sub> O	ashing	%	0.06	0.89	
	K <sub>2</sub> O	ashing	%	0.84	1.32	
	V <sub>2</sub> O <sub>5</sub>	ashing	%	0.03	-	
	Cr <sub>2</sub> O <sub>3</sub>	ashing	%	0.04	-	
	CuO	ashing	%	0.01	-	
Fusibility of ash	Oxidization	softening point	ashing	°C	1460	1490
		sphere point	ashing	°C	≥1550	-
		hemi sphere point	ashing	°C	≥1550	≥1500
		flow point	ashing	°C	≥1550	≥1500
	Reduction	softening point	ashing	°C	1450	1340
		sphere point	ashing	°C	≥1550	-
		hemi sphere point	ashing	°C	≥1550	1500
		flow point	ashing	°C	≥1550	≥1500
Button index		air-dried	CSN	0	-	

\*: Average of six samples ( ): Reference value below the lower limit of quantitation

### 3.1.3 Operation conditions and evaluation items

Table 3.1-2 shows operation conditions and evaluation items of each test day. The device was started on Monday and continuously operated day and night. Test was conducted during the day from Tuesday to Saturday. At the time of start, the temperature of the furnace was raised by firing heavy oil. It was moved to single coal combustion in the evening after mixed combustion of heavy oil and coal. During night the device was operated to maintain temperature of each unit, etc. for the test conditions of the following day.

The amount of burnt coal, combustion air ratio and denitrification conditions were fixed, temperature and charging of DEP and liquid-to-gas ratio (L/G) of desulfurization were changed to evaluate dust removal characteristics, operability of GGH (heat transfer characteristic due to ash adhesion onto heat-transfer tubes and differential pressure change), desulfurization performance, etc.

High mercury oxidation-type denitrification catalyst produced by MHPS was set in the denitrification catalyst device. Gas temperature at the DEP inlet was adjusted to 160°C for the low temperature EP condition by using a gas cooler and to 90°C for a very low temperature EP condition by using a gas cooler and a GGH (heat recovery unit). Four steps of spray headers were installed to spray desulfurization absorbing solution in the wet FGD and the ratio of the solution to the exhaust gas amount (L/G) was varied within the range from 18 to 45L/m<sup>3</sup>N by changing the number of spray steps to be operated.

Table 3.1-2 Scheduled operation conditions and evaluation items

	Test day	Oct. 5th (Mon.)	Oct. 6th (Tue.)	Oct. 7th (Wed.)	Oct. 8th (Thu.)	Oct. 9th (Fri.)	Oct. 10th (Sat.)
Operation conditions	System conditions	Start of device	very low temperature EP (90°C)		low temperature EP (160°C)		
	Feeding amount of coal		185 kg/h				
	Exhaust gas amount (air ratio: 1.4)		1,400 m <sup>3</sup> N/h, wet				
	Denitrification inlet temperature		380°C				
	Denitrification rate		90%				
	EP charge voltage (kV) (25 to 45, rating: 45)		Rating+ 2 conditions	25	25	Rating + 2 conditions	Rating
	Desulfurization L/G (L/m <sup>3</sup> N) (18 to 45, rating: 45)		Rating	Rating + 3 conditions	Rating + 2 conditions	Rating	Rating
Evaluation item	Smoke dust removal performance	-	○	○	○	○	○
	Desulfurization inlet smoke dust particle size	-	○	-	○	-	-
	Desulfurization mist spreading amount	-	-	○	-	-	-
	GGH heat transfer characteristics, change of differential pressure	-	○	○	○	○	-
	Desulfurization rate	-	○	○	○	○	-

### 3.1.4 Measurement points

Figure 3.1-4 shows specific duct flows under the condition of a very low temperature EP (the high-performance smoke dust removal system) and the condition of a low temperature EP (conventional systems) and points of exhaust gas components measurement (sampling). Manual analysis sampling was performed at each inlet and outlet of the denitrification device, the dry EP and the FGD to evaluate characteristics of harmful component removal for each device. In addition, concentration of SO<sub>2</sub>, NO<sub>x</sub>, CO, CO<sub>2</sub> and O<sub>2</sub> in exhaust gas was continuously measured with a gas monitor at the denitrification inlet and the desulfurization outlets

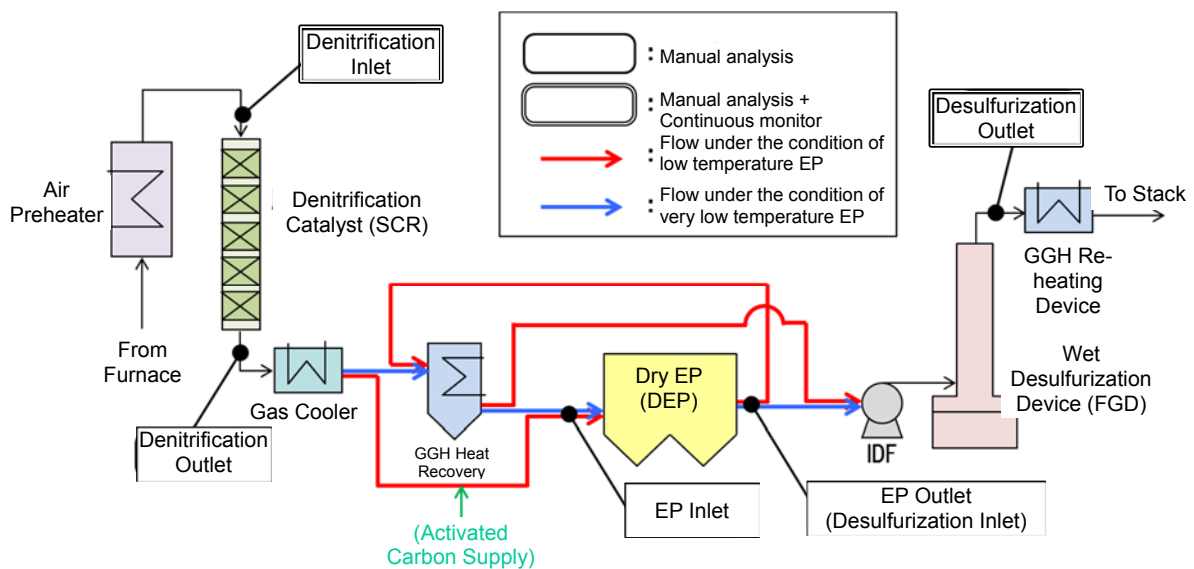


Figure 3.1-4 Duct flows for each EP temperature condition and measurement points of exhaust gas components

### 3.1.5 Measurement method

#### (1) Major exhaust gas components

At the denitrification inlet and the outlet of the FGD, concentration of SO<sub>2</sub>, NO<sub>x</sub>, CO, CO<sub>2</sub> and O<sub>2</sub> in exhaust gas was measured and recorded with a continuous five components gas monitor (HORIBA, Ltd./ENDA-5800) shown in Figure 3.1-5. Detection methods were the Non-dispersive infrared method for SO<sub>2</sub>, NO<sub>x</sub>, CO and CO<sub>2</sub>, and the magnetic pressure method for O<sub>2</sub>.

Water content was measured and manually analyzed by moisture absorption tube method (JIS Z 8808) using a calcium chloride tube. In addition, at the time of evaluation of desulfurization performance, etc., concentration of each component was calculated by correcting O<sub>2</sub> concentration to a certain level (6%).

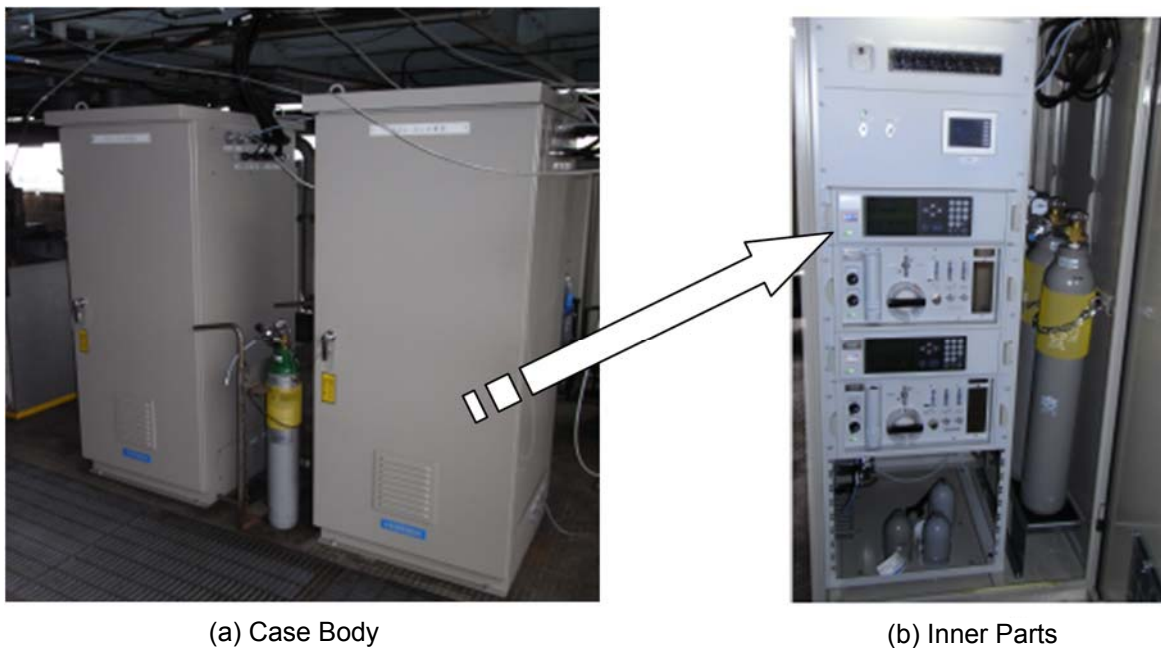


Figure 3.1-5 Continuous gas monitor (HORIBA, Ltd./ENDA-5800)

#### (2) Amount of exhaust gas

With regard to the measurement of exhaust gas amount, pursuant to JIS Z8808, wet gas amount was calculated based on the exhaust gas flow velocity measured by using a pitot tube and the duct area, and the measured water content was subtracted from the obtained gas amount to calculate dry gas amount.

### (3) Smoke dust concentration

Dust concentration in exhaust gas was measured by the sampling flow (complying with JIS Z8808) shown in Figure 3.1-6. The sampling nozzle was set facing the gas flow at the center of the duct, samples of exhaust gas were collected by constant velocity suction, and dust concentration was calculated based on dry weight of particles trapped on filter paper (dry temperature: 105 to 110°C) and suctioned gas amount. Cylindrical filter paper was used at the upstream of DEP inlet where dust concentration is higher and circular filter paper was used at the downstream of DEP outlet where dust concentration is lower.

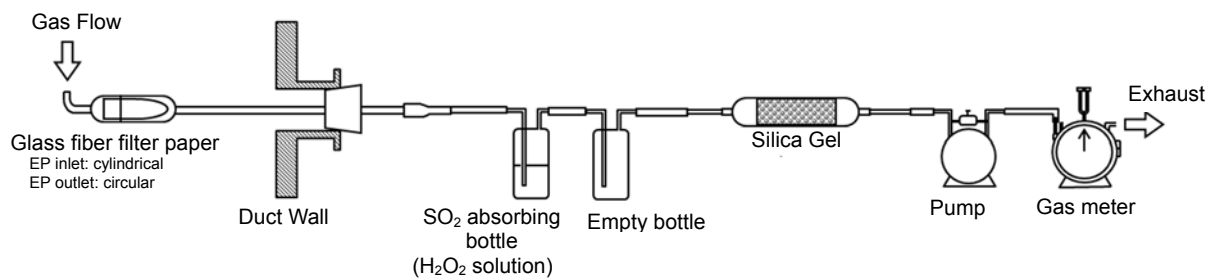


Figure 3.1-6 Sampling flow of smoke dust in exhaust gas (complying with JIS Z8808)

### (4) Particle size distribution of smoke dust

Particle size distribution of fly ash (EP ash) collected from the hopper of DEP was measured by a laser diffraction particle size analyzer (Malvern/MASTERSIZER Micro) shown in Figure 3.1-7. Ethanol was used as dispersion liquid.

With regard to smoke dust which passed through DEP and flowed into FGD, samples of smoke dust in exhaust gas were collected as described above at DEP outlet (FGD inlet) to measure particle size distribution. The measurement was performed by MITSUBISHI HITACHI POWER SYSTEMS, LTD. Magnified pictures of particles trapped on the surface of circular filter paper were taken by using a scanning electron microscope (SEM) and the diameter of each particle was measured and aggregated after image processing to obtain particle size distribution. Magnification was 5000, and the diameter of around 400 to 700 particles in total was measured in 10 fields for each sample.



Figure 3.1-7 Laser diffraction particle size analyzer (Malvern/MASTERSIZER Micro)

#### (5) Mist

Since mist in exhaust gas which was counted as smoke dust at the outlet of the FGD was a group of fine airborne droplets of desulfurization solution, Cl included in desulfurization solution was measured as a tracer. Figure 3.1-8 shows sampling flow of mist in exhaust gas. This is the same sampling flow as that of HCl in exhaust gas (complying with JIS K 0107). Cylindrical filter paper set inside the duct in exhaust gas was ultrasonically processed in the predetermined amount of pure water (one hour or longer), concentration of chlorine ion eluted into the solution was determined by using an ion chromatography device (former Dionex/ICS-2000) shown in Figure 3.1-9 to calculate Cl amount ( $\text{mg}/\text{m}^3\text{N}$ ) trapped on the cylindrical filter paper. The obtained value was translated into mist concentration in exhaust gas ( $\text{mg}/\text{m}^3\text{N}$ ) by using the Cl concentration ( $\text{mg}/\text{L}$ ) in desulfurization solution obtained by separate measurement.

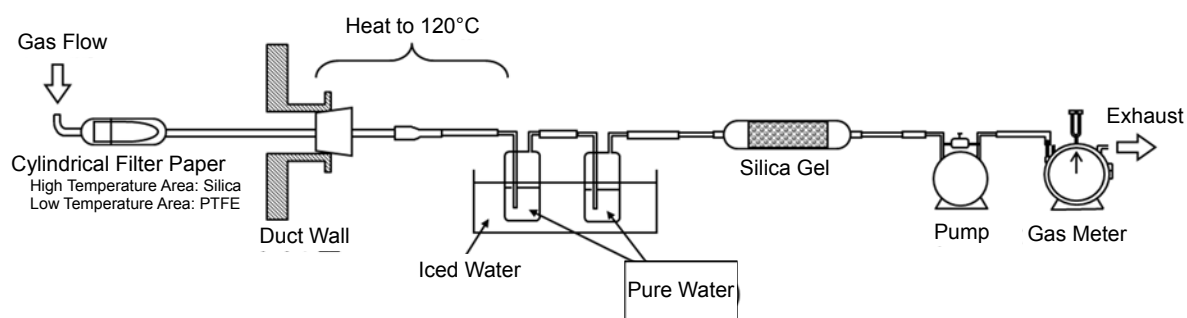


Figure 3.1-8 Sampling flow of HCl in exhaust gas (complying with JIS K 0107)

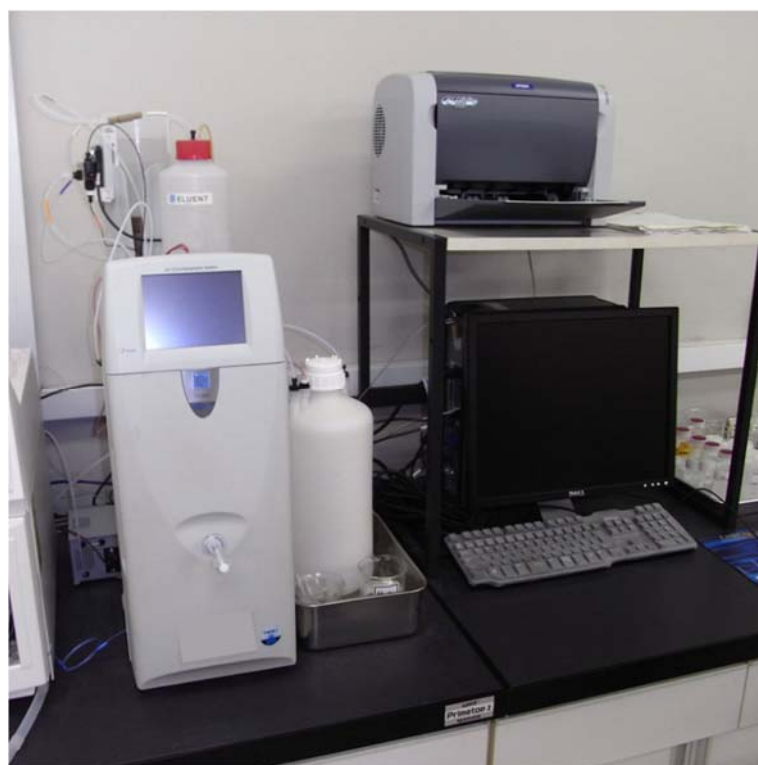


Figure 3.1-9 Ion chromatography device (former Dionex/ICS-2000)



## 3.2 Evaluation of smoke dust removal performance

### 3.2.1 Dry electrostatic precipitator (DEP)

#### (1) Test method

Figure 3.2-1 shows the dry electrostatic precipitator (DEP) of the Combustion-AQCS Integrated Facility. This device has two segments in which gas flows horizontally, and each segment has discharge electrodes and dust collection electrodes. Figure 3.2-2 shows the picture of discharge electrodes and dust collection electrodes viewed from the lower side. The dust collection electrode is flat and installed parallel to the gas flow. The discharge electrode is fixed on discharge flame supported by an insulator and placed at the center between two dust collection electrodes. Insulation properties of insulators were maintained by purging hot air inside the insulator chamber in the upper part of DEP to prevent contamination. Coal ash adhered on the discharge electrode and the dust collection electrode was taken off by beater, fell into the hopper in the lower part of the device. Then it was carried by the screw conveyor and stored in the first and second segments, respectively.

Dust collection performance at DEP was calculated based on deference in smoke dust concentration at DEP inlet and outlet, and comparison was made between conventional systems and the high-performance smoke dust removal system. Table 3.2-1 shows operation conditions of DEP and exhaust gas conditions at the time when smoke dust concentration was measured. In general, exhaust gas temperature at DEP in conventional systems is around 150 ~ 170°C. On the contrary, in the case of high-performance smoke dust removal system, since GGH heat recovery device is set before DEP to lower exhaust gas temperature, exhaust gas temperature at DEP is approx. 90°C which is lower than that of conventional systems. Exhaust gas flow velocity in the dust collection chamber was 0.7 ~ 0.8m/s and is within the scope of 0.5 ~ 2.0m/s which is the general design value of actual DEP. In addition, charge voltage at low temperature EP is 25 ~ 40kV and is lower than that of very low temperature EP which is 30 ~ 45kV. This is because charging was not easy when compared with very low temperature EP and the detailed reason for this is described later.

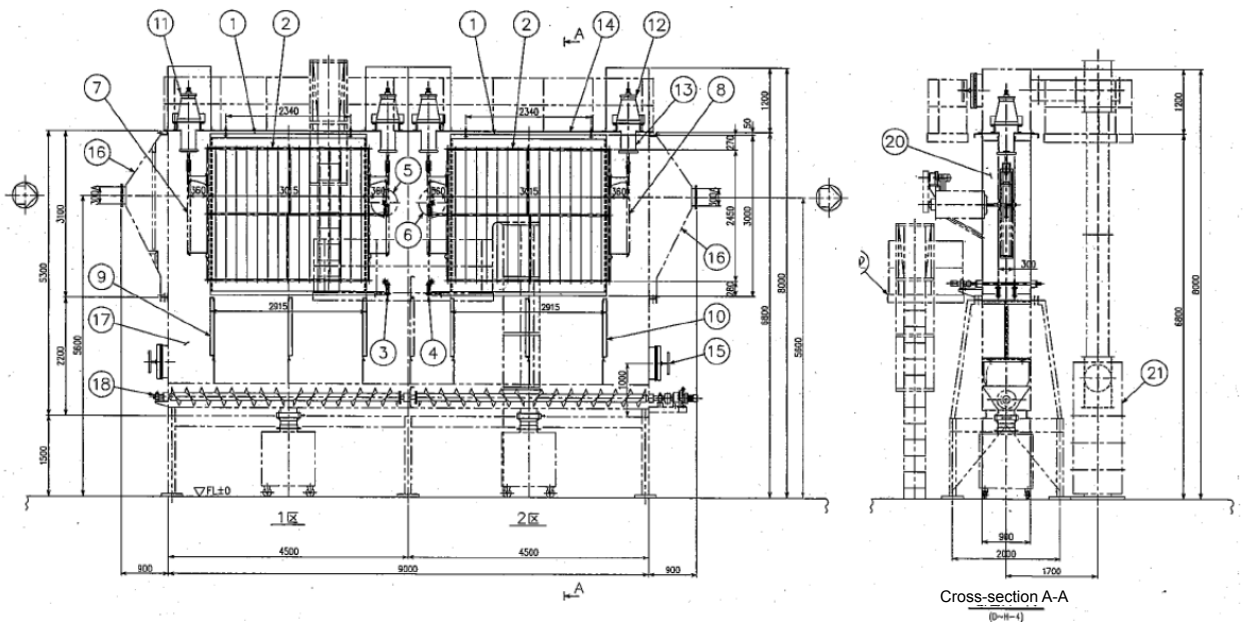


Figure 3.2-1 Structure of DEP



Figure 3.2-2 Inside of the dust collection chamber

Table 3.2-1 Exhaust gas conditions and operation conditions of DEP

Item	Unit	Conventional systems	High-performance smoke dust removal system
Exhaust gas amount (wet)	m <sup>3</sup> N/h	1,400	
Water concentration in exhaust gas	vol%	8~10	
DEP inlet exhaust gas temperature	°C	149~154	92~93
DEP inlet smoke dust concentration	g/m <sup>3</sup> N	23~25	
DEP dust collection area	m <sup>2</sup>	29	
Exhaust gas flow velocity in DEP	m/s	0.84	0.72
Exhaust gas retention time	s	6.9	8.1
SCA*	s/m	47	54
Charge voltage	kV	25~40	30~45
Current density	mA/m <sup>2</sup>	0.3~1.0	

\*Specific Collecting Area: (s/m) = Dust collection area (m<sup>2</sup>)/exhaust gas amount (m<sup>3</sup>/s)

(2) Method to measure electrical resistivity of coal ash

In addition, in order to evaluate dust collection characteristics of Talcher coal combustion ash, electrical resistivity ( $\rho_d$ ) of coal ash collected in DEP first segment was measured. The measurement method was the procedure from (a) to (d) described below which complies with JIS B9915 and parallel plate electrodes shown in Figure 3.2-3 were used.

(a) Place ash collected at DEP on the plate electrodes so as to ensure that the thickness of placed ash is 5mm or more and perform weighting (10g/cm<sup>2</sup>).

(b) Release weighting, level the surface to make 5mm-thick coal ash layer.

(c) Place electrodes on the upper part of the coal ash layer, adjust temperature and water concentration in the constant-temperature bath and retain it for one hour.

(d) Apply voltage using a super insulation resistance tester and measure electrical resistivity in two minutes.

Ambient temperature to measure electrical resistivity was increased from 80°C to 160°C by 20°C. For both conditions, water concentration was 9 vol% which was the same condition as that of exhaust gas.

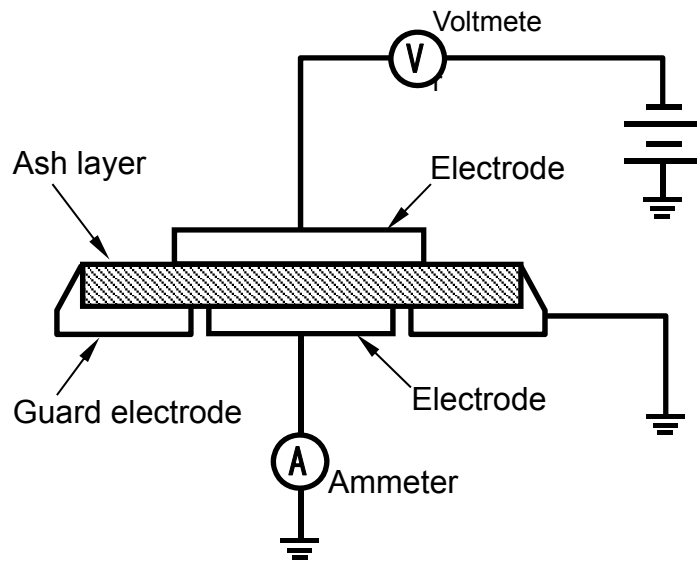


Figure 3.2-3 Electrode to measure electrical resistivity (parallel plate electrode)

### 3.2.2 Flue gas desulfurization (FGD)

The smoke dust removal performance at FGD was evaluated under the conditions shown in Table 3.2-2. Desulfurization L/G was set by changing the number of spray steps. With this, the drop size of spray liquid does not change even when L/G is changed, and influence of L/G on dust removal performance can be evaluated without change of the drop size of spray liquid. The specification of FGD is described in section 3.3. The spray nozzle used for the FGD was small, leading to higher spray pressure than that of actual device. Accordingly, with regard to influence on dust removal performance, spray velocity was fast and the drop size of spray liquid was small compared with actual devices. In addition, since the drop size of smoke dust may influence on dust removal performance at FGD, smoke dust at DEP outlet was trapped by using circular filter paper and observed with a SEM to obtain particle size distribution, as described in the above.

Table 3.2-2 Exhaust gas conditions at desulfurization inlet and operation conditions

Item	unit	Conventional systems	High-performance smoke dust removal system	Remark
Exhaust gas amount (wet)	m <sup>3</sup> N/h	1,440		
Water concentration in exhaust gas	vol%	8~10		
Desulfurization inlet smoke dust concentration	mg/m <sup>3</sup> N	200~1,300	8~78	
L/G	L/m <sup>3</sup> N	8~32		
Spray pressure	MPa	0.1		Actual device: 0.05~0.08MPa
Spray velocity	m/s	10		Actual device: 7~9m/s
Spray droplet average size	μm	690		Actual device: 2,000μm

### 3.3 Performance evaluation of desulfurization

#### 3.3.1 Combustion-AQCS Integrated Facility

Figure 3.3-1 shows the structure of FGD in the Combustion-AQCS Integrated Facility. The structure of spray nozzle enables spraying at four steps at maximum. The interval of steps is 1.5m. Contact of absorbing solution ( $\text{CaCO}_3$  slurry) sprayed from the nozzle set on each step and exhaust gas introduced from the lower part of the absorption tower removes  $\text{SO}_2$  in exhaust gas. Sulfurous acid generated by  $\text{SO}_2$  absorption is oxidized by oxidized air blowing into the circulation tank.

Table 3.3-1 shows the specification of the spray nozzle. The spray nozzle is 1/2-inch small hollow cone type to be used for spraying in a downward direction. Sixteen spray nozzles of the same type were set on one spray header while maintaining the same L/G and desulfurization rate as those of actual devices.

Table 3.3-2 shows conditions of desulfurization performance evaluation test. Tests of the high-performance smoke dust removal system and conventional systems were conducted on different days and the gas amount at the inlet of FGD was slightly different in the two tests. Since comparison of the two systems under the condition of high desulfurization ration was difficult, test was conducted with setting L/G as a parameter for a comparison method including the condition of lower desulfurization ratio.

L/G was adjusted by changing the steps of nozzles from one to four and set to be 10 to 40. In addition, spray solution spreads radially and part of the solution falls down along the wall after it hits the wall inside the device. Since this wet part of the wall also absorbs  $\text{SO}_2$  in gas, the length of the wet wall should be fixed under the all L/G conditions. Consequently, in this test, the number of nozzles was increased by operating nozzles from the upper steps serially to ensure evaluation with the fixed length of the wet wall. By setting the stable spray pressure of the spray nozzle to be 0.1Mpa, parameters that may influence desulfurization performance such as drop size of spray solution and relative velocity of spray solution and gas were set to be stable.

Inlet concentration of  $\text{SO}_2$ , alkali concentration in absorbing solution and gypsum concentration in absorbing solution were set to ensure the same value for the high-performance smoke dust removal system and for conventional systems. In addition, since the existence of sulfurous acid ( $\text{SO}_3$ ) in solution may decrease desulfurization performance, FGD was operated under the

condition where sufficient oxidized air was sent from the stage where gas was flowed before conducting performance test, and the test was started after sulfurous acid concentration was confirmed to be 0.

Desulfurization ratio was calculated based on the values of SO<sub>2</sub> concentration indicated on the exhaust-gas analyzers (manufactured by HORIBA, Ltd., ENDA-5800) set at the inlet and outlet of the FGD. In both systems, after the number of spray steps corresponding to each L/G was set, data was obtained in the state where values of inlet SO<sub>2</sub> concentration and outlet SO<sub>2</sub> concentration were stable. In addition, before and after the test, from the line to collect sample solution branching from the circulation pump of the absorption tower, absorbing solution was collected to measure alkali concentration in the solution by the neutralization titration.

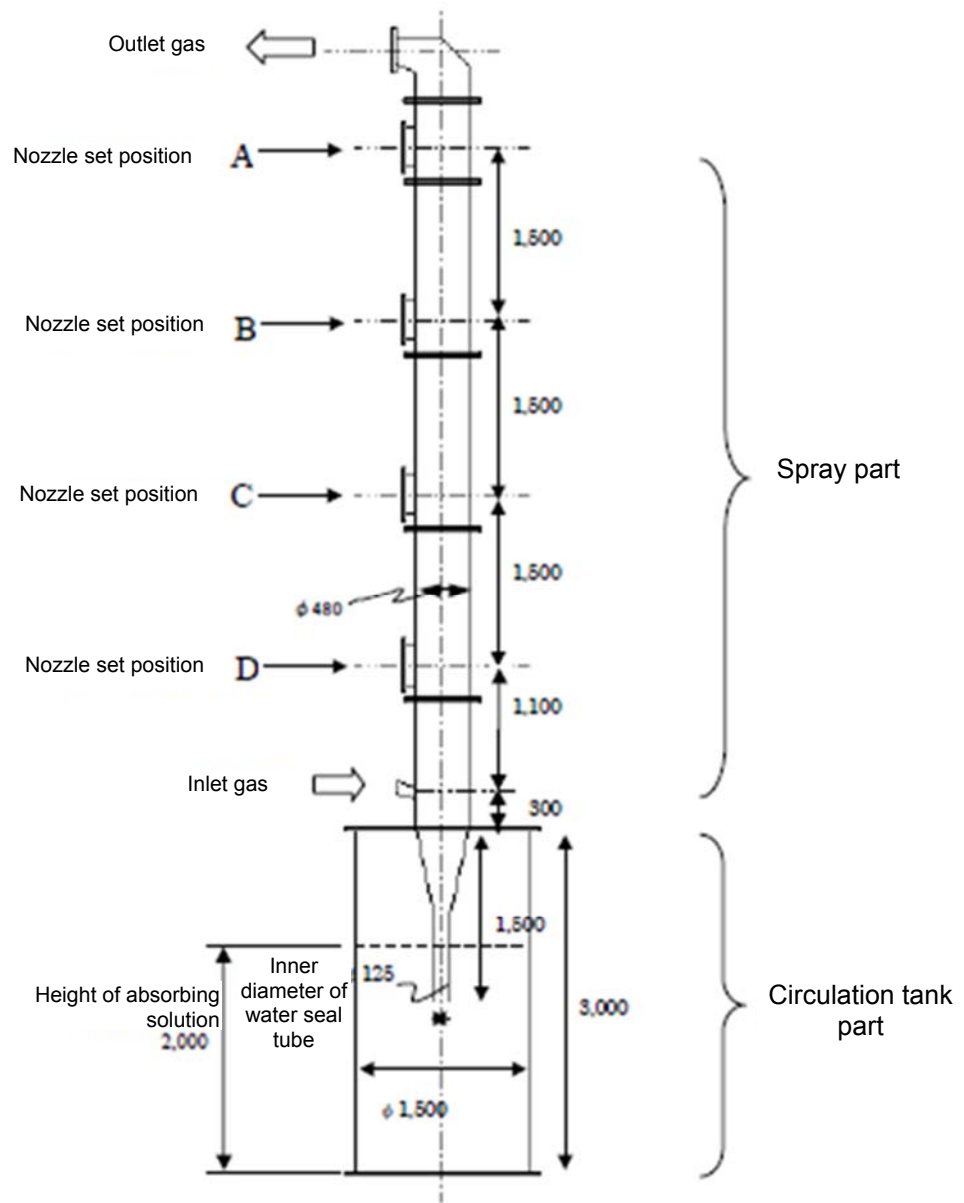


Figure 3.3-1 Structure of FGD



Table 3.3-1 Spray nozzle specification

Item	Unit	Specification
Manufacturer	-	IKEUCHI
Model	-	AAP16
Size	inch	1/2
Spraying method	-	hollow cone
Spray angle	deg	80 (downward)
Number of nozzles on each step	piece/step	16

Table 3.3-2 test conditions of comparative evaluation test of desulfurization performance

Item	Unit	Conventional systems	High-performance smoke dust removal system
Gas amount	m <sup>3</sup> N/h(dry)	1,200	1,300
Number of spray steps	step	1, 2, 3, 4	
Set L/G (calculated value)	L/m <sup>3</sup> N	10 to 40	
Spray pressure	MPa	0.1	
Spraying amount per step	m <sup>3</sup> /hr	11.0	
Inlet SO <sub>2</sub> concentration	ppm	500	
Alkali concentration in absorbing solution	mM	30	
Gypsum concentration in absorbing solution	wt%	15	
Sulfurous acid concentration in solution	mM	0	

### 3.3.2 Basic test device

#### (1) Al elution basic test

Under the condition of high smoke dust concentration, possible reaction that has influence on desulfurization performance is elution of Al in smoke dust. When spray solution whose pH decreased due to absorption of SO<sub>2</sub> in gas contacts with exhaust gas smoke dust in gas, Al in smoke dust may be eluted depending on pH conditions and contact time of spray solution and characteristics of smoke dust. On this occasion, F derived from exhaust gas absorbed in spray solution together with smoke dust and eluted Al react, and AlF<sub>x</sub> compound is generated. The generated compound covers the surface of limestone particle, which possibly inhibits dissolution of limestone.<sup>1),2),3)</sup> As a result, pH of spray solution does not rise but stays low due to SO<sub>2</sub> absorption. However, FGD is operated to keep pH stable, and hence limestone slurry is excessively fed. When this phenomenon occurs, alkaline agent such as NaOH should be added in the absorption tower to cause rise of pH and detach AlF<sub>x</sub> compound, which requires installation of device to add NaOH. Since elution of Al in coal ash increases Al concentration in absorbing solution under the condition of high smoke dust concentration, whether or not the aforementioned phenomenon inhibiting dissolution of limestone occurs due to coal and smoke dust concentration to be used should be clarified. Whether or not inhibition of limestone dissolution occurs should be determined after the operation until Al and F concentration in the system strikes balance at a fixed level. However, operating the Combustion-AQCS Integrated Test device for several tens of hours is insufficient for Al and F in the system to balance. Accordingly, in parallel with desulfurization performance comparison by using the Combustion-AQCS Integrated Test device, basic test was conducted in a laboratory in order to confirm phenomenon inhibiting dissolution of limestone.

First, test to confirm whether or not Al is eluted from coal ash was conducted. Figure 3.3-2 shows the drawing of test device, and Table 3.3-3 shows test conditions. H<sub>2</sub>SO<sub>4</sub> was added so that SO<sub>2</sub> concentration in eluate was 2.1mM which is equivalent to SO<sub>2</sub> concentration absorbed in the FGD. Calculation was made to ensure that SO<sub>2</sub> concentration was equivalent to the SO<sub>2</sub> amount absorbed by spray solution under operation conditions of FGD used in the Combustion Integrated Test Facility. Then, immersion in a constant-temperature bath was made to ensure simulation of 60°C solution temperature in the FGD by solution temperature in the reaction

device.

After the solution temperature of the reaction device became stable at 60°C, 0.135g of coal ash was added, and the solution was collected regularly. Coal ash was Talcher coal collected in the Combustion Integrated Test Facility. For comparison, evaluation was also made under the condition where coal ash from the U.S. was added. The additive amount of coal ash was set so that high concentration of around 1,300mg/m<sup>3</sup>N was produced. This concentration was the highest smoke dust concentration in gas at the Combustion Integrated Test Facility.

After filtration of collected solution by using membrane filter of 0.45µm, dilution with pure water was performed and Al concentration in the solution was measured by using ICP emission spectrometer (Figure 3.3-3, manufactured by Shimadzu Corporation, ICPE-9820).

In addition, since Talcher coal ash and coal ash from the U.S. have different Al concentration in their ash, in order to make comparison of Al elution, the rate of elution to Al amount in added ash was calculated and compared, not using eluted Al amount as shown in the following formula 3.3-1. In addition, specific gravity of solution was set to be 1g/cm<sup>3</sup>.

$$\text{Al elution rate}[\%] = \frac{\text{Al concentration in eluate [mg/g]}}{\text{Al concentration in coal ash [mg/g]}} \times 100 \cdot \cdot \cdot \cdot 3.3 - 1$$

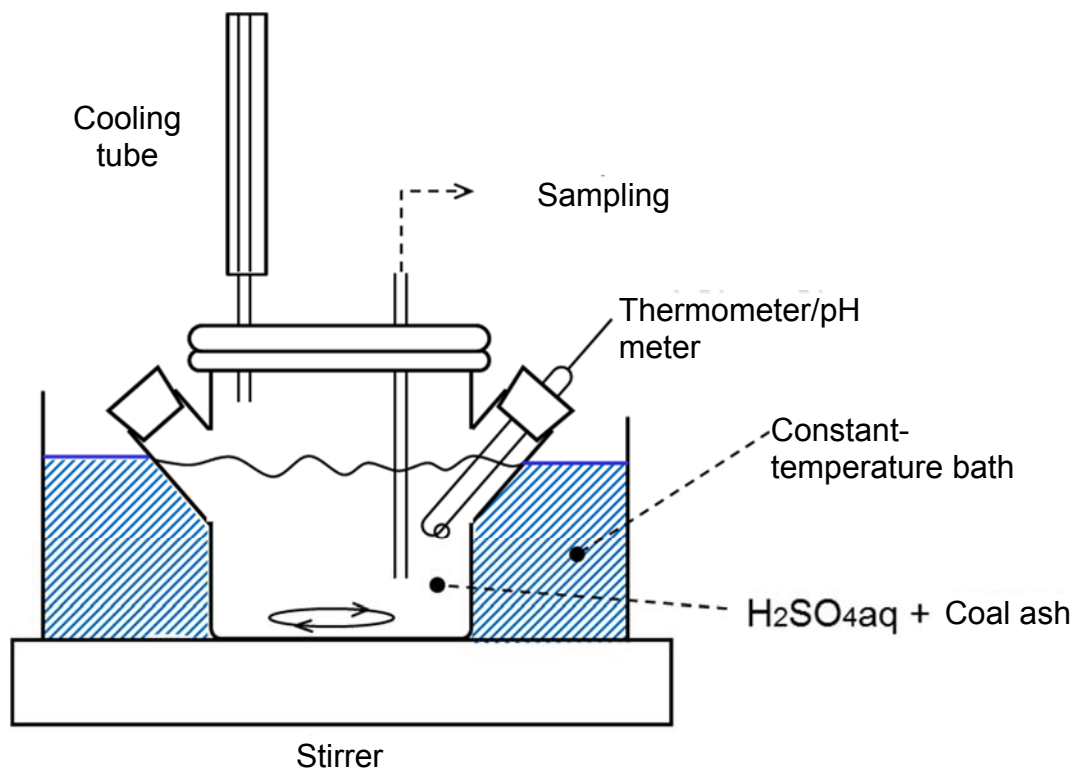


Figure 3.3-2 Al elution basic test Overview of device

Table 3.3-3 Test conditions of Al elution basic test

Item	Unit	Value
Solution amount	mL	500
SO <sub>2</sub> concentration in solution	mM	2.1
Elution temperature	°C	60
Coal ash amount	g	0.135
Elution time	min	3 to 120



Figure 3.3-3 Appearance of ICP emission spectrometer

## (2) Limestone inactivation verification test

After Al elution characteristics of ash described above was obtained, a small desulfurization test device was used to see whether or not inhibition of limestone dissolution occurs in the simulation of actual SO<sub>2</sub> absorption reaction condition.

Figure 3.3-4 shows overview of a small desulfurization test device and Figure 3.3-5 shows the photo of the actual device. In addition, Table 3.3-4 shows device operation conditions. Since SO<sub>2</sub> load to absorbing solution determines the amount of Al eluted from ash, in this test, L/G, inlet SO<sub>2</sub> concentration and desulfurization rate were set to ensure the same SO<sub>2</sub> load as that of the Combustion Integrated Test Facility. In addition, since spray part of the device was the shower type which lowers desulfurization performance compared with the spray type, perforated plates were installed in the tower to adjust desulfurization rate. In this test, two perforated plates were installed to obtain desulfurization performance equivalent to the set value. SO<sub>2</sub> were mixed into air to adjust concentration of inlet SO<sub>2</sub> gas, and inlet and outlet SO<sub>2</sub> concentration was monitored with a SO<sub>2</sub> continuous analyzer (HORIBA, Ltd., VIA-510).

For the F feeding system, 1000mg/L of NaF solution was used. Feeding amount was adjusted to ensure the concentration of 9.5mg/m<sup>3</sup>N which is equivalent to F concentration in gas at the inlet of the FGD in the Combustion Integrated Test Facility, and the solution was added on the perforated plates.

For the feeding system of ash, 0.5% slurry diluted with pure water was used. Under the condition of high smoke dust concentration in which inactivation tends to occur, feeding amount was adjusted to ensure 90mg/m<sup>3</sup>N of smoke dust concentration in gas, and the slurry was added on the perforated plates.

In operation of actual FGD, to make gypsum concentration in the system stable, gypsum is extracted on a regular basis. In addition, apart from this, water is discharged regularly to keep Cl concentration in the system stable. At the time of gypsum extraction and water discharge, the amount of Al and F taken out of the system balances with Al and F concentration flowing into the system of FGD, and the final Al and F concentration in the system is determined. In this test, Calculation was made to ensure that setting of Cl concentration in gas to be 2.7ppm (calculated value based on coal exhaust gas) balances with 10,000ppm of Cl concentration in the system, and the condition in which gypsum concentration was 20wt%, discharged water amount was

80mL/h was set.

Since most of F in solution is supposed to exist in the form of  $\text{CaF}_2$ , and the solubility of  $\text{CaF}_2$  is approx. 20mg/L, low under the condition of this test where pH is 5.5 and solution temperature is  $20^\circ\text{C}$ , all of flowing F except the amount of dissolved  $\text{CaF}_2$  is assumed to be solid. At this time, the final balancing F concentration in the system is calculated to be approx. 15mM based on the relation of extraction amount of gypsum, discharge amount and inflow amount.

With regard to Al concentration in the system, since the solubility of  $\text{Al}^{3+}$  when pH was 5.5 was low as with the case of F, all of it except approx. 10mg/L of the solubility of  $\text{Al}(\text{OH})_3$  was assumed to be solid. At this time, based on the relation of discharge amount and inflow amount, the final balancing Al concentration in the system is calculated to be approx. 16 mM when Talcher coal is fed and to be approx. 6mM when coal from the U.S. is fed.

First,  $\text{SO}_2$  gas and  $\text{CaCO}_3$  were fed in the device, and continuous feeding of coal ash and NaF was started when outlet  $\text{SO}_2$  concentration became stable. In parallel,  $\text{CaCO}_3$  concentration in the system was measured on a regular basis.

In this test device, pH is controlled to be stable at 5.5. Accordingly, if  $\text{CaCO}_3$  concentration in the system continues to increase, it is judged that the feeding amount of  $\text{CaCO}_3$  slurry necessary to maintain pH in the system is increasing; that is, AIFx is generated and pH buffer action is occurring in the system. Similarly, pH of spray solution falling from the shower part to the tank part is not expected to decrease due to buffer action.

In contrast, in the stage where Al and F are fed until Al and F concentration reaches the final balance concentration, if  $\text{CaCO}_3$  concentration in the system shows no significant rise and is stable, it is judged that balance is kept in low concentration where AIFx is not generated or inhibition of dissolution does not occur.

In addition, coal ash from the U.S. whose rate of Al elution from ash was high in Al elution test was fed under the same condition for this test device, and the result was evaluated by comparison with the Talcher coal result.

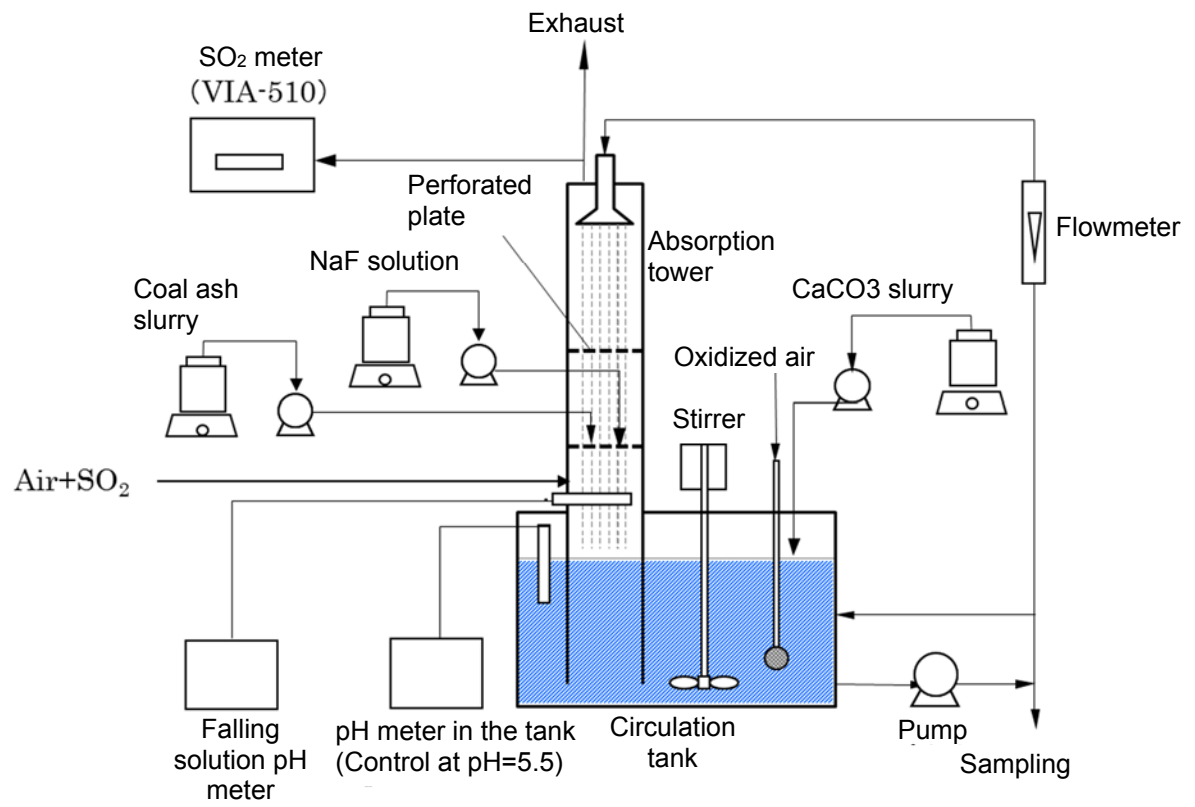


Figure 3.3-4 Verification test of limestone inactivation - Device overview



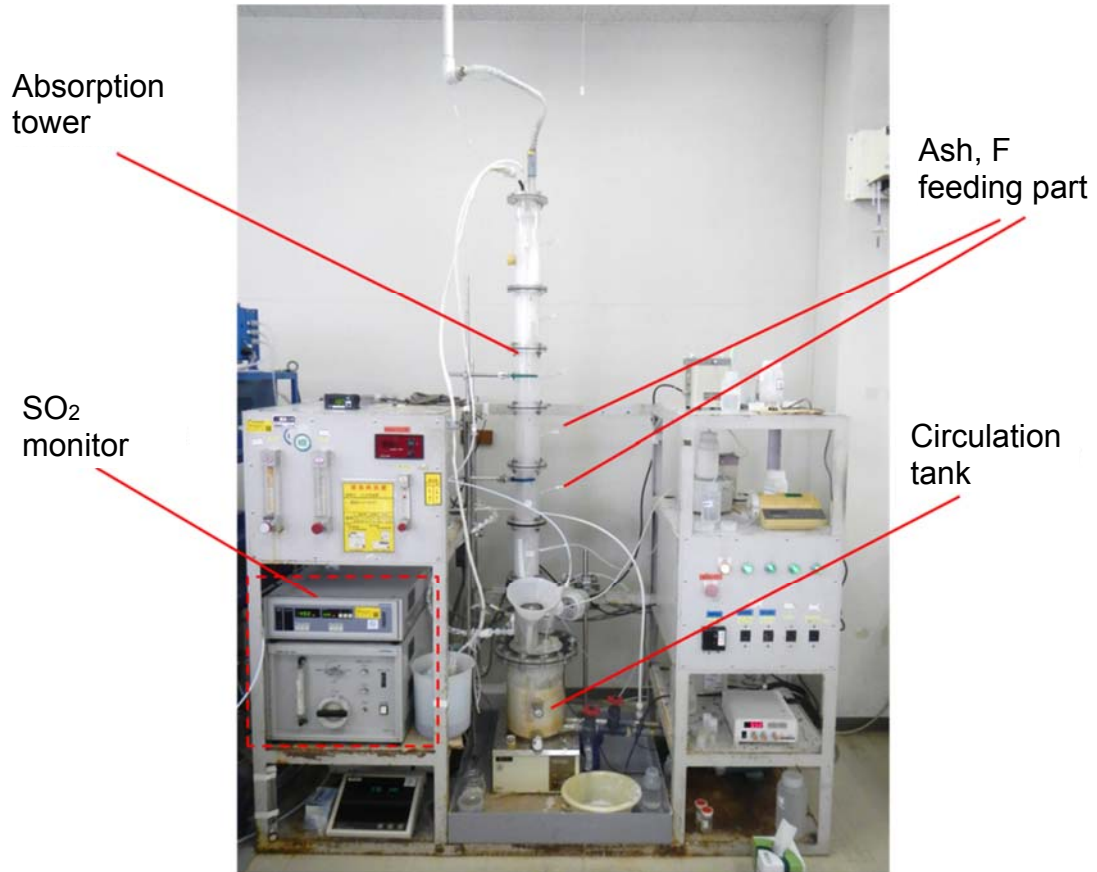


Figure 3.3-5 Small desulfurization test device - Photo of appearance

Table 3.3-4 Verification test of limestone inactivation - Test conditions

Item	Unit	Value	
Device conditions	Gas amount	LN/min	50
	Tank solution amount	L	6
	Gypsum slurry concentration	wt%	20
	L/G	L/m <sup>3</sup> N	20
	Inlet SO <sub>2</sub> concentration	ppm	1,000
	Desulfurization rate	%	95
	SO <sub>2</sub> absorption amount	mmol/min	2.1
	Operation pH	-	5.5
	Discharged water amount	mL/h	80
F feeding system	F concentration in gas	ppm	9.5
	NaF concentration	mg/L	1,000
	NaF feeding amount	mL/min	1.03
Ash feeding system	Ash concentration in gas	mg/m <sup>3</sup> N	90
	Ash slurry concentration	wt%	0.5
	Ash slurry feeding amount	mL/min	0.9

[Chapter 3 Reference]

- 1) Mori T. et. al.: Effect of Al<sup>3+</sup> and F<sup>-</sup> on Desulfurization Reaction in the Limestone Slurry Scrubbing Process: Ind. Eng. Chem. Process Des. Dev., Vol.20, No.1, pp.144-147, 1981
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### 3.4 Measurement of overall heat transfer coefficient in GGH

To improve heat transfer, fin tubes as shown in Figure 3.4-1 are set inside the GGH heat recovery device installed in the Combustion-AQCS Integrated Test Facility. Headers placed on each tube unit distribute cooling media. Figure 3.4-2 shows the unit configuration of heat recovery device. A unit with three rows and a unit with four rows are set alternatively. The device consists of eight units in all. The heat transfer area of GGH heat recovery device is equivalent to the total of the surface area of eight fin tube units. Accordingly, heat transfer coefficient  $\alpha$  [W/(m<sup>2</sup> · K)] to fin tubes was obtained based on Formula 3.4-1, Formula 3.4-2 and Formula 3.4-3, where,  $T_{gin}$ ,  $T_{gout}$ : temperature[K] of gas before and after passing through the tube,  $T_{win}$ ,  $T_{wout}$ : temperature[K] of media before and after passing through the tube, A: total surface area of fin tubes [m<sup>2</sup>], W: amount of media [g],  $C_p(\text{water})$ : heat capacity of water = 4.19[J/(K · g)]. Passage of time of heat transfer coefficient  $\alpha$  was calculated by observation of media flow volume flowing inside the fin tubes of each unit with a flowmeter and constant monitoring of  $T_{gin}$ ,  $T_{gout}$ ,  $T_{win}$ ,  $T_{wout}$  with a thermocouple.

$$Q = A \cdot \alpha \cdot \Delta T \quad \cdot \cdot \cdot \cdot \cdot \quad 3.4 - 1$$

$$\Delta T = \frac{(T_{gin} - T_{win}) - (T_{gout} - T_{wout})}{\ln\left(\frac{T_{gin} - T_{win}}{T_{gout} - T_{wout}}\right)} \quad \cdot \cdot \cdot \cdot \cdot \quad 3.4 - 2$$

$$Q = W \cdot C_{p(\text{water})} \cdot (T_{win} - T_{wout}) \quad \cdot \cdot \cdot \cdot \cdot \quad 3.4 - 3$$

Q: amount of heat transferred [W]                      A: heat transfer area [m<sup>2</sup>]  
 $\alpha$ : heat transfer coefficient [W/(m<sup>2</sup> · K)]       $\Delta T$ : log average temperature [K]

In addition, for actual devices, soot blow method is mainly used to remove ash adhered on a heat transfer tube. Similarly, in the Combustion-AQCS Integrated Test device, ash was removed by soot blow method at the timing when DEP changed and other operation conditions ended. Figure 3.4-3 shows the appearance of a soot blower. As shown in Figure 3.4-2, each unit has

three steps. The specification of the device is as shown in Table 3.4-1. The soot blower was fixed rotating type, and compressed air was used as spray medium. As shown in Figure 3.4-2, the upper or lower side of a soot blower has an inspection window, through which photos were taken to check situations of ash accumulation on fin tubes before and after soot blow in conventional systems and the high-performance smoke dust removal system.

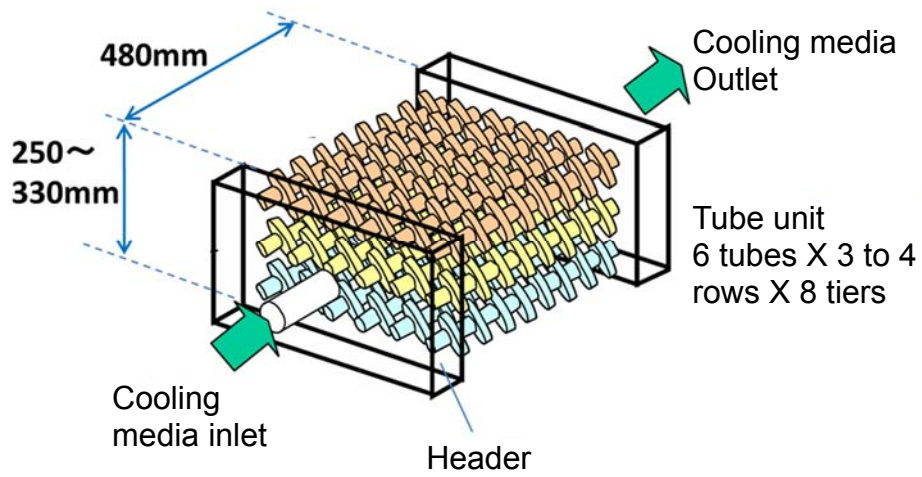


Figure 3.4-1 Appearance of fin tubes in GGH heat recovery device and structure of tube unit

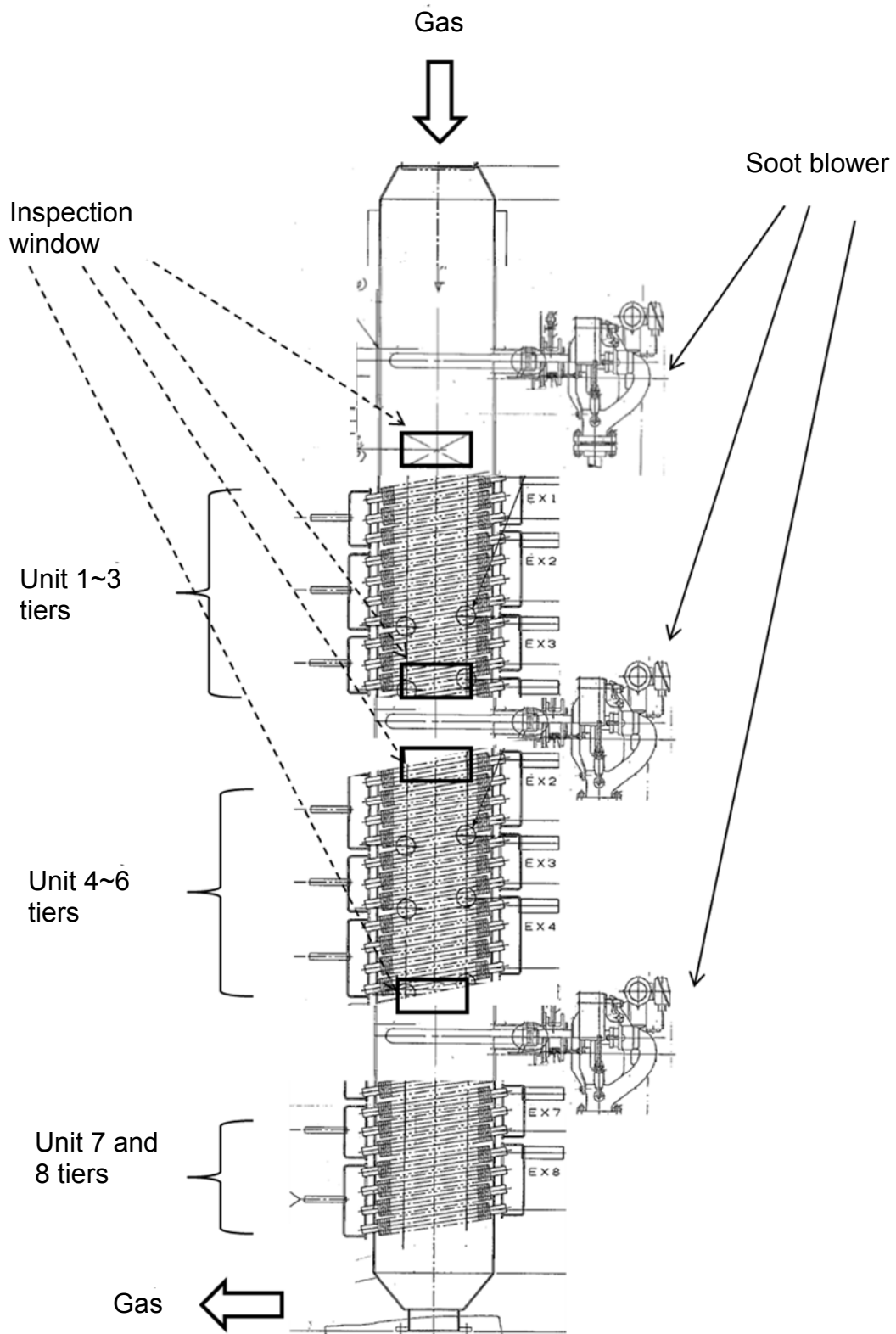


Figure 3.4-2 Unit structure of heat recovery device and installation position of soot blower

Table 3.4-1 Specification of soot blower

Model	Fixed rotating type
Nozzle specification	$\phi 5.5\text{mm}$ hole $\times$ 4 nozzles (interval of 100mm)
Spray pressure	0.7MPa
Receiving pressure	486mmH <sub>2</sub> O
Spraying time	10 sec. $\times$ twice
Spraying cycle	When each operation condition ends (every 2 to 3hr)



Figure 3.4-3 Appearance of soot blower

### 3.5 Abrasion property evaluation of GGH fin

In the high-performance smoke dust removal system, since GGH heat recovery device is installed before DEP, fin tubes are exposed to smoke dust with high concentration. Furthermore, since Talcher coal which is the subject of the evaluation in this test has high ash content, abrasion characteristics were evaluated in addition to heat transfer characteristics evaluation of GGH heat recovery device under the condition of high smoke dust concentration.

Abrasion characteristics were evaluated by the use of two kinds of materials, carbon steel (SS400) and sulfuric acid resistant steel (manufactured by Nisshin Steel, material similar to S-TEN) shown in Table 3.5-1, which are equivalent to those used for casing and fin tubes of actual GGH heat recovery devices. These two kinds of materials were processed in the size shown in Table 3.5-2 to be used as test pieces and set on the inlet side of GGH heat recovery device as shown in Figure 3.5-1 to be exposed to coal combustion exhaust gas. Position of test pieces was set to be between soot blower and fin tubes, and the removal of coal ash accumulated on test pieces by regular soot blow was made possible in the same manner as the case with fin tubes.

Table 3.5-3 shows exhaust gas conditions of abrasion evaluation for GGH heat recovery device in conventional systems and the high-performance smoke dust removal system. After the exposure to exhaust gas, scale of collected test pieces was removed, decreased weight was measured and abrasion rate was calculated based on Formula 3.5-1 to make comparison between conventional systems and the high-performance smoke dust removal system.

$$\text{Abrasion rate } \left[ \frac{\text{mm}}{\text{year}} \right] = \frac{\text{decreased weight [g]} \times 10 \left[ \frac{\text{mm}}{\text{cm}} \right] \times 8,000 \left[ \frac{\text{hr}}{\text{year}} \right]}{\text{specific weight } \left[ \frac{\text{g}}{\text{cm}^3} \right] \times \text{exposure area [cm}^2\text{]} \times \text{operation hour [hr]}}$$

• • • 3.5-1



Table 3.5-1 Test piece materials and content of various components

	Carbon steel (SS400)	Sulfuric acid resistant steel (manufactured by Nisshin Steel, material similar to S-TEN)
C	0.12 to 0.2	0.04
Si	≤ 0.3	0.30
Mn	0.3 to 0.7	0.90
Cu	-	0.30
Ni	-	0.15
Sb	-	-
Other	-	Cr: 0.15, Mo: 0.05

Table 3.5-2 Test piece size

Condition	Material	Mark	Size (mm)			Hole diameter (mm)	
			L	W	T	1	2
High-performance smoke dust removal system	SS400	CS1	50.07	29.89	1.97	5.02	5.04
		CS2	49.87	28.16	1.98	5.17	5.10
	S-TEN	S1	49.98	30.76	2.97	5.12	5.06
		S2	50.77	28.81	2.86	5.13	5.14
Conventional systems	SS400	CS3	49.67	30.85	1.98	5.09	5.10
		CS4	50.69	31.84	1.98	5.11	5.11
	S-TEN	S3	51.55	28.92	2.92	5.09	5.09
		S4	49.33	29.03	2.92	5.09	5.09

Table 3.5-3 Exhaust gas conditions for GGH heat recovery device

Item	Unit	Conventional systems	High-performance smoke dust removal system
Exhaust gas amount (wet)	m <sup>3</sup> N/h	1,400	
Water concentration	vol%	8~10	
GGH heat recovery device inlet exhaust gas temperature	°C	140~160	170~220
GGH heat recovery device outlet exhaust gas temperature	°C	70~80	90~100
GGH heat recovery device inlet smoke dust concentration	g/m <sup>3</sup> N	0.18 (at the time when DEP charge voltage = 35kV)	29.1

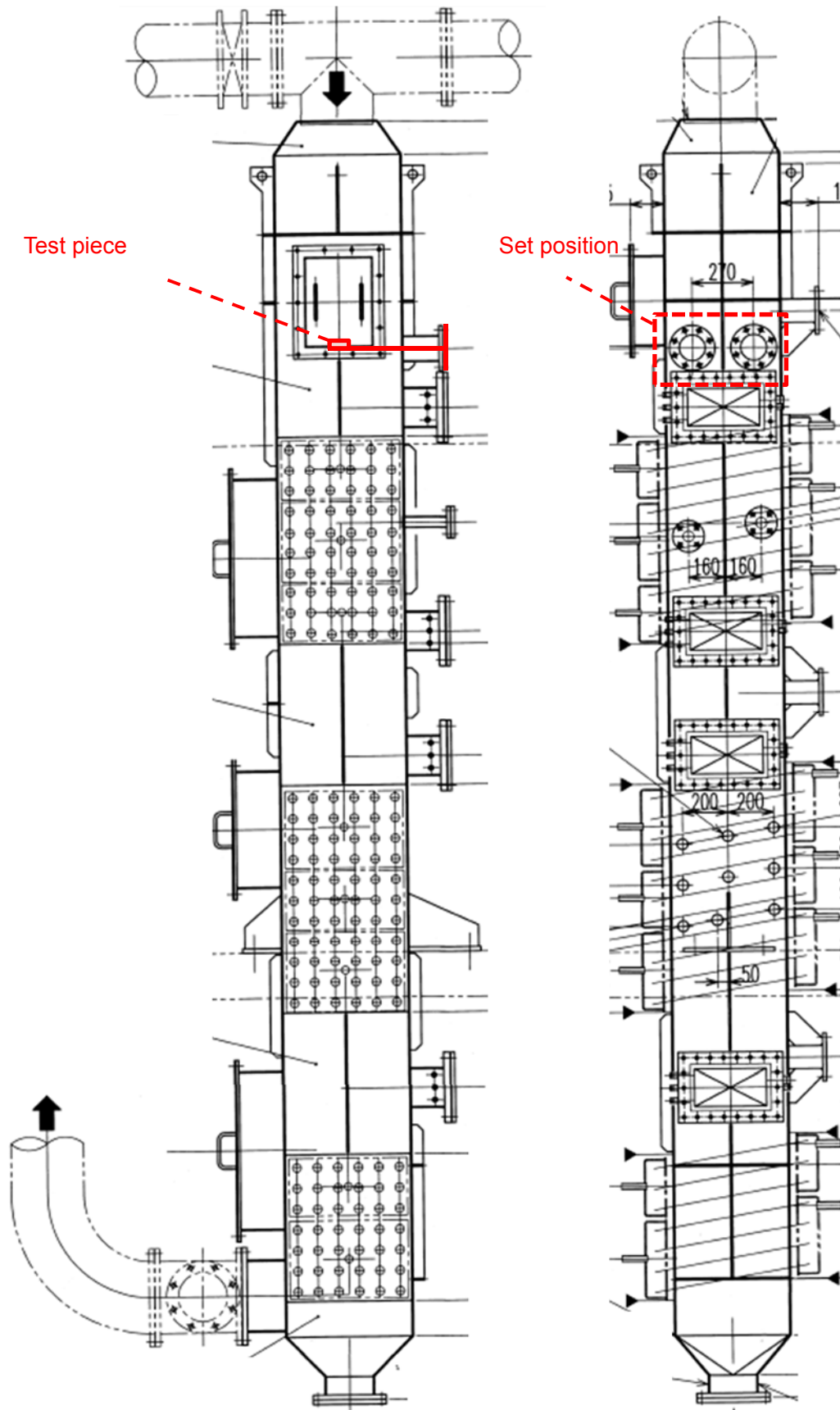


Figure 3.5-1 GGH heat recovery device of Combustion-AQCS Integrated Test Facility and set position of test piece

## 4. RESULTS AND DISCUSSION

### 4.1 Characteristics of coal and combustion exhaust gas

#### 4.1.1 Evaluation of coal under test

Table 4.1-1 shows comparison of characteristics (published data) of Talcher coal used in this test and other representative coal (A, B, C) previously used in the Combustion-AQCS Integrated Facility.

The most distinct characteristics of Talcher coal is its high ash content of 34.5%. Although the percentage is lower than that of coal A (from China) which is 47.9%, Talcher coal has approx. three fold higher ash content than that (around 10%) of general coal from North America, Australia, etc. Since high ash content leads to low calorific value, increase of burning amount is required to obtain prescribed heat input amount. With regard to composition of ash, SiO<sub>2</sub>, the main acid component is 60.8% which is high, whereas CaO, the main alkali component is 0.82% which is very low. This imbalance between acid and alkali may partly contribute to high melting point of ash which is 1,550°C or more (See Appended figure 4.1-1, 4.1-2).

Total S was 0.47% which is low, and S in ash was 0.04%, most of which was combustible S.

Other characteristics are that content of mercury (Hg), and fluorine (F) is high (200mg/kg), and content of boron (B) was very low (8mg/kg) compared with other kinds of coal.

Table 4.1-1 Comparison of characteristics of India/Talcher coal and coal previously tested at the integrated facility

Analysis item		Coal (production area)		Talcher (India)	Coal A (China)	Coal B (Eastern U.S.)	Coal C (Canada)	
		Base	Unit					
Higher calorific value		air-dried	kJ/kg	19,530	15,660	27,330	26,270	
Total water content		arrival	%	12.3	8.67	12.2	10.3	
Industrial analysis	Water content of air-dried sample	air-dried	%	6.51	2.04	9.23	5.62	
	Volatile content	anhydrous	%	30.03	19.04	40.43	35.86	
	Fixed carbon	anhydrous	%	35.45	33.04	50.15	51.84	
	Ash content	anhydrous	%	<b>34.52</b>	<b>47.92</b>	<b>9.42</b>	<b>12.3</b>	
Elemental analysis	C	anhydrous	%	51.20	40.88	71.80	68.66	
	H	anhydrous	%	3.68	2.34	4.67	4.38	
	O	anhydrous	%	9.12	7.95	10.21	13.75	
	N	anhydrous	%	1.06	0.60	1.32	0.79	
	Total S	anhydrous	%	<b>0.46</b>	<b>0.77</b>	<b>2.68</b>	<b>0.30</b>	
	S in ash	anhydrous	%	0.04	0.46	0.10	0.18	
	Combustible S	anhydrous	%	0.42	0.31	2.58	0.12	
	Cl	anhydrous	mg/kg	<b>&lt;100 (30)</b>	410	420	<50	
	F	anhydrous	mg/kg	200	170	40	60	
	B	anhydrous	mg/kg	8 (8.7)	29	146	-	
	Se	anhydrous	mg/kg	2 (2.1)	3.6	1.3	-	
	Hg	anhydrous	µg/kg	<b>220</b>	280	110	35	
Ash composition analysis	SiO <sub>2</sub>	ashing	%	60.8	49.1	44.4	54.9	
	Al <sub>2</sub> O <sub>3</sub>	ashing	%	28.1	34.2	20.9	19.8	
	Fe <sub>2</sub> O <sub>3</sub>	ashing	%	3.89	5.50	19.1	5.56	
	CaO	ashing	%	<b>0.82</b>	<b>3.01</b>	<b>5.27</b>	<b>10.4</b>	
	MgO	ashing	%	0.28	0.99	1.06	1.88	
	TiO <sub>2</sub>	ashing	%	2.01	-	-	-	
	SO <sub>3</sub>	ashing	%	0.14	2.39	2.27	3.56	
	Na <sub>2</sub> O	ashing	%	0.06	0.47	1.10	0.78	
	K <sub>2</sub> O	ashing	%	0.84	1.30	2.27	0.72	
	V <sub>2</sub> O <sub>5</sub>	ashing	%	0.03	0.04	-	0.03	
	Cr <sub>2</sub> O <sub>3</sub>	ashing	%	0.04	-	-	-	
	CuO	ashing	%	0.01	-	-	-	
Fusibility of ash	Oxidization	softening point	ashing	°C	1,460	1,370	1,260	1,250
		hemi sphere point	ashing	°C	≥1,550	≥1,500	1,310	1,330
		flow point	ashing	°C	≥1,550	≥1,500	1,340	1,390
	Reduction	softening point	ashing	°C	1,450	1,300	-	1,120
		hemi sphere point	ashing	°C	≥1,500	≥1,500	-	1,290
		flow point	ashing	°C	≥1,500	≥1,500	-	1,380
Button index		air-dried	CSN	0	1/2	3	0	

( ): Reference value below the lower limit of quantitation

#### 4.1.2 Characteristics of combustion exhaust gas

Table 4.1-3 shows measurement value and Table 4.1-4 shows 6%O<sub>2</sub> translated value of exhaust gas components calculated from coal compositions and exhaust gas compositions measured at denitrification catalyst inlet at the time of test operation, respectively. Measurement values of SO<sub>2</sub>, NO<sub>x</sub>, CO<sub>2</sub>, O<sub>2</sub> were average of measurement values obtained every minute through continuous monitoring (from 9 o'clock in the morning to 6 o'clock in the afternoon, excluding clear abnormal values). In addition, smoke dust concentration was average value of two measurements by exhaust gas sampling.

Exhaust gas composition during test operation greatly varied within a day and from day to day. This was seemingly due to great variation of coal characteristics. In 6%O<sub>2</sub> translation, SO<sub>2</sub> was from 460 to 500ppm, and NO<sub>x</sub> was from 140 to 250ppm. Smoke dust was from 30 to 35g/m<sup>3</sup>N which is low compared with the calculated value (48g/m<sup>3</sup>N). This is possibly because the existence of an approx. five-meter long horizontal duct between the furnace outlet and denitrification inlet caused decrease of smoke dust as it fell and accumulated in this horizontal duct.

Table 4.1-3 Exhaust gas compositions at the inlet of denitrification device (measurement value, dry base)

Item	Unit	Calculated value *1	Oct. 6th (Tue.)	Oct. 7th (Wed.)	Oct. 8th (Thu.)	Oct. 9th (Fri.)	Oct. 10th (Sat.)
O <sub>2</sub>	%	6.0	6.8	9.4	4.9	8.0	6.9
CO <sub>2</sub>	%	13.4	11.4	9.6	13.7	10.9	11.8
SO <sub>2</sub>	ppm	412 (Combustion S) 451 (Total S)	437	382	538	435	431
NO <sub>x</sub>	ppm	-	158	167	147	161	158
Smoke dust	g/m <sup>3</sup> N	48.4	30.2	23.0	-	30.6	-

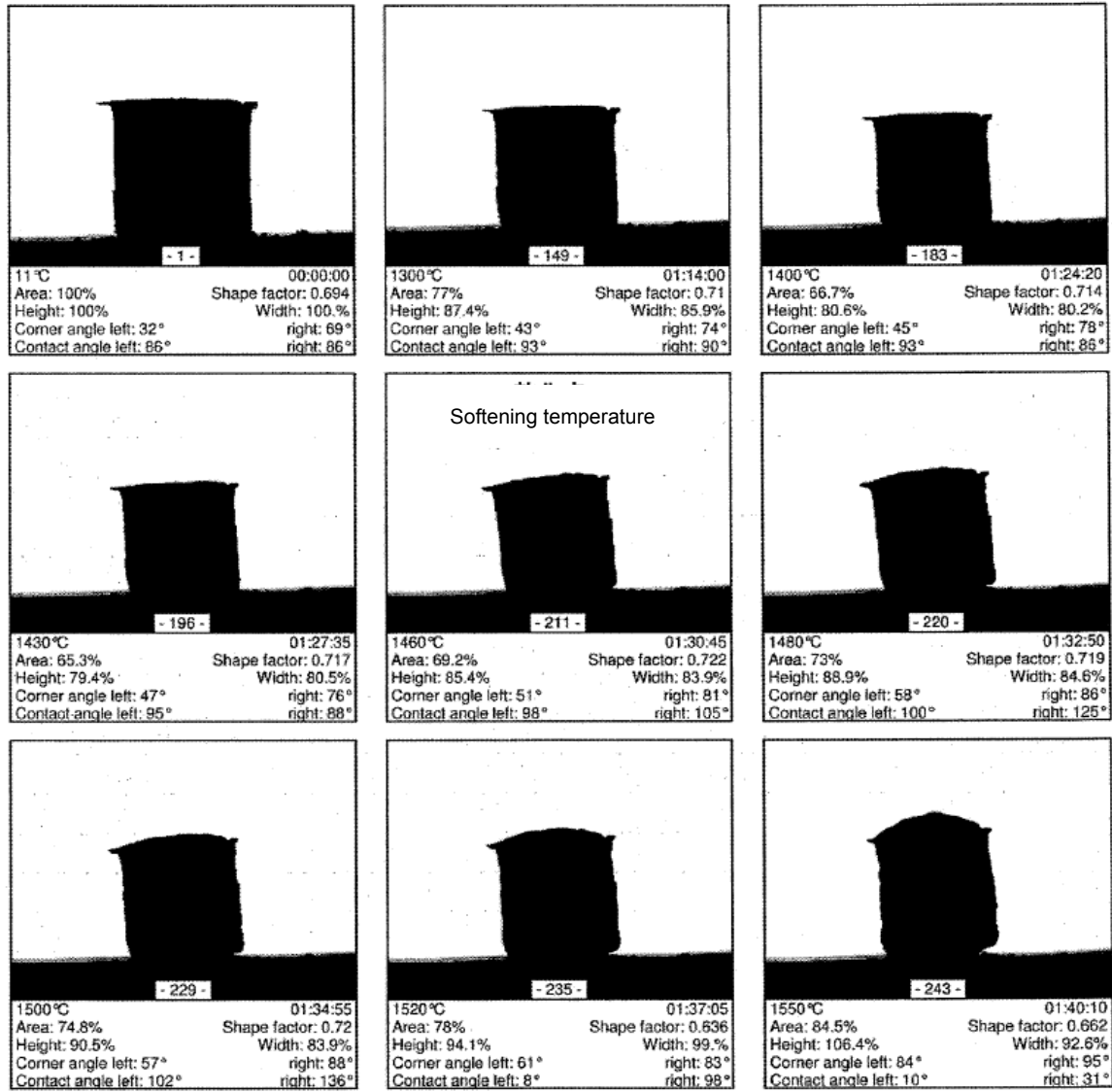
\*1: Air ratio at the time of calculation is 1.4, remaining O<sub>2</sub>=6%

Table 4.1-4 Exhaust gas compositions at the inlet of denitrification device (6%O<sub>2</sub> translated value, dry base)

Item	Unit	Calculated value *1	Oct. 6th (Tue.)	Oct. 7th (Wed.)	Oct. 8th (Thu.)	Oct. 9th (Fri.)	Oct. 10th (Sat.)
CO <sub>2</sub>	%	13.4	12.4	12.2	12.8	12.4	12.5
SO <sub>2</sub>	ppm	412 (Combustion S) 451 (Total S)	462	500	501	500	458
NO <sub>x</sub>	ppm	-	176	253	140	214	175
Smoke dust	g/m <sup>3</sup> N	48.4	31.9	29.7	-	35.3	-

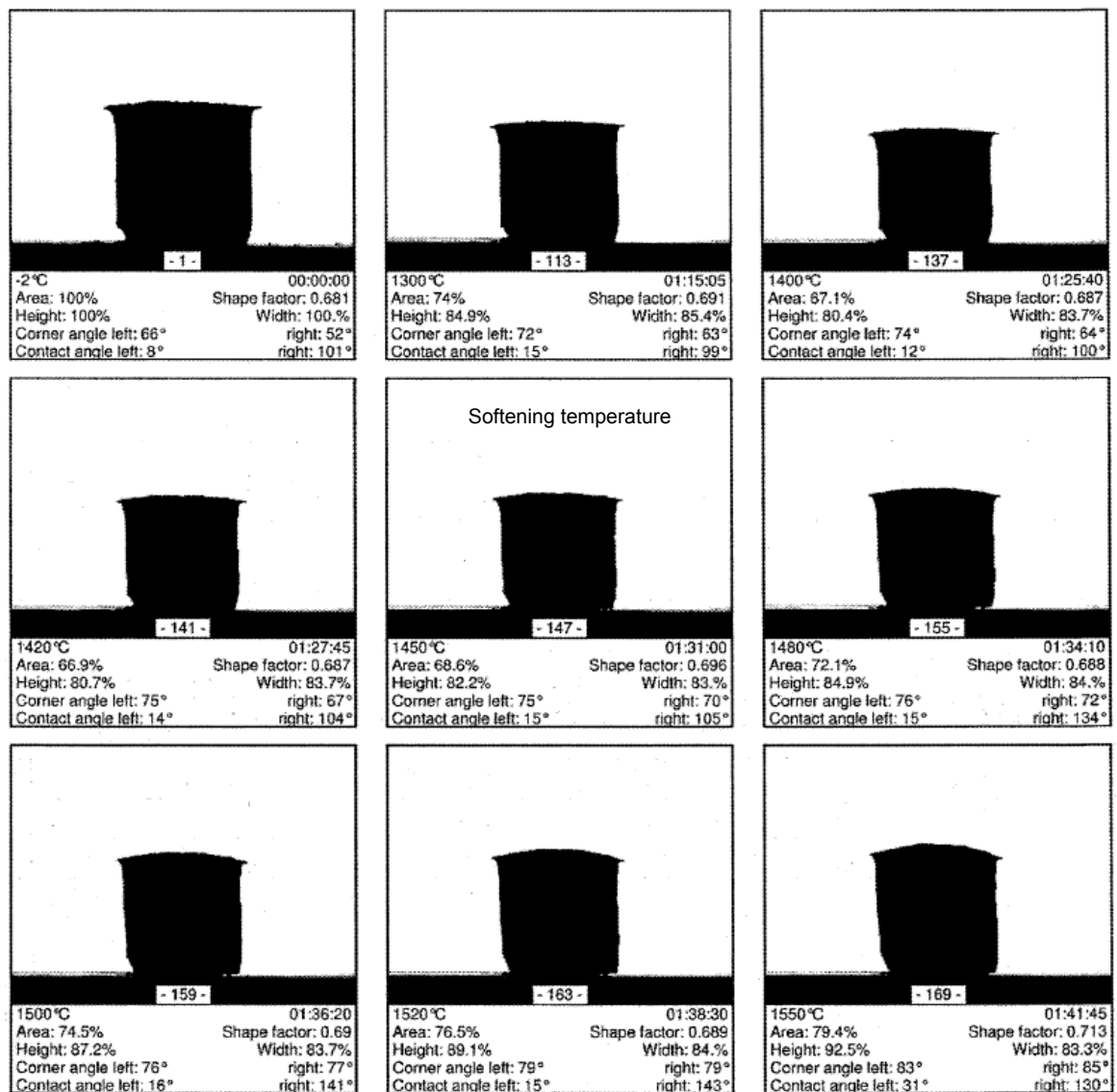
\*1: Air ratio at the time of calculation is 1.4, remaining O<sub>2</sub>=6%

[Appendix]



Appended figure 4.1-1 Fusibility measurement of ash under test (oxidizing atmosphere, DIN method)





Appended figure 4.1-2 Fusibility measurement of ash under test (reducing atmosphere, DIN method)

## 4.2 Smoke dust removal performance

### 4.2.1 Dry electrostatic precipitator (DEP)

#### (1) Performance comparison by system

Figure 4.2-1 shows dust collection performance with DEP. Increase in applied voltage resulted in improvement of dust collection performance in both systems. The dust collection performance of very low temperature EP was higher than that of low temperature EP, and as shown in Figure 4.2-2, when charge voltage of 35kV was applied, DEP outlet smoke dust concentration of low temperature EP was approx. 150mg/m<sup>3</sup>N, whereas the concentration of very low temperature EP was 30mg/m<sup>3</sup>N. Table 4.2-1 shows filters to trap smoke dust at this time. 300L of outlet exhaust gas was passed through these filters of low temperature EP and very low temperature EP and from the result, improvement of dust collection efficiency of DEP was confirmed when the high-performance smoke dust removal system was applied. In addition, at very low temperature EP, DEP outlet smoke dust concentration was 10mg/m<sup>3</sup>N or less at the time of 45kV of charging, whereas 45kV of charging was not available due to rise of current density at low temperature EP. Since this was possibly due to characteristic of coal ash, electrical resistivity of coal ash was measured, and the result was reviewed.

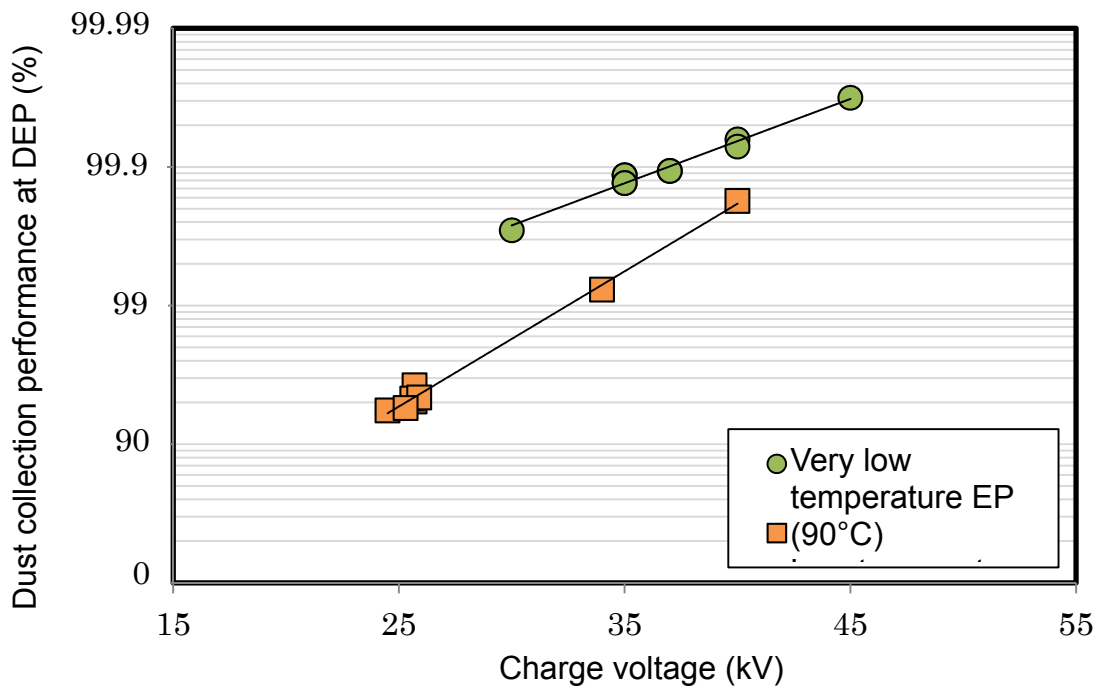


Figure 4.2-1 Dust collection performance at DEP

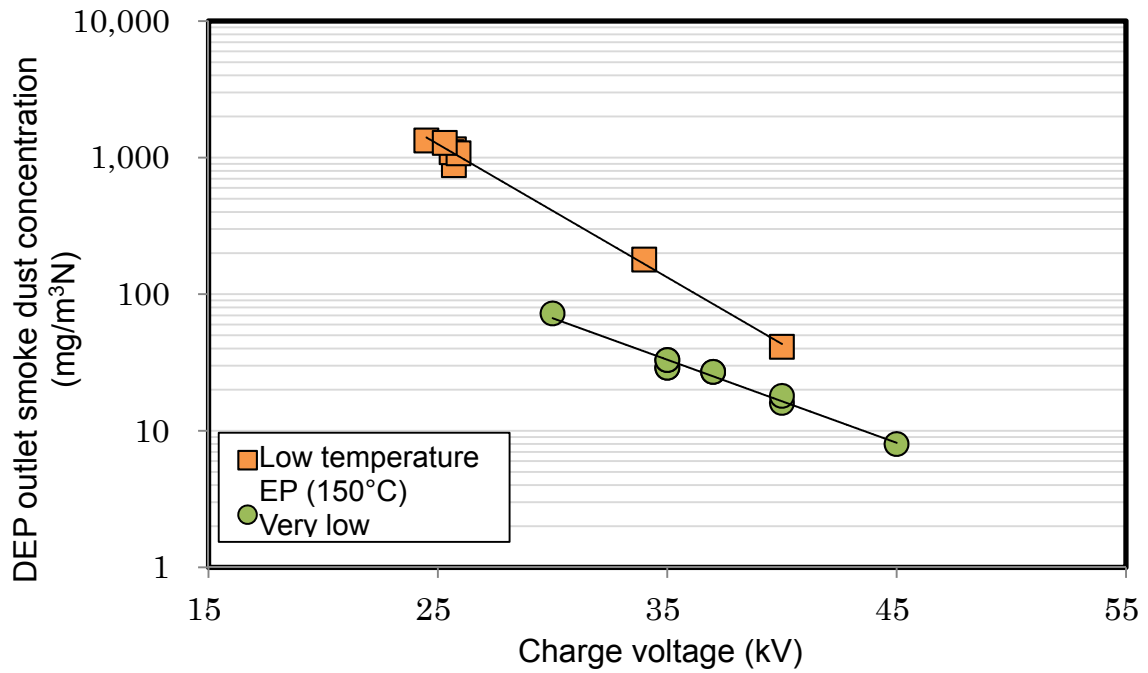


Figure 4.2-2 Smoke dust concentration at DEP outlet

Table 4.2-1 Appearance of filter to trap smoke dust

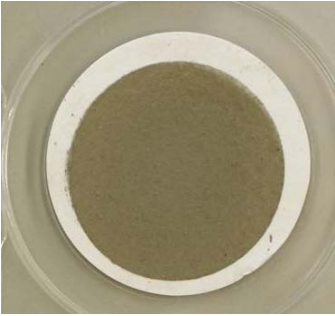
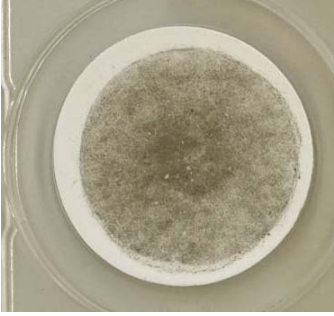
System	Conventional systems	High-performance smoke dust removal system
DEP inlet exhaust gas temperature	150°C	90°C
DEP charge voltage	35kV	35kV
DEP outlet smoke dust concentration	180mg/m³N	29mg/m³N
Suctioned gas amount	300L	300L
Appearance of filter to trap smoke dust		

Figure 4.2-3 shows the results of measuring electrical resistivity of coal ash collected in DEP together with electrical resistivity of bituminous coal ash from eastern part of the U.S. obtained from previous test using the Combustion-AQCS Integrated Facility. Electrical resistivity was measured by adjusting water concentration to 9%, the same condition as that of exhaust gas and changing temperature. Electrical resistivity of both Talcher coal and bituminous coal ash from eastern part of the U.S. tended to increase along with the rise of temperature. However, electrical resistivity of Talcher coal was found to be higher than that of bituminous coal ash from eastern part of the U.S.

Figure 4.2-4 shows relation between electrical resistivity and dust collection characteristics of coal ash. Particles whose electrical resistivity is  $10^4\Omega$  cm or less are easily charged and reach a dust collection electrode. However, since charge stripping also occurs easily in those particles, jumping phenomenon occurs, and therefore collision and rebound are repeated, which results in decreased dust collection efficiency. In contrast, particles whose electrical resistivity is  $10^{11}\Omega$ cm are not easily charged and hence, dust collection efficiency decreases. In particular, for particles with electrical resistivity of  $10^{13}\Omega$  cm or more, charge stripping of particles is difficult to occur in particles accumulated on a dust collection electrode and charges accumulate on a dust collection electrode. Because of this, accumulated charges are discharged from a dust collection electrode (inversive ionization phenomenon), resulting in decreased dust collection efficiency.

Electrical resistivity ( $10^{10}\Omega$  cm) of Talcher coal ash under the very low temperature EP condition was within the scope of electrical resistivity ( $10^4$  to  $10^{11}\Omega$  cm) of coal ash in which DEP operates normally and dust removal efficiency is high, and hence stable charging and normal dust removal appeared to be attained. In contrast, electrical resistivity of Talcher coal ash under the low temperature EP condition was  $10^{13}\Omega$  cm which is high, and dust collection performance possibly decreased because inversive ionization phenomenon caused unstable charging. In addition, since dust collection performance at DEP is also influenced by particle sizes of smoke dust, particle size distribution of smoke dust collected from hoppers of low temperature EP and very low temperature EP was checked. Figure 4.2-5 and Figure 4.2-6 show particle size distribution of ash collected from hoppers of low temperature EP and very low temperature EP,

respectively. Average diameter ( $d_{50}$ ) of smoke dust removed at low temperature EP was  $26.4\mu\text{m}$  in the segment 1 and  $16.2\mu\text{m}$  in the segment 2. On the contrary, average diameter of smoke dust removed at very low temperature EP was  $20.5\mu\text{m}$  in the segment 1 and  $10.2\mu\text{m}$  in the segment 2, showing smaller values than those of low temperature EP. In other words, even though particle size of smoke dust is small in very low temperature EP compared with that in case of low temperature EP, dust collection performance of very low temperature EP was found to be higher than that of low temperature EP.

Based on the above, lowering exhaust gas temperature at DEP by applying the high-performance smoke dust removal system and lowering electrical resistivity of coal ash is assumed to be an effective way to improve dust collection performance.

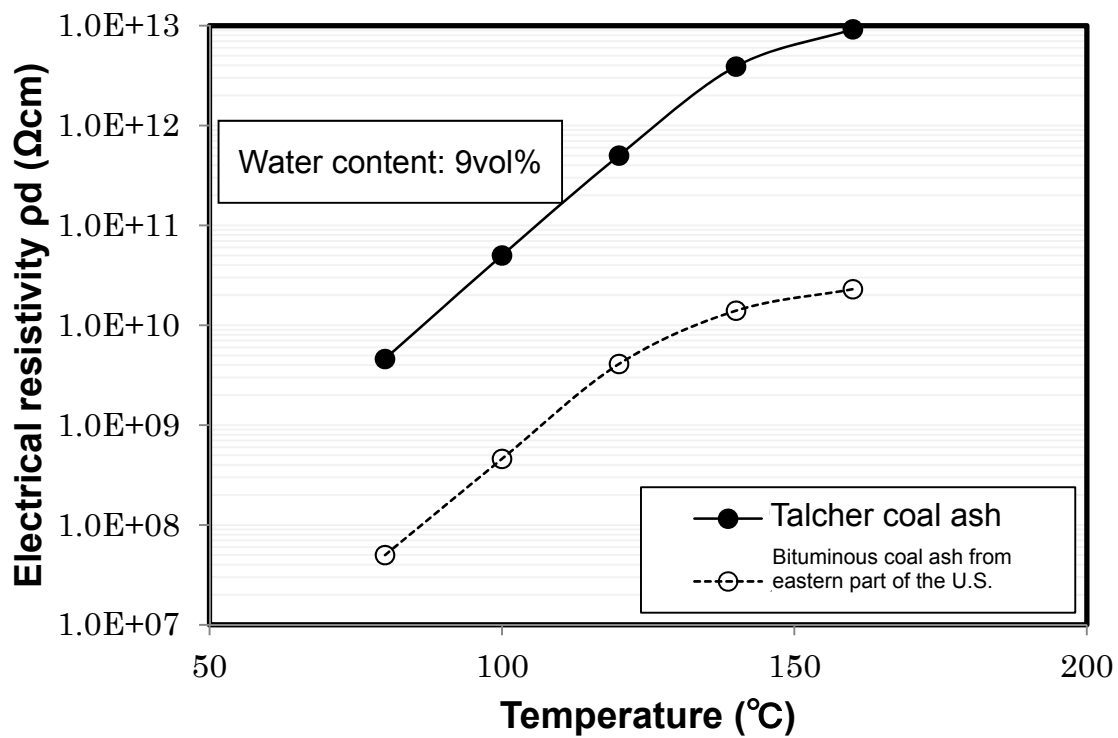


Figure 4.2-3 Electrical resistivity of Indian coal ash

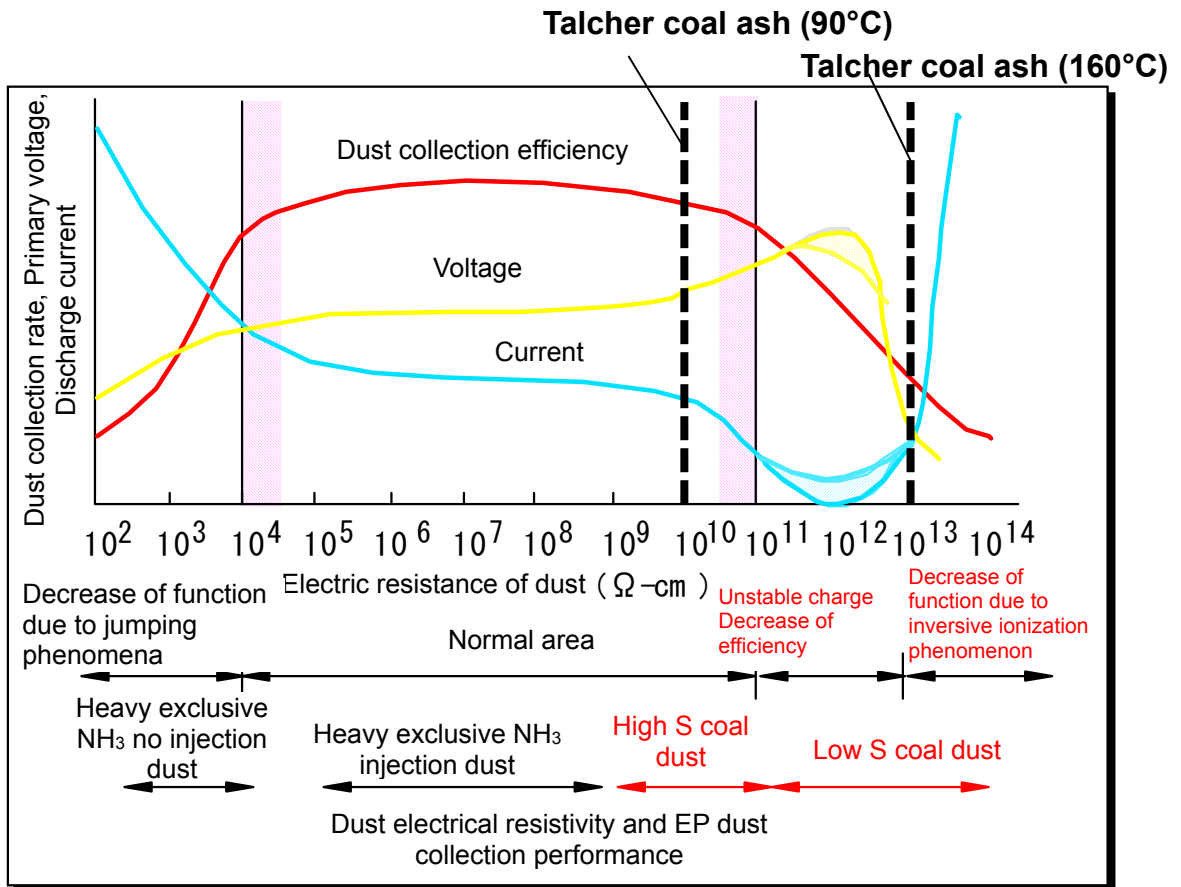


Figure 4.2-4 Relation between electrical resistivity and dust collection characteristics of coal ash

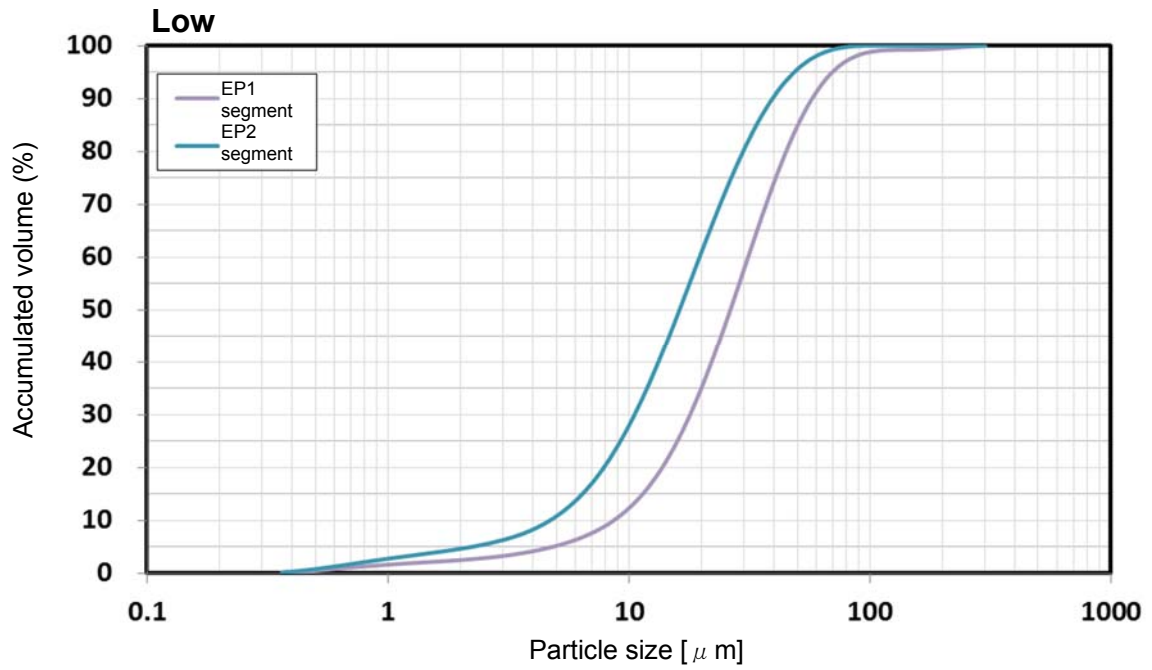


Figure 4.2-5 Particle size distribution of ash collected at low temperature EP

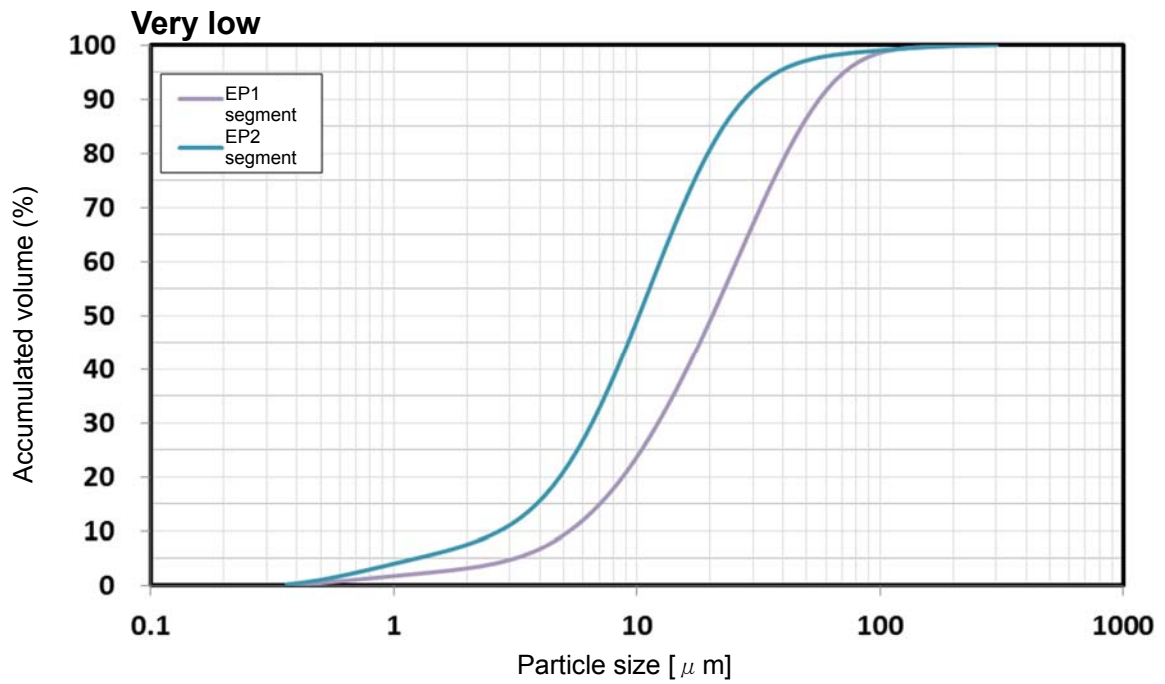


Figure 4.2-6 Particle size distribution of ash collected at very low temperature EP



(2) Consideration of economic efficiency

Based on the results of this test showing that very low temperature EP is superior to low temperature EP in dust removal performance, the degree of decrease in dust collection area of DEP in the high-performance smoke dust removal system was estimated. Figure 4.2-7 shows dust collection performance of low temperature EP and very low temperature EP expressing charge condition  $fv^2$  on horizontal axis. This is called performance line<sup>1)</sup> of charge conditions and smoke dust removal performance. Charge condition  $fv^2$  was obtained by Formula 4.2-1 based on Specific Collecting Area (SCA) and applied voltage.

$$fv^2 = (\text{Specific Collecting Area [s/m]}) \times (\text{applied voltage [kV]})^2 \cdot \cdot \cdot 4.2 - 1$$

where,

$$\text{Specific Collecting Area (SCA)[s/m]} = \text{dust collection area[m}^2\text{]}/\text{exhaust gas amount [m}^3\text{/s]}$$

From Figure 4.2-7,  $fv^2(\times 10^{-4})$  value in which DEP outlet smoke dust concentration is  $30\text{mg/m}^3\text{N}$  is 12.2 at low temperature EP and 9.2 at very low temperature EP, and dust collection area (DEP volume) of very low temperature EP can be reduced by approx. 25% compared with low temperature EP.

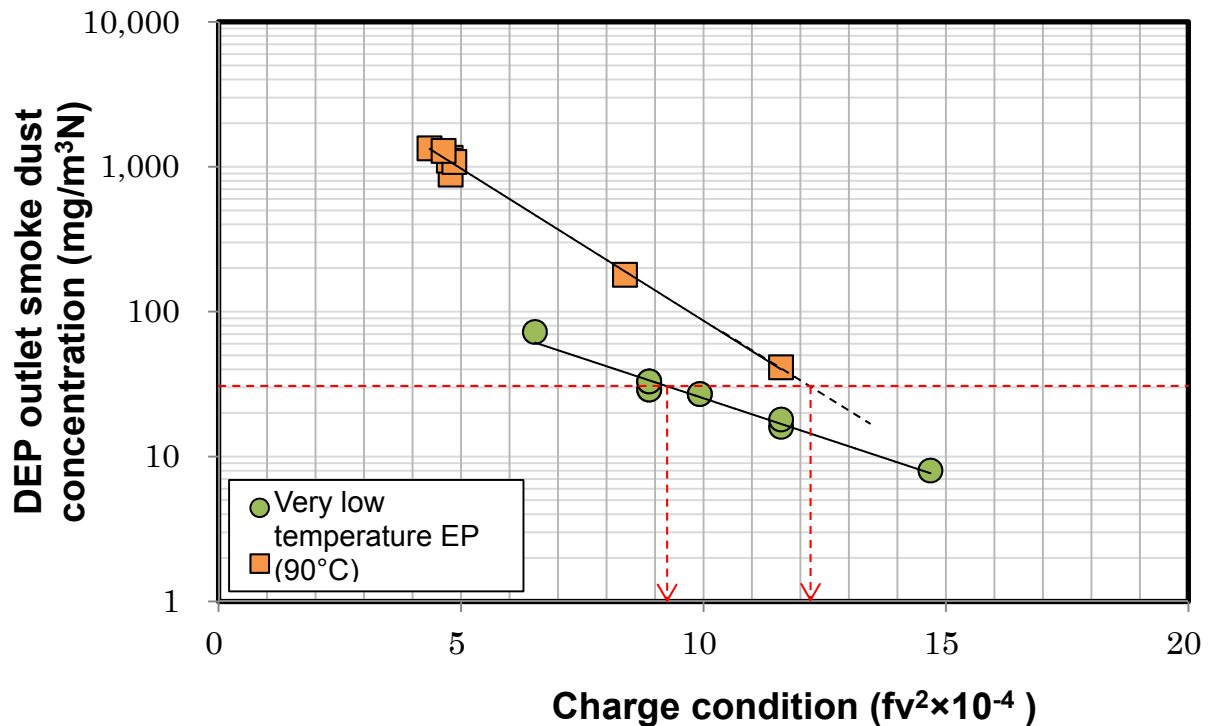


Figure 4.2-7 Charge conditions and dust collection performance (performance line)

#### 4.2.2 Dry flue gas desulfurization (FGD)

Dust removal performance of FGD in both systems is described below. Hereafter, DEP outlet smoke dust concentration is described as FGD inlet smoke dust concentration. In addition, dust collection performance at DEP differs in conventional systems and the high-performance smoke dust removal system, and the range of FGD inlet smoke dust concentration is large. Consequently, dust collection performance with FGD in conventional systems was evaluated separately from that in the high-performance smoke dust removal system.

Figure 4.2-8 shows relation between inlet smoke dust concentration and outlet smoke dust concentration at FGD when L/G was changed in conventional systems. Desulfurization inlet smoke dust concentration was 200~1,300 $mg/m^3N$ , which is high, and FGD outlet smoke dust concentration of  $L/G=32L/m^3N$  was almost stable and not influenced by inlet concentration. However, FGD outlet smoke dust concentration was influenced by L/G, and when L/G became smaller, FGD outlet smoke dust concentration increased.

Figure 4.2-9 shows relation between inlet and outlet smoke dust concentration of FGD when L/G was changed in the high smoke dust removal system. FGD inlet smoke dust concentration was within the range of 8~78mg/m<sup>3</sup>N, and when inlet concentration increased, outlet smoke dust concentration also increased. Influence of L/G on FGD outlet smoke dust concentration was not found. In general, it is thought that with higher LG, the collision efficiency of spray droplets and smoke dust particles increases and dust removal performance also increases. However, since FGD outlet smoke dust concentration at this time was 2.5~5.0mg/m<sup>3</sup>N, which was very low, the improved collision efficiency of spray droplets and smoke dust along with increase in L/G was not obtained.

In this test, for both low temperature EP and very low temperature EP, smoke dust concentration at FGD outlet was controlled to low concentration of 15mg/m<sup>3</sup>N or below, and when smoke dust concentration of inlet of the device was decreased especially in very low temperature EP, outlet concentration showed further low value of 5mg/m<sup>3</sup>N or less. However, as described above, since spray nozzle was small and the diameter of spray droplet was small, dust removal performance was possibly overestimated in conventional systems with high inlet smoke dust concentration. In addition, based on Figure 4.2-10 that shows the amount of mist spreading from FGD, the amount of mist spreading from FGD increases along with the increase of L/G and is found to have same tendency and value of approx. 50~70mg/m<sup>3</sup>N as that of actual devices.

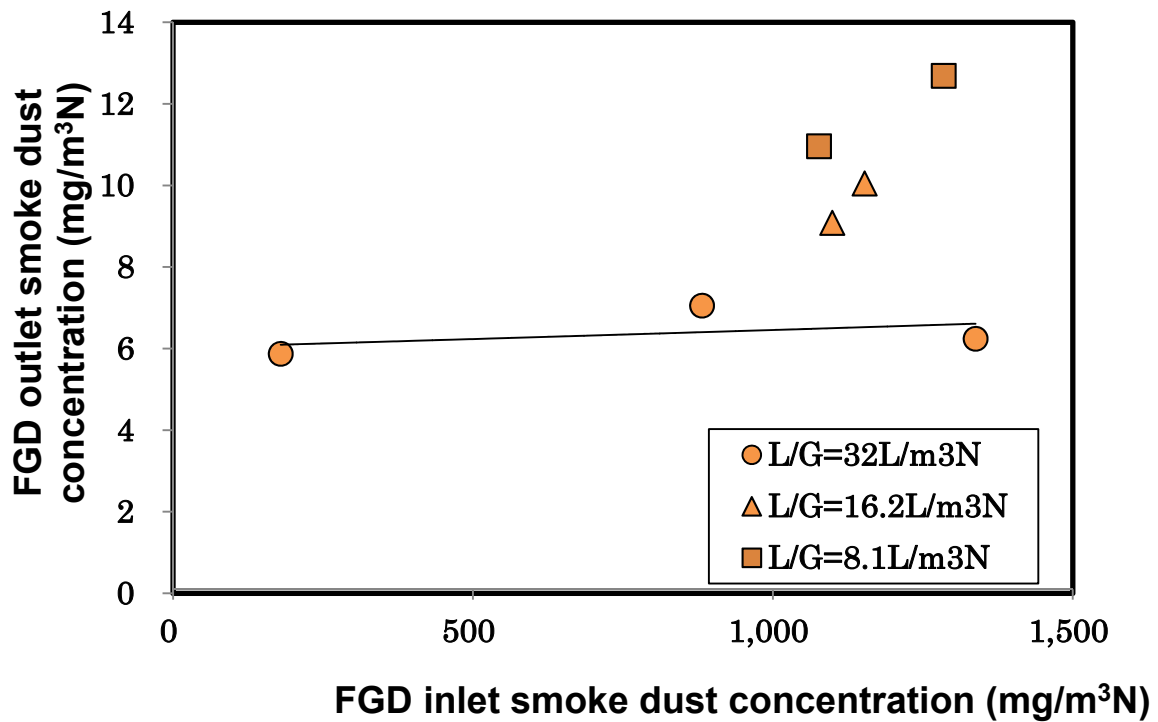


Figure 4.2-8 Relation between FGD inlet smoke dust concentration and dust removal rate at FGD (conventional systems)

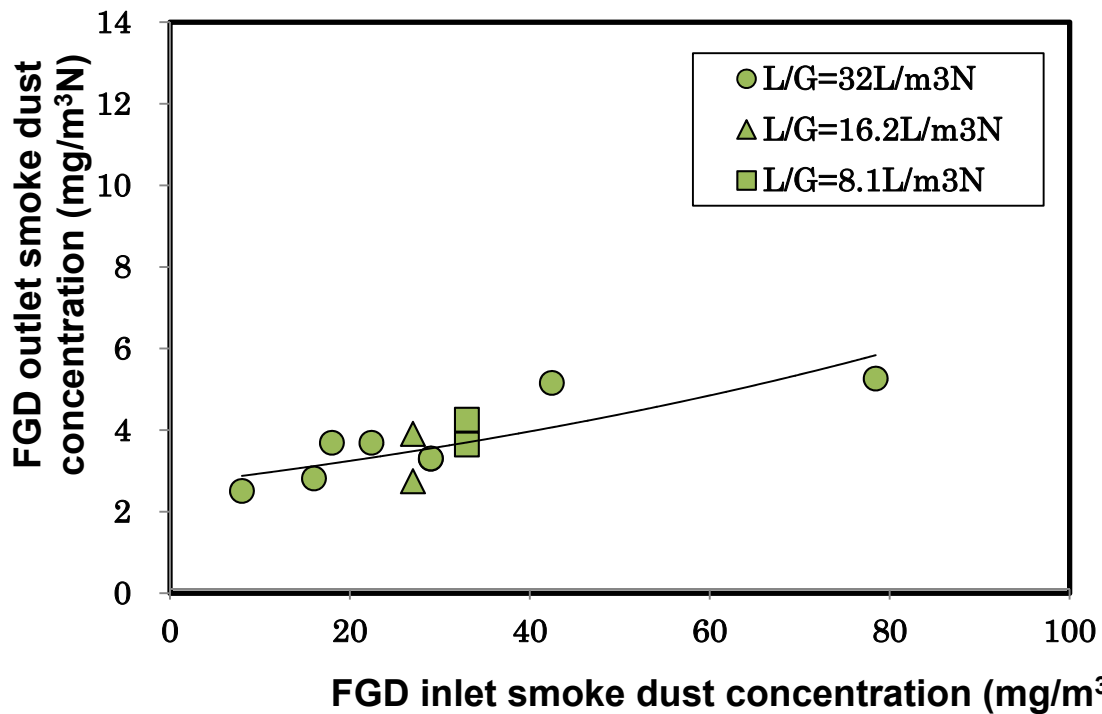


Figure 4.2-9 Relation between FGD inlet smoke dust concentration and dust removal rate at FGD (high-performance smoke dust removal system)

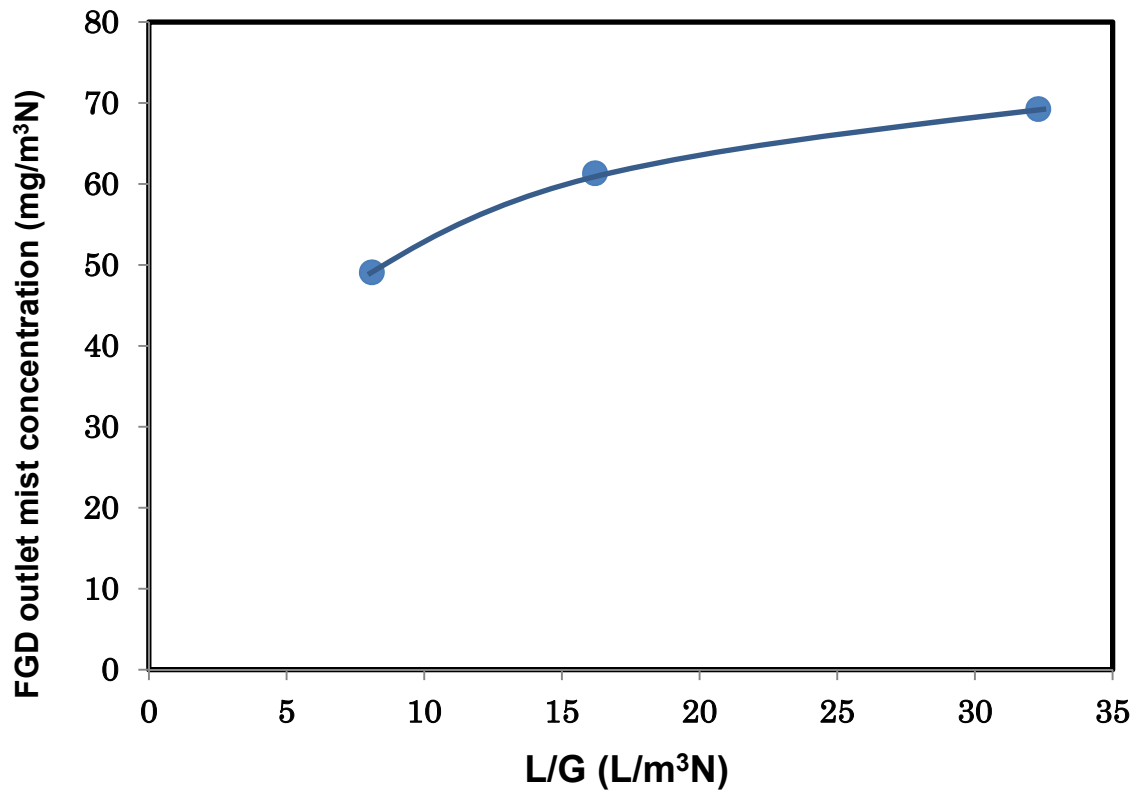


Figure 4.2-10 Amount of mist spreading from FGD

The study result of particle sizes of smoke dust flowing in FGD is described here. Dust removal in FGD was possibly due to inertial collision of spray droplets and smoke dust particles, and efficiency of collision with spray droplets varies depending on smoke dust particle sizes. Consequently, measurement of smoke dust drop size at FGD inlet is important. In this study, sampling of DEP outlet exhaust gas was conducted by using circular filter paper, and SEM images of coal ash trapped on the filter surface were analyzed to obtain particle size distribution. Figure 4.2-11 and Figure 4.2-12 show SEM observation images of DEP outlet smoke dust in conventional systems and the high-performance smoke dust removal system, respectively. Individual particles were measured by using these SEM images of coal ash as shown in Figure 4.2-13 to obtain average drop size. Figure 4.2-14 shows particle size distribution of smoke dust in DEP outlet exhaust gas in conventional systems and the high-performance smoke dust removal system obtained from SEM image analysis. From Figure 4.2-14, the average drop size ( $d_{50}$ ) of coal ash not removed at DEP and flowing in FGD was  $4.6\mu\text{m}$  at low temperature EP and  $6.5\mu\text{m}$  at very low temperature EP. Dust removal performance of very low temperature EP is high, and removal of smaller particles than the case with low temperature EP leads to stronger influence of coarse particles, suggesting that the average drop size of coal ash in DEP outlet exhaust gas tends to be large.

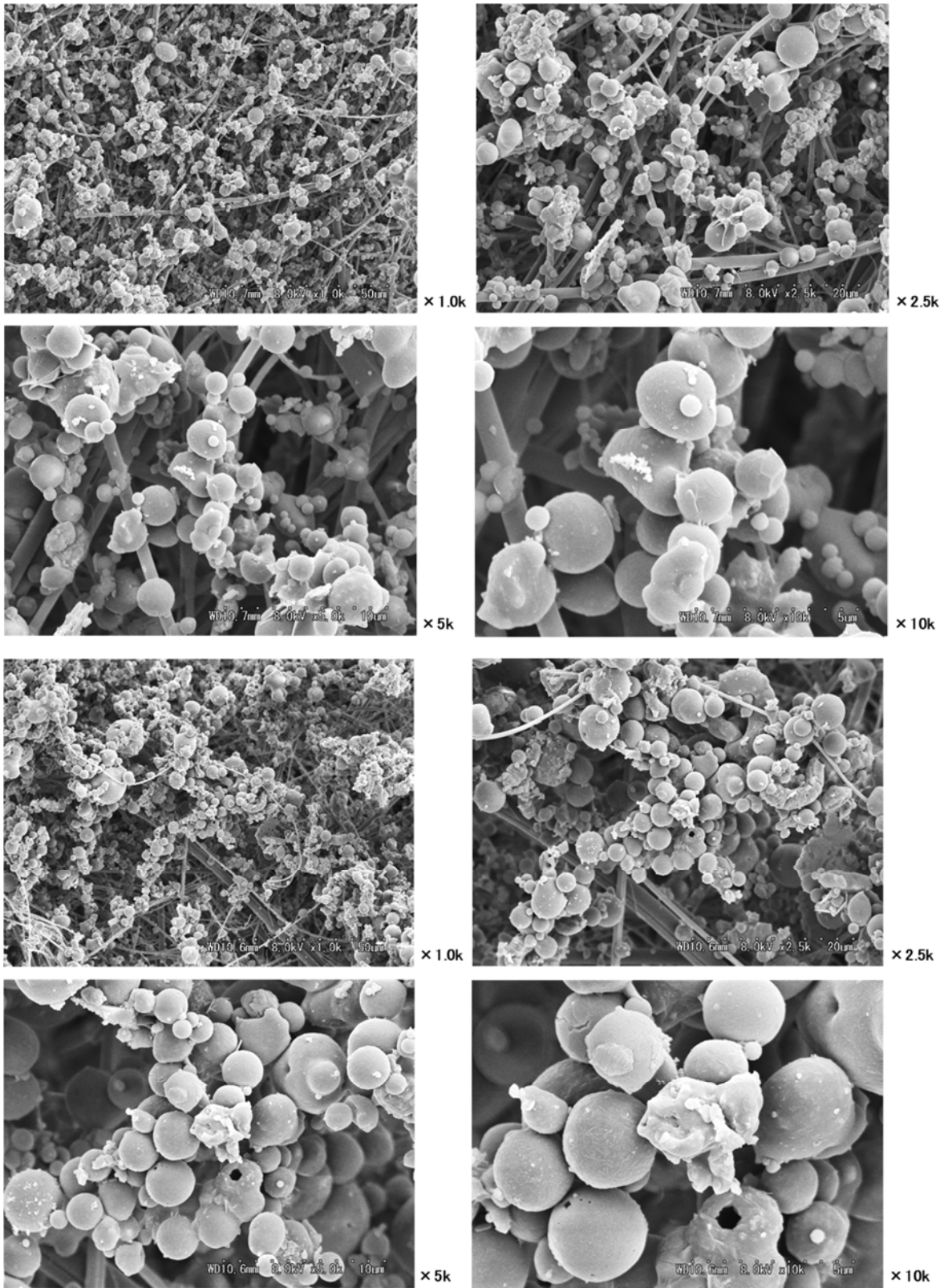


Figure 4.2-11 Observation result of SEM images of low temperature EP outlet smoke dust

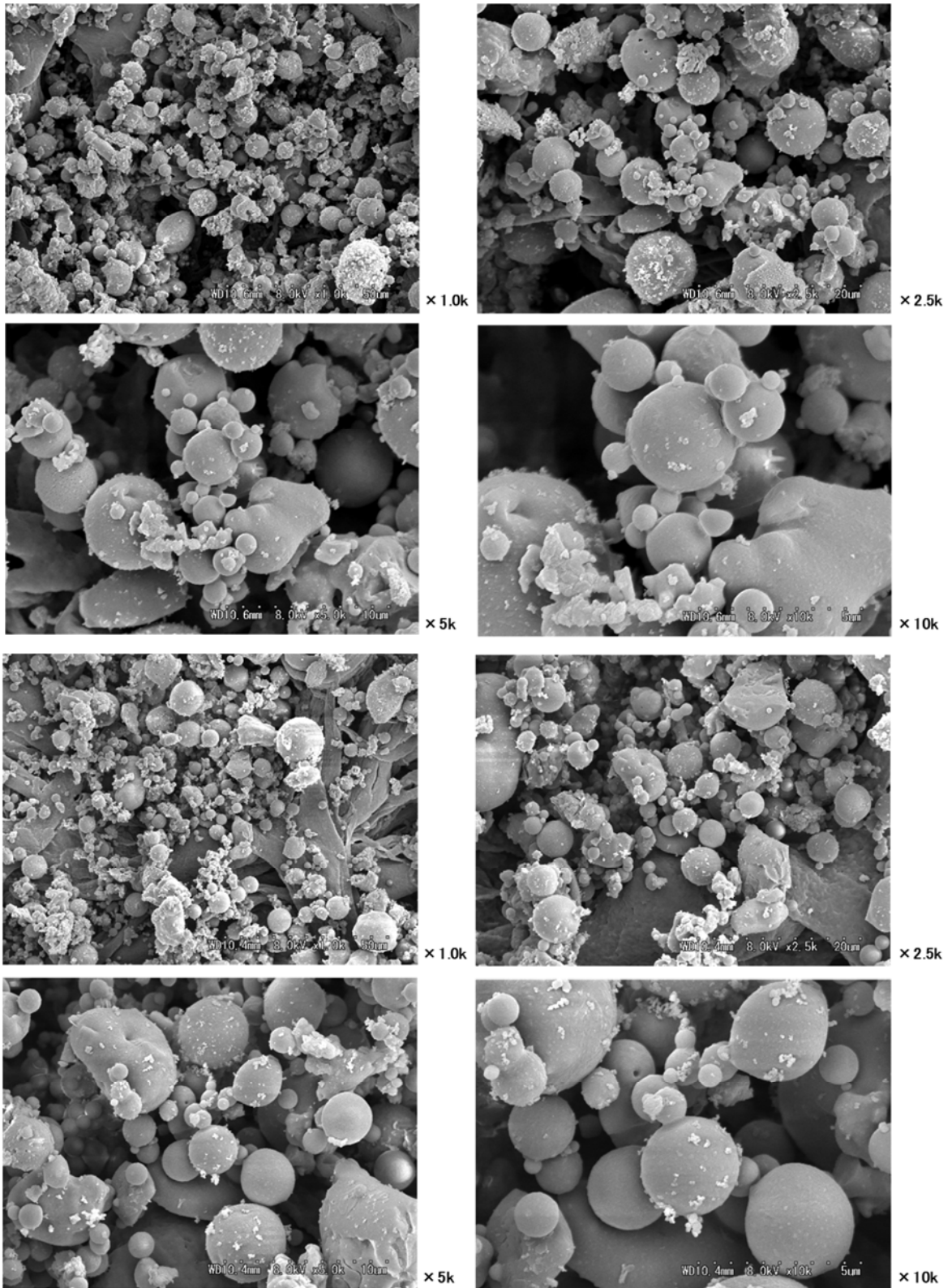
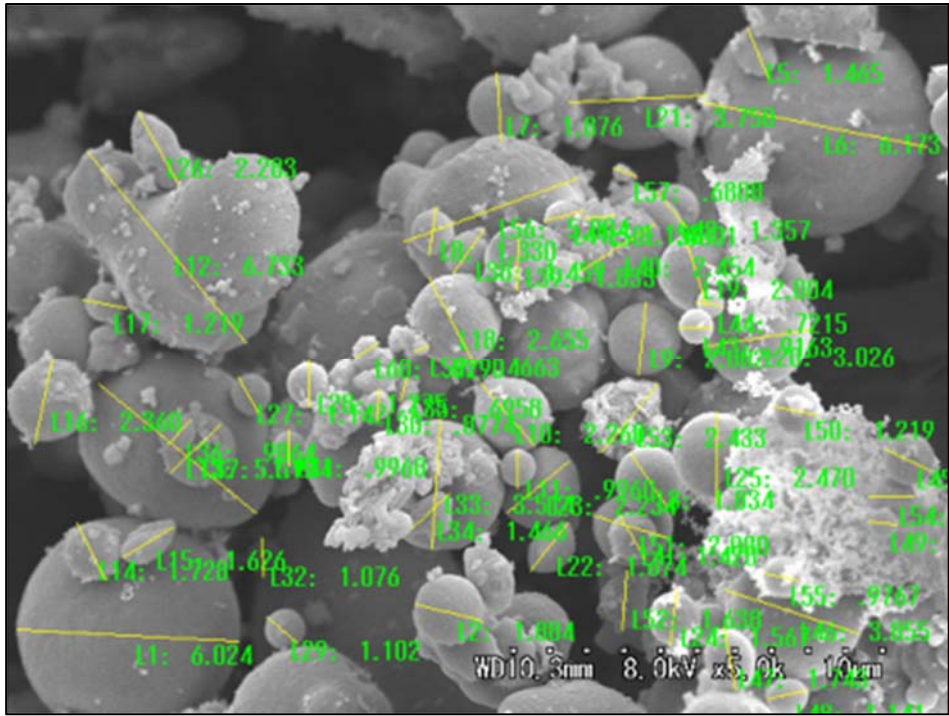
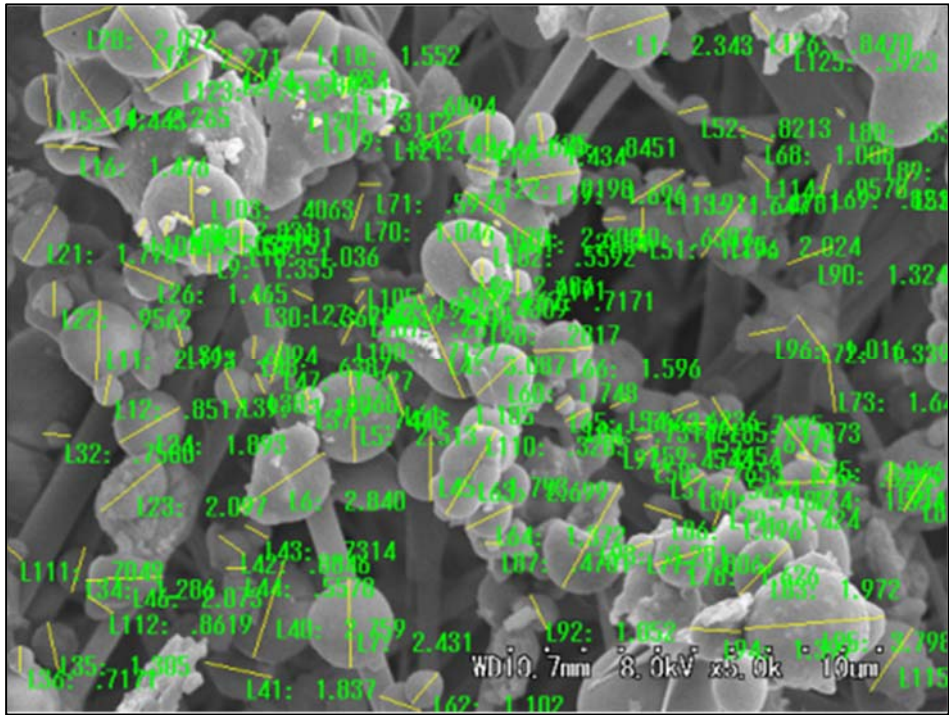


Figure 4.2-12 Observation result of SEM images of very low temperature EP outlet smoke dust





Field 1



Field 2

Figure 4.2-13 Example of SEM image measurement

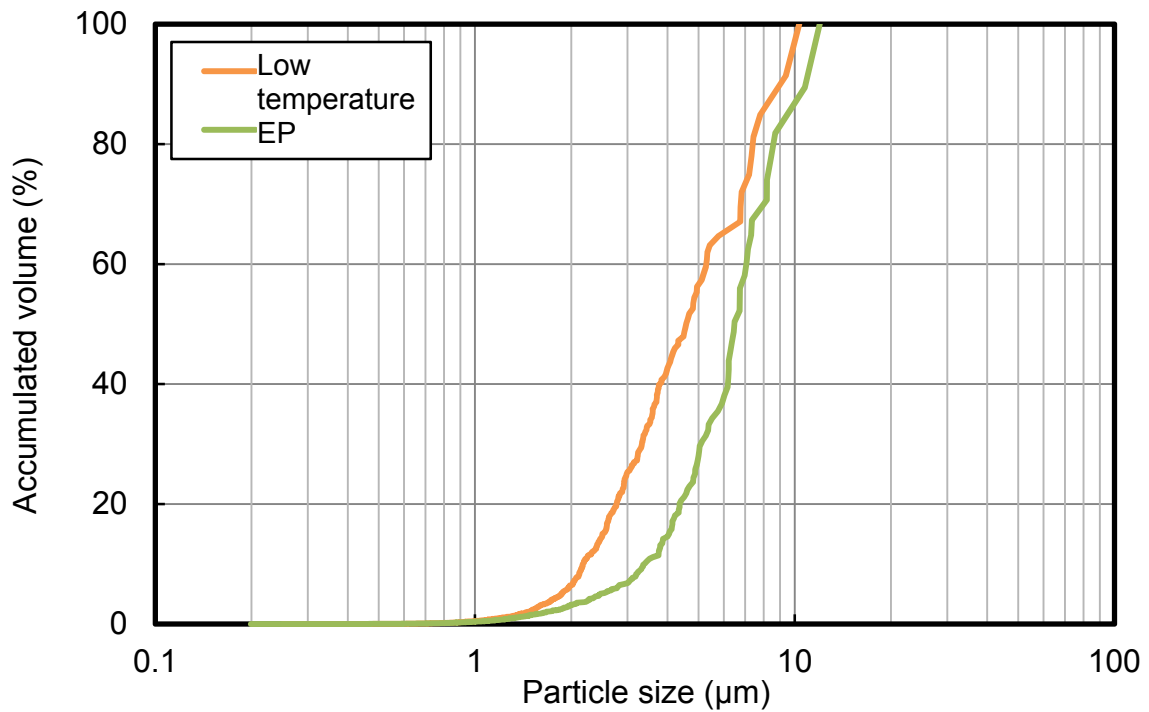


Figure 4.2-14 Particle size distribution of DEP outlet smoke dust

[Chapter 4 Reference]

- 1) The Institute of Electrostatics Japan, Ed., Handbook of Electrostatics, Ohm-Sha, p506 (1998)

### 4.3 Desulfurization performance

#### 4.3.1 Test at the Combustion Integrated Facility

Table 4.3-1 shows gas conditions and absorbing solution characteristics at the time of desulfurization performance test. DEP outlet smoke dust concentration was different in the two systems, and comparison was made under the same condition where inlet SO<sub>2</sub> concentration was 500ppm and CaCO<sub>3</sub> concentration in absorbing solution was 30mM.

Figure 4.3-1 shows relation between L/G and desulfurization performance in conventional systems and the high-performance smoke dust removal system. Desulfurization performance of conventional systems and the high-performance smoke dust removal system was on the same line, and the level was equal. However, as described in Chapter 3, influence of limestone dissolution inhibition should be evaluated under the situation where amounts of substances in the system strike balance. Accordingly, discussion was made based on the result of the basic test described in Clause 4.3.2 and 4.3.3. In addition, in Figure 4.3-1, desulfurization rate hit the peak when the condition of L/G was 30 L/m<sup>3</sup>N or more. This is possibly because under the operation condition of four spray steps which was equivalent to 40L/m<sup>3</sup>N of L/G, outlet SO<sub>2</sub> concentration was 1 to 2ppm and this value was equivalent to 1ppm of detection limit of a SO<sub>2</sub> analyzer.

Table 4.3-1 Desulfurization performance test - Characteristics of gas and absorbing solution

Item	Unit	Conventional systems	High-performance smoke dust removal system
Desulfurization device inlet gas amount (actual measurement on test day)	m <sup>3</sup> N/hr (dry)	1,200	1,300
DEP outlet smoke dust concentration	mg/m <sup>3</sup> N	90	30
Inlet SO <sub>2</sub> concentration average	ppm	500	
Alkali concentration	mM	30	
Gypsum concentration	wt%	15.0	

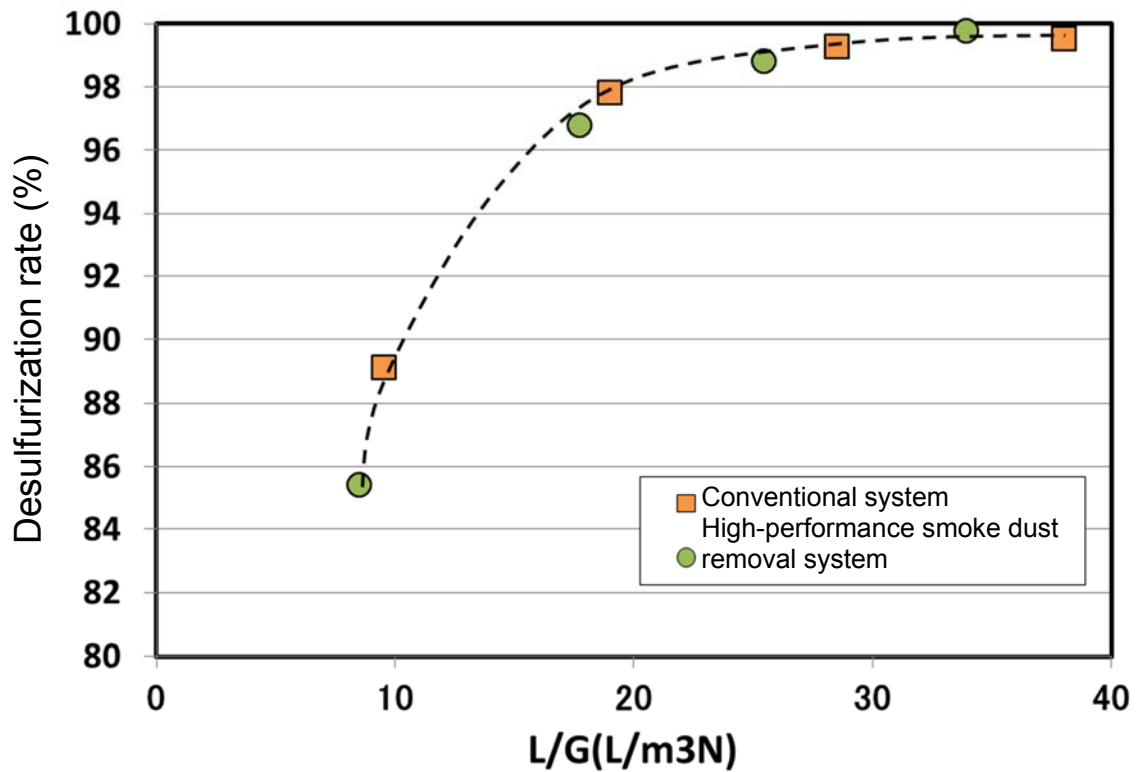


Figure 4.3-1 Relation between L/G and desulfurization performance

#### 4.3.2 Basic test

##### (1) Elution test of coal ash

As a preliminary test to see whether or not smoke dust inhibits dissolution of limestone, Al elution test in which coal ash was added in  $H_2SO_4$  solution was conducted by using a small test device. Figure 4.3-2 shows relation of elution time, pH of eluate and Al elution rate of Talcher coal ash and coal ash from the U.S., respectively. Al elution rate when Talcher coal ash was fed was around 1% at the elution time of 120 minutes, which was low. On the contrary, Al elution rate when coal ash from the U.S. was fed was 70% or more at the elution time of 120 minutes. From these values, characteristics of Al elution from ash were found to be greatly different depending on kinds of coal.

In other words, since Al elution from ash is low in Talcher coal, even in the Combustion Integrated Test Facility with high smoke dust concentration, desulfurization performance was highly unlikely to be influenced. However, Al elution from ash occurred, although it was very small quantity, and  $AlF_x$  compound may be produced in FGD. Consequently, after the elution test, inactivation test was conducted with the small FGD.

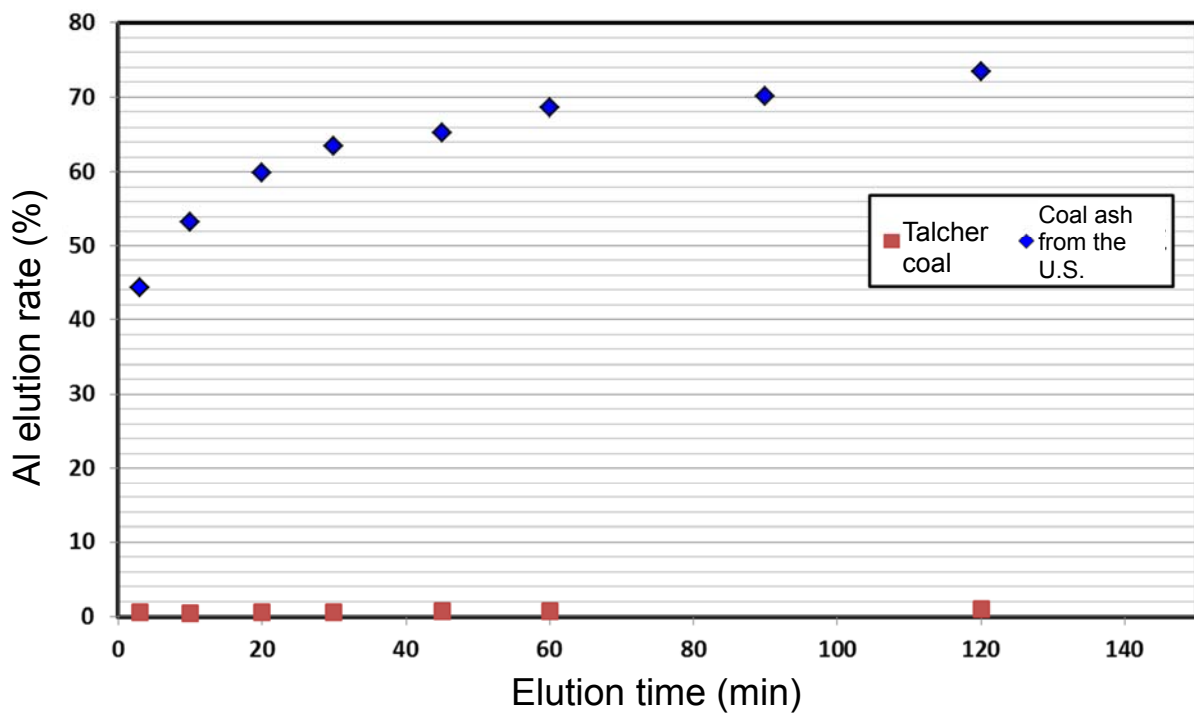


Figure 4.3-2 Relation between elution time and Al elution rate

## (2) Inactivation test of limestone

After the elution test described above, the possibility of dissolution inhibition of limestone was studied with a small desulfurization test device by continuously feeding ash and NaF. First, Figure 4.3-3 shows Al concentration, F concentration and CaCO<sub>3</sub> concentration in the system, pH of solution falling from the absorption tower and desulfurization rate during continuous operation test using Talcher coal ash. L/G was 20 L/m<sup>3</sup>N, pH in the system was 5.5 and the system was operated under certain conditions. In order to shorten test time, addition speed of ash and NaF was increased temporarily in some period for which the graph shows rise (NaF: 600 to 930min, ash: 930 to 1260min). Since ash and NaF were continuously fed, the level of Al concentration and F concentration in the system continued to increase. However, absorbing solution and gypsum were extracted regularly, and hence the final Al concentration of approx. 16 mM and F concentration of approx. 15mM are assumed to be balanced in the system as described in Chapter 3.

When the feeding of ash and F in the system was started, the level of CaCO<sub>3</sub> concentration temporarily increased to 20mM at a maximum. At this time, desulfurization rate also tended to increase and CaCO<sub>3</sub> concentration in the system was seemingly unstable. Then CaCO<sub>3</sub> concentration became stable at around 10 to 15mM, and even after Al and F concentration in the system reached the calculated balancing concentration of 16mM and 15mM, respectively, increase of CaCO<sub>3</sub> concentration was not found. pH of falling solution was stable at around 3.5, suggesting that inhibition of limestone dissolution did not occur.

Consequently, for Talcher coal, it is assumed that limestone dissolution is not inhibited and desulfurization performance is not influenced even under the condition where smoke dust of high concentration flows in FGD. This assumption is consistent with the result showing the same level of desulfurization performance in the same CaCO<sub>3</sub> concentration both in conventional systems and the high-performance smoke dust removal system as described in 4.3.1.

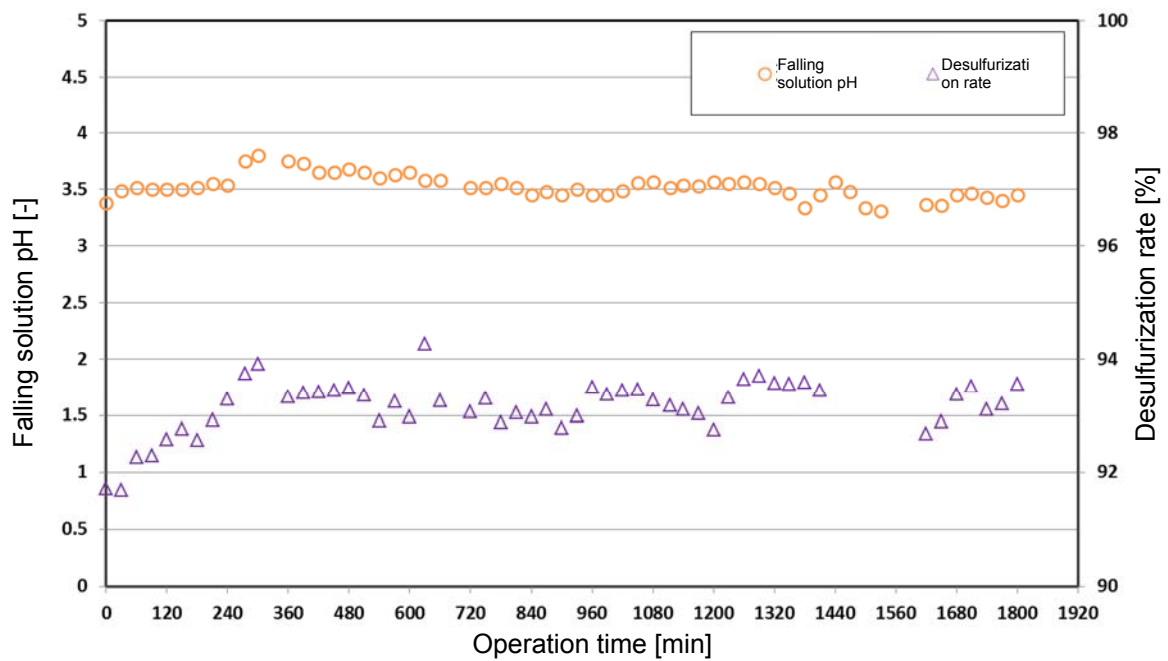
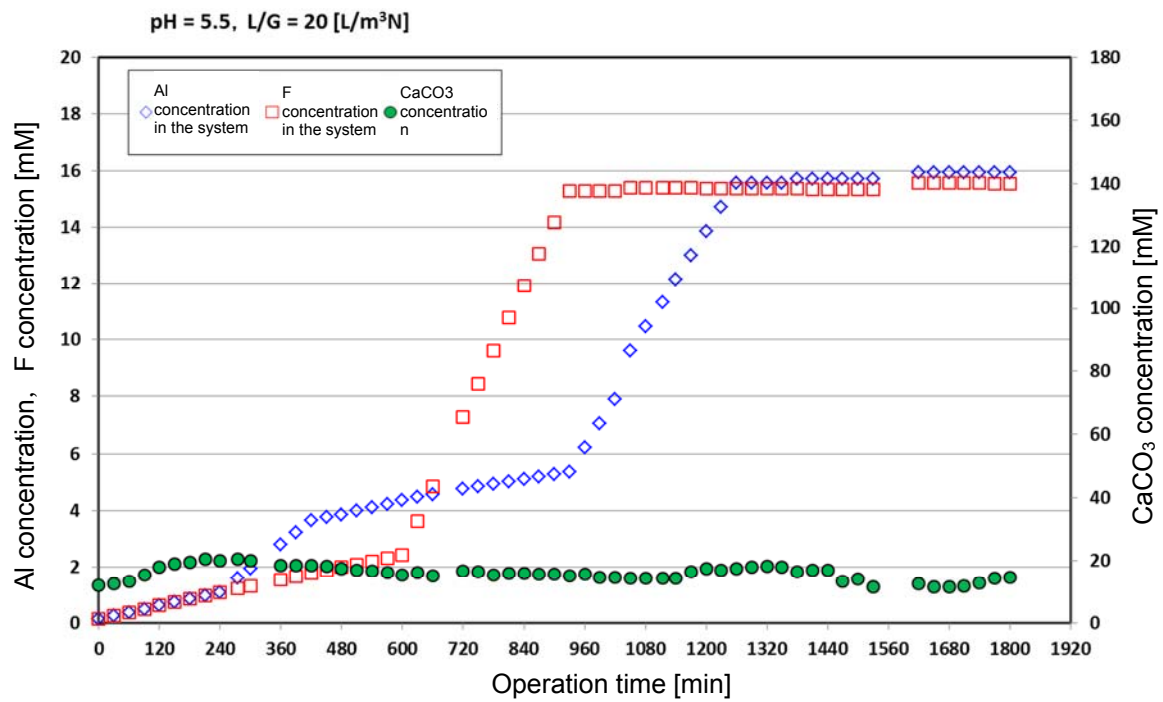


Figure 4.3-3 Change of Al, F, CaCO<sub>3</sub> concentration in the system, pH of falling solution, desulfurization rate when coal ash (Talcher coal) was fed

Then, Figure 4.3-4 shows changes of Al concentration, F concentration and CaCO<sub>3</sub>

concentration in the system, pH of falling solution, and desulfurization rate during continuous operation test using coal ash from U.S. For coal ash from U.S., immediately after ash and F were added in the system,  $\text{CaCO}_3$  concentration continued to rise, suggesting that limestone dissolution was inhibited. Since Al concentration in ash of coal from the U.S. is low, Al concentration that strikes balance in the system is 6mM and the value is lower than that of Talcher coal.  $\text{CaCO}_3$  concentration continued to rise until it reached that concentration and the value was 100mM or more. Based on the result that  $\text{CaCO}_3$  concentration was around 10 to 20mM when Talcher coal was fed, more than ten times of  $\text{CaCO}_3$  are assumed to be fed in the system to maintain pH when coal from the U.S. is fed.

In addition, pH of falling solution rose to approx. 4.5 to 5 after the addition of ash and F. Based on the result that pH of falling solution was stable at around 3.5 when Talcher coal was fed, pH buffer action of  $\text{AlF}_x$  associated with inhibition of limestone dissolution seems to work when coal ash from the U.S. was fed. Along with this, desulfurization performance improved.

Furthermore, during operation time of 250 min to 460 min, feeding of ash and F was stopped on a temporary basis to see if limestone dissolution was hindered. In particular, during operation time of 250 min to 400 min, feeding of  $\text{CaCO}_3$  was also stopped. At this time,  $\text{CaCO}_3$  concentration decreased due to consumption of  $\text{CaCO}_3$  in the system. After that, during the period until 460 min only  $\text{CaCO}_3$  was fed again, and  $\text{CaCO}_3$  concentration was stable at approx. 70mM and did not fall below this value when pH was controlled to 5.5. This result suggests that  $\text{AlF}_x$  compound remains in the system when it is once produced unless pH is increased as shown by conventional knowledge related to inhibition of dissolution

As the summary of results described above, in Talcher coal used in this test, Al elution does not easily occur and hence, operation under high smoke dust conditions seemingly had no problem. However, as with the case of coal from the U.S., use of coal with high Al elution rate may inhibit limestone dissolution. Based on this, it can be said that under high smoke dust concentration condition, application of the high-performance smoke dust removal system and control of Al concentration to low concentration are preferable.



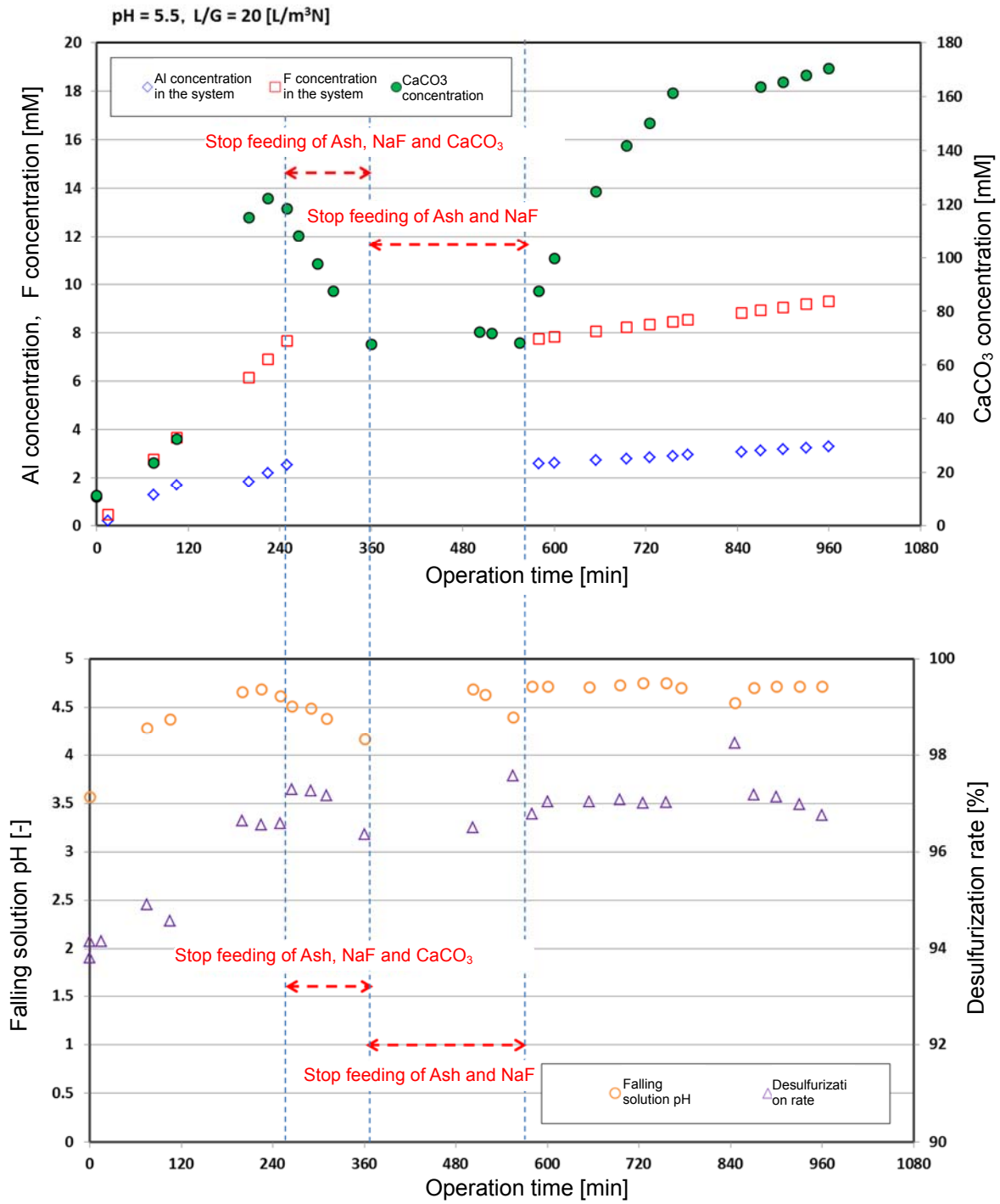


Figure 4.3-4 Change of Al, F, CaCO<sub>3</sub> concentration in the system, pH of falling solution, desulfurization rate when coal ash (coal from the U.S.) was fed

#### 4.4 Overall heat transfer coefficient in GGH

Figure 4.4-1 shows change of overall heat transfer coefficient  $\alpha$  at GGH heat recovery device in conventional systems. The change of overall heat transfer coefficient was from 10 to 13  $W/(m^2 \cdot K)$ . Soot blower was operated at 10:00, 11:30, 14:00 and 16:20 as expressed with red line in the figure. After the operation of soot blower, ash accumulated on fin tubes as time passed, heat transfer area on the surface of heat exchanger decreased, and overall heat transfer coefficient decreased. Average decrease rate of heat transfer coefficient for a certain period of time was 0.6 to 0.9  $W/(m^2 \cdot K)/h$ . After that, by removal of accumulated ash at the timing of soot blower operation, heat transfer coefficient recovered to the initial 12 to 13  $W/(m^2 \cdot K)$ . However, in conventional systems, GGH heat recovery device is installed after DEP, smoke dust concentration flowing in GGH heat recovery device is low, and the amount of ash accumulated on fin tubes is small compared to the case where the high-performance smoke dust removal system is operated as described later. Figure 4.4-1 shows images of fine tubes taken before and after soot blow. Significant difference in accumulated amount of ash was not found before and after soot blow, and these images indicate that the degree of heat transfer coefficient decrease is small.

Then, Figure 4.4-2 shows the change of overall heat transfer coefficient  $\alpha$  at GGH heat recovery device in the high-performance smoke dust removal system. The change of overall heat transfer coefficient was from 8 to 13  $W/(m^2 \cdot K)$ , showing almost the same level as conventional systems although the lower level was found in some time zones. Soot blower was operated at 10:05, 12:40, 15:25 and 17:20 as expressed with red line in the figure. As is the case with conventional systems shown in Figure 4.4-1, after soot blower was operated, heat transfer coefficient decreased and recovered to the initial 12  $W/(m^2 \cdot K)$  immediately after soot blow. As described above, in the high-performance smoke dust removal system, since GGH heat recovery device was set before DEP, smoke dust concentration flowing in the heat recovery device is higher and the ash amount accumulated on fin tubes is larger than the case of conventional systems. Accordingly, average decrease rate of heat transfer coefficient for a certain period of time was 1.0 to 1.4  $W/(m^2 \cdot K)/h$  showing higher values than those of conventional systems. However, the high-performance smoke dust removal system shows the same recovery of heat transfer coefficient to 12  $W/(m^2 \cdot K)$  or more as conventional systems immediately after soot blower

operation. Based on this, if accumulated ash is removed on a regular basis in actual devices, even under the condition of high smoke dust concentration, GGH heat recovery devices can be operated without problem. Figure 4.4-2 shows images that were taken before and after soot blower operation and soot blow was found to remove almost all ash accumulated on and covered the whole fin tube.

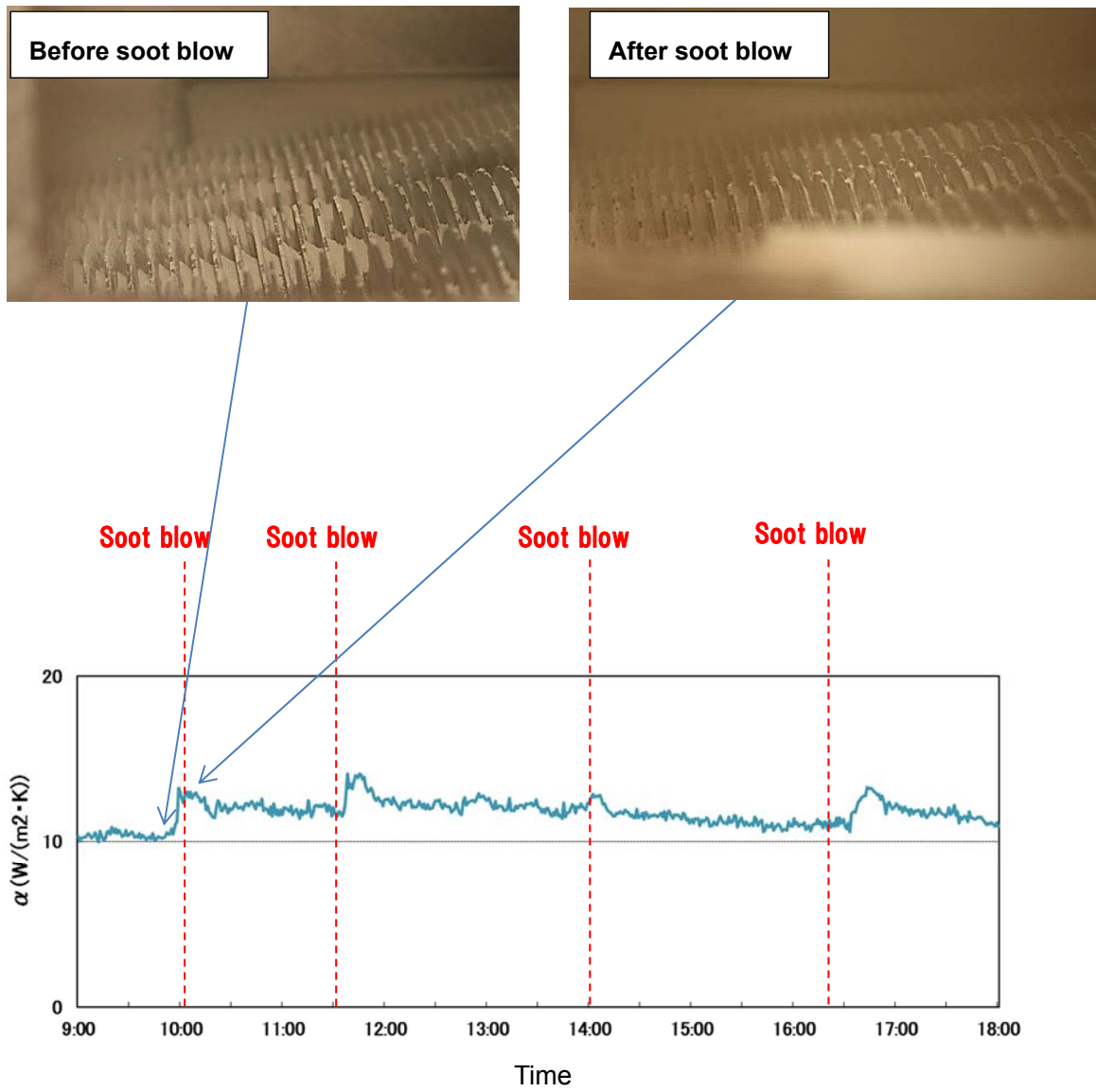


Figure 4.4-1 Temperature at the inlet and outlet of the GGH heat recovery device and overall heat transfer coefficient in conventional systems

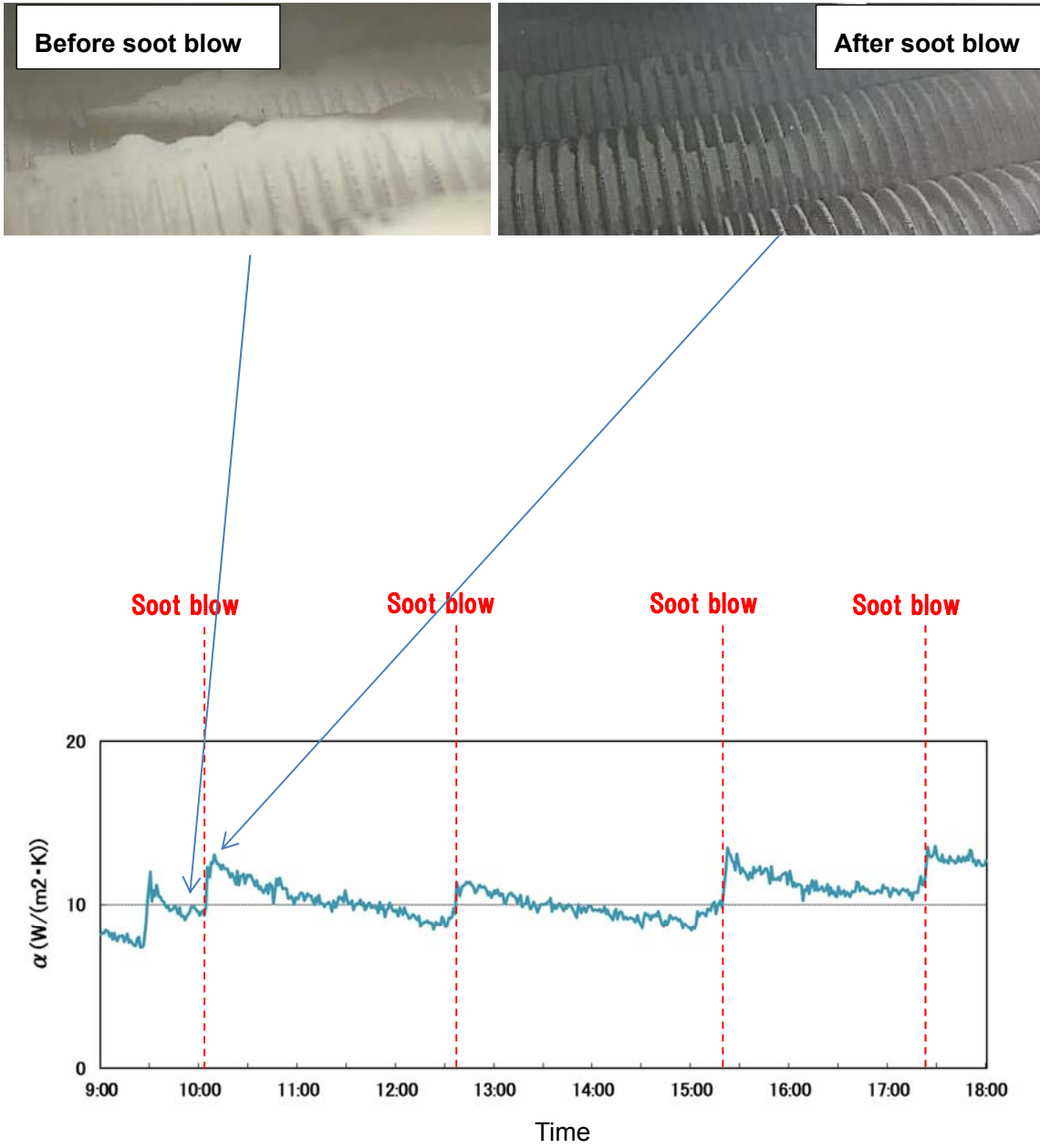


Figure 4.4-2 Temperature at the inlet and outlet of the GGH heat recovery device and overall heat transfer coefficient in the high-performance smoke dust removal system

#### 4.5 Abrasion characteristics of GGH fins

Comparison of appearance and weight of test pieces set in the GGH heat recovery device were made before and after exposure to coal combustion exhaust gas. Table 4.5-1 shows the result of test pieces made of carbon steel and Table 4.5-2 shows the result of test pieces made of sulfuric acid resistant steel. After exposure to coal combustion exhaust gas, test pieces were descaled for observation and weight measurement. Test pieces were separately exposed to exhaust gas in conventional systems and the high-performance smoke dust removal system. Exposure time was 40 hours for the high-performance smoke dust removal system and 55 hours for conventional systems.

Figure 4.5-1 shows abrasion speed obtained based on the weight before and after exposure to coal combustion exhaust gas. Although both test pieces made of carbon steel and sulfuric acid resistant steel had variation in abrasion speed in the high-performance smoke dust removal system, great difference was not found in abrasion speed depending on materials and exhaust gas conditions of conventional systems and the high-performance smoke dust removal system. In other words, under the condition of the high-performance smoke dust removal system in this test, GGH heat recovery device inlet smoke dust concentration was approx. 160 times higher than that under the condition of conventional systems (when applied voltage at DEP was 35kV). However, abrasion speed of materials showed the same level as that of conventional systems. From these results, in terms of abrasion characteristics of GGH heat recovery devices, adoption of the high-performance smoke dust removal system as an exhaust gas processing system of coal with high ash content such as Indian coal is assumed to cause no problem.

Table 4.5-1 Appearance and weight decrease of test pieces before and after the exposure  
(carbon steel)

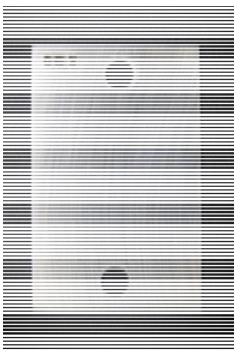
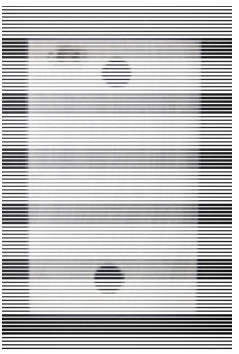
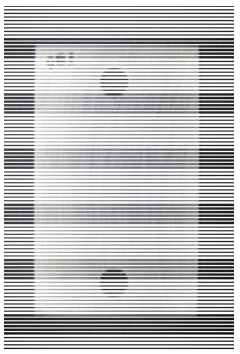
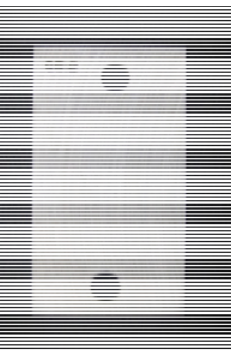
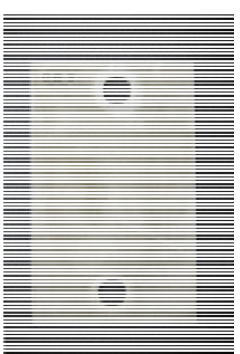
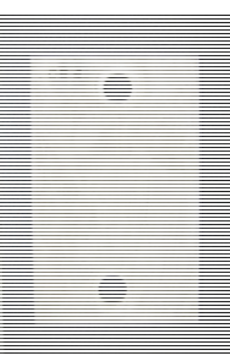
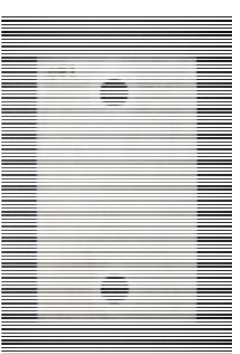
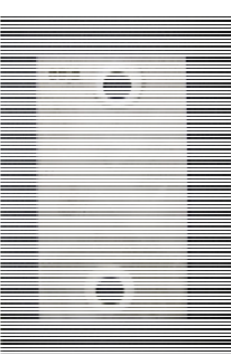
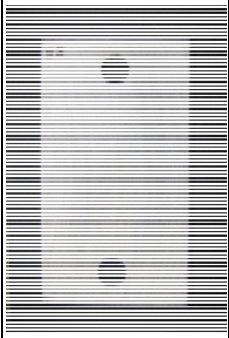
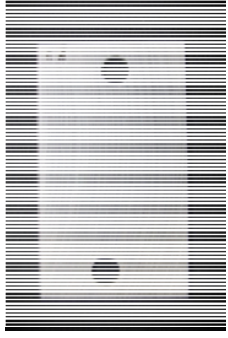

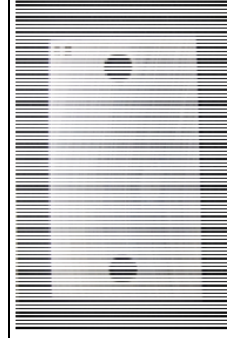
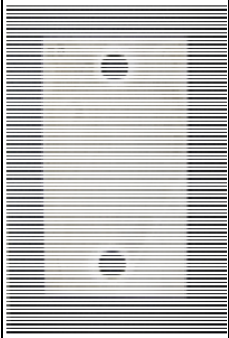

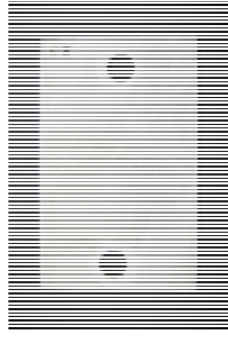

System		Conventional systems		High-performance smoke dust removal system	
Exposure time		55 h		40 h	
Mark		CS3	CS4	CS1	CS2
Before exposure	Appearance				
	Weight	23.2883 g	24.2372 g	22.5912 g	21.2807 g
After exposure	Appearance				
	Weight	23.2733 g	24.2226 g	22.5835 g	21.2704 g
Weight decrease		0.0150 g	0.0146 g	0.0077 g	0.0103 g

Table 4.5-2 Appearance and weight decrease of test pieces before and after the exposure  
(sulfuric acid resistant steel)

System		Conventional systems		High-performance smoke dust removal system	
Exposure time		55 h		40 h	
Mark		S3	S4	S1	S2
Before exposure	Appearance				
	Weight	33.0475 g	31.9396 g	34.3022 g	32.3558 g
After exposure	Appearance				
	Weight	33.0326 g	31.9260 g	34.2966 g	32.3466 g
Weight decrease		0.0149 g	0.0136 g	0.0056 g	0.0092 G



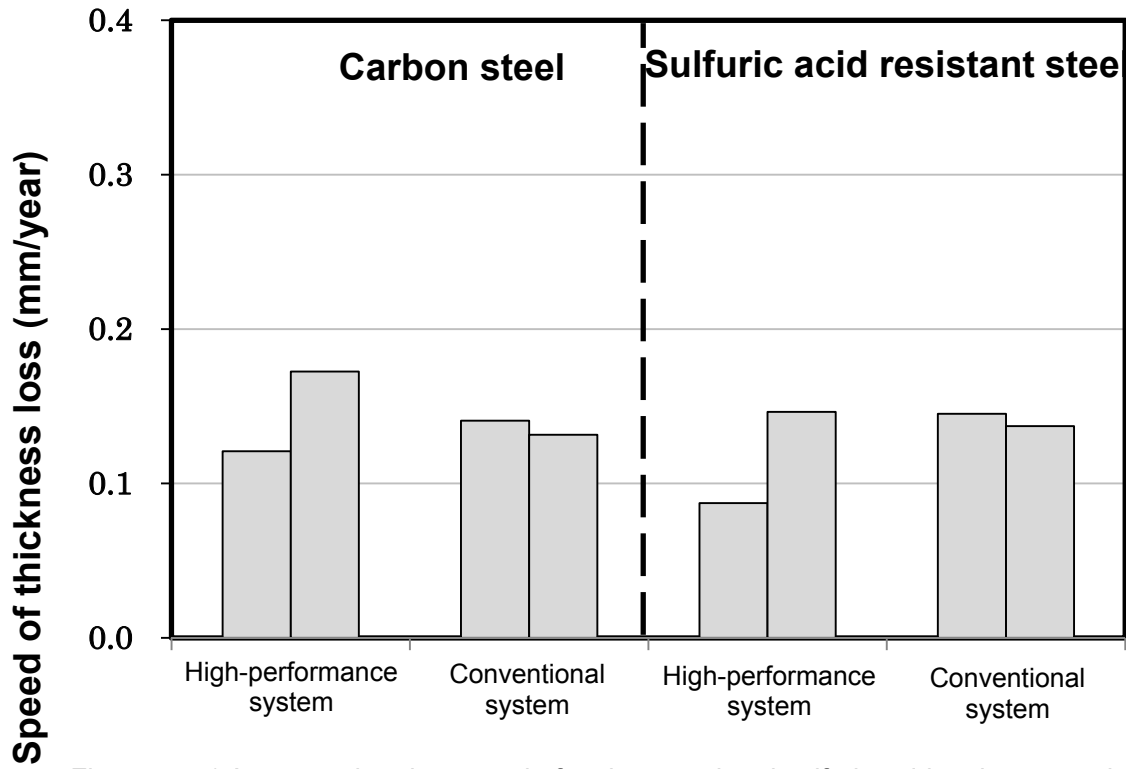


Figure 4.5-1 Average abrasion speed of carbon steel and sulfuric acid resistant steel

## 5. SUMMARY OF COMBUSTION TEST

### 5.1 Overview of test results

Indian coal contains a lot of ash, which leads to high load of smoke dust to flue gas treatment facilities with possible negative influence on dust removal/desulfurization performance. Accordingly, in this research, comparative evaluation of conventional systems and the high-performance smoke dust removal system was performed by using the Combustion-AQCS Integrated Test device and basic test devices in a laboratory. Major results are described below.

#### (1) Smoke dust removal performance

Stable charging and possibility of highly efficient dust removal were confirmed for very low temperature EP (the high-performance smoke dust removal system). On the contrary, for low temperature EP (conventional systems), applying high voltage was impossible and DEP outlet smoke dust concentration was higher than that of very low temperature EP. This is seemingly because high electrical resistivity of ash resulted in the occurrence of inversive ionization phenomenon. Consequently, when electrical resistivity of ash is high as with the case of Talcher coal, an effective way is that applying very low temperature EP is applied and exhaust gas temperature at DEP is decreased to lower the electrical resistivity of ash.

In addition, for both low temperature EP and very low temperature EP, smoke dust concentration at the outlet of FGD was controlled to low concentration of  $15\text{mg}/\text{m}^3\text{N}$  or below. In particular, when inlet smoke dust concentration was decreased by very low temperature EP,  $5\text{mg}/\text{m}^3\text{N}$  of outlet concentration or less is achievable.

#### (2) Desulfurization performance

For low temperature EP (conventional systems) and very low temperature EP (the high-performance smoke dust removal system), smoke dust concentration at the inlet of FGD was  $30\text{mg}/\text{m}^3\text{N}$  and  $90\text{mg}/\text{m}^3\text{N}$ , respectively. However, under the same condition (L/G,  $\text{CaCO}_3$  concentration), desulfurization rate of both systems was equal and influence of smoke dust concentration was not found.

In order to understand the reason for this, test of Al elution from ash was conducted. The result

of this test showed that the rate of Al elution from coal ash was a small value of less than 1% for elution time of Talcher coal with actual FGD. In addition, limestone inactivation was not found when ash and F were fed under the condition of high smoke dust concentration at a small FGD. However, for the same test device, limestone inactivation was found when coal from the U.S. with high rate of Al elution from ash was fed. Based on this result, the reason why limestone inactivation did not occur under the condition of high smoke dust concentration for Talcher coal was low rate of Al elution from ash. Consequently, for coal in which Al elution from ash easily occurs and under the condition of high smoke dust concentration, limestone inactivation is highly likely to occur.

#### (3) Overall heat transfer coefficient in GGH

Overall heat transfer coefficient of GGH in conventional systems and the high-performance smoke dust removal system was equal. In the high-performance smoke dust removal system, the amount of ash deposit on fin tubes was larger and decrease rate of heat transfer coefficient over time was higher than the case of conventional systems, and the heat transfer coefficient recovered to the initial value by regular soot blower operation every 2 to 3 hours. This result suggests that operation under the condition of high smoke dust concentration has no problem.

#### (4) Abrasion characteristic of GGH fin

Abrasion speed in both systems was studied by using test pieces made of carbon steel and sulfuric acid resistant steel. Difference in both systems was not found and in terms of abrasion characteristics, operation of the high-performance smoke dust removal system is assumed to cause no problem even under the condition of high ash content.

#### (5) Evaluation of economic efficiency

Based on relation between smoke dust removal performance and charge conditions, under the condition where charge is 45kV and DEP outlet smoke dust concentration is 30mg/m<sup>3</sup>N, very low temperature EP is estimated to reduce dust collection area (EP volume) by approx. 25% compared to the case of low temperature EP.

## 5.2 Vision of verification test in India

Vision of verification test in India includes a possible method to introduce part of exhaust gas of actual device in a test device by bypassing it from AH inlet (SSR: Slip Steam Reactor).

There are two types of structure of flue gas treatment devices; (a) denitrification catalyst + DEP and (b) full specification (denitrification catalyst + DEP + FGD) and the flow of each type is shown below. In (a) denitrification catalyst + DEP shown in Figure 5.2-1, pressure loss is evaluated by flowing exhaust gas and performance is evaluated by extracting denitrification catalyst after a certain period. In addition, abrasion of dust collection electrodes and discharge electrodes is evaluated by inspecting the inside of DEP. In (b) full specification (denitrification catalyst + DEP + FGD) shown in Figure 5.2-2, performance of the denitrification device, DEP and the FGD is evaluated by operating them.

In addition, in light of the prevention of pipe blocking due to ash, appropriate amount of exhaust gas is assumed to be 500m<sup>3</sup>/h (pipe diameter: 150mm, gas flow velocity:10m/s) or more.

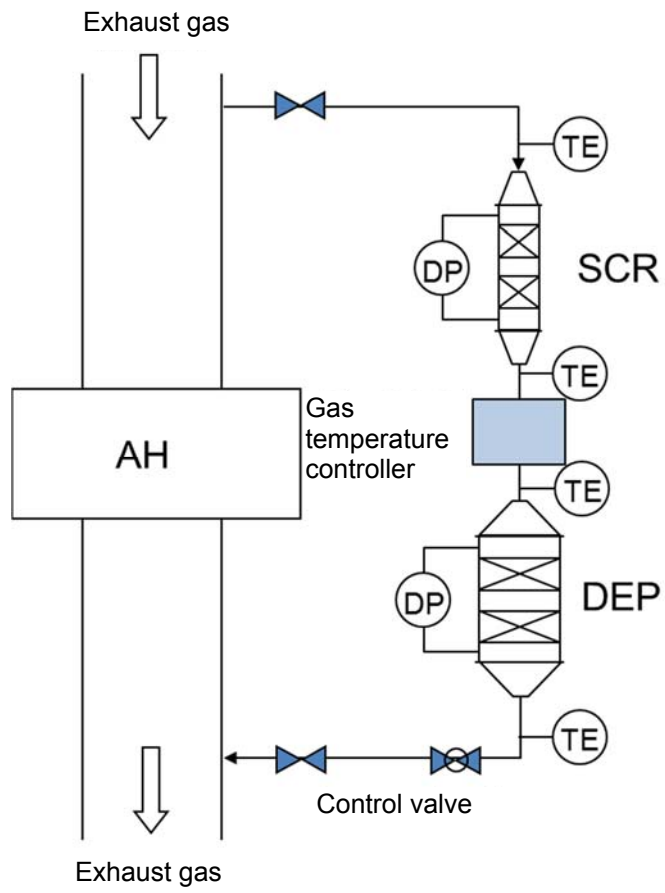


Figure 5.2-1 Flow example of SSR (denitrification catalyst + DEP)

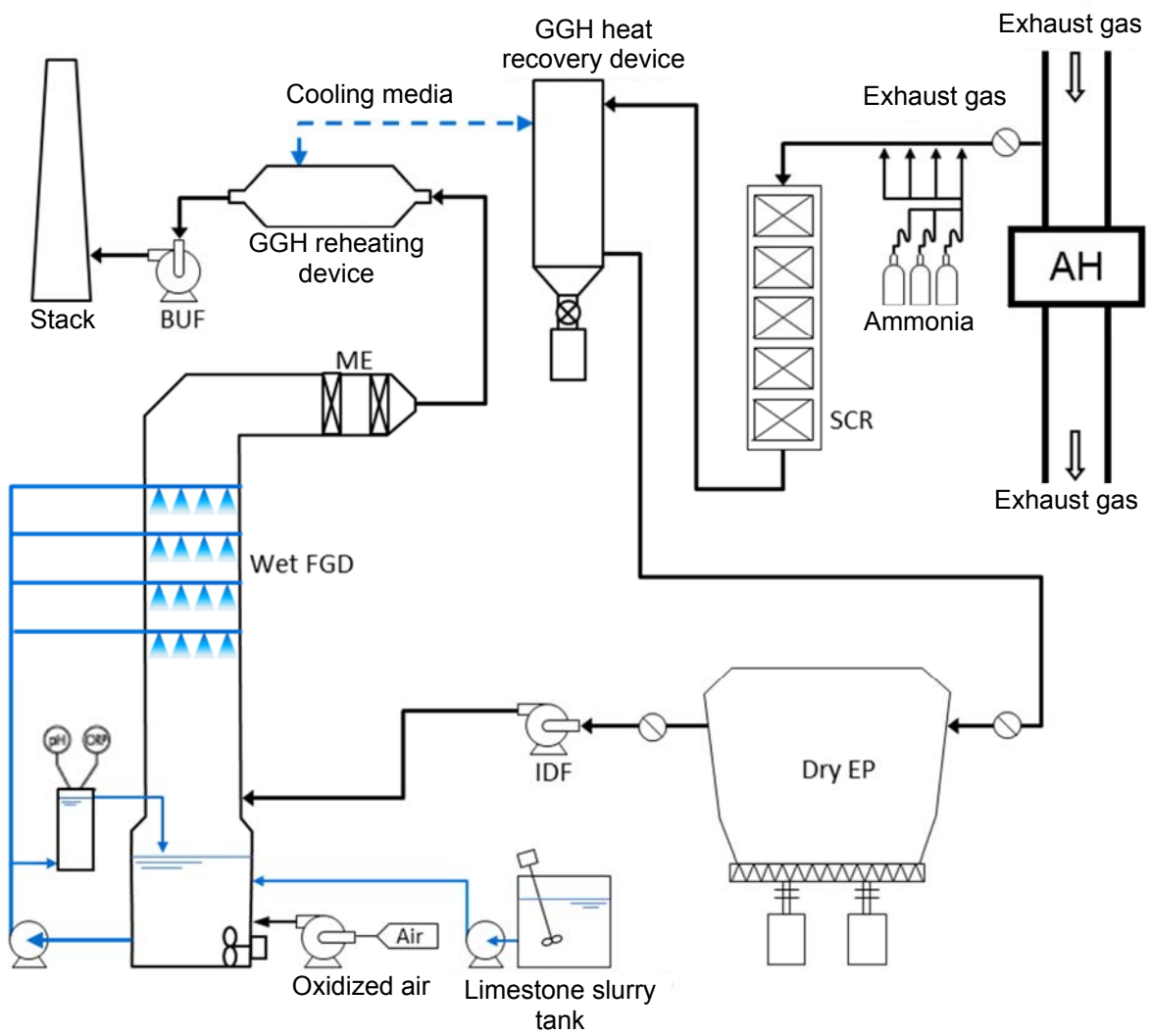


Figure 5.2-2 Flow example of SSR (denitrification catalyst + DEP + FGD)

## 6. Mercury Removal

### 6.1 Background and objective

The limit of mercury in India specified in the regulation announced this time is  $30\mu\text{g}/\text{m}^3\text{N}$  which is applied to units newly established from January 2017. This limit is significantly high compared the regulation of the US MATS (Mercury and Air Toxics Standards) ( $3.0\times 10^{-3}$  lb/GWh  $\approx 0.45\mu\text{g}/\text{m}^3\text{N}$  for newly established unit/not low rank virgin coal). However, coal from India might contain high concentration of mercury and low concentration of chlorine like the coal tested this time (Talcher coal) and the removal performance could be lowered due to low oxidation rate of mercury. Accordingly, mercury behavior in the exhaust gas and effectiveness of the removal performance improvement method should be confirmed. Then, evaluation and examination were made at a large-scale test facility held by MHPS as to mercury removal characteristics in the high mercury oxidation-type denitrification catalyst + high smoke dust removal system (very low temperature EP) which is MHPS technology and the system highly anticipated mainly in the U.S. in which activated carbon is added to exhaust gas and mercury is removed by DEP.

### 6.2 Mercury Removal performance improvement method

#### 6.2.1 Denitrification catalyst + high-performance smoke dust removal system

Although mercury (Hg) in coal is emitted from high-temperature boiler furnace mainly as metallic mercury vapor in reduced state, it is converted into oxidized mercury ( $\text{HgCl}_2$ ) by combining mostly with chlorine (Cl) in exhaust gas as the exhaust gas is cooled and adsorbed by smoke dust or dissolved in the liquid of the wet desulfurization device, then, removed from the exhaust gas. Therefore, improvement of the mercury oxidation rate, the adsorption rate of oxidized mercury on smoke dust and the removal rate of smoke dust on which mercury is adsorbed are important.

The latest MHPS exhaust gas treatment system<sup>2),3)</sup> allows to promote adsorption of oxidized mercury on ash and significantly improve mercury removal rate at in EP by efficiently oxidizing mercury with high mercury oxidation-type denitrification catalyst and then introducing the exhaust gas to very low temperature EP after lowering the temperature to about  $90^\circ\text{C}$  by the heat recovery device (high-performance smoke dust removal system). Furthermore, since a

small amount of oxidized mercury which passed through EP is efficiently absorbed and removed at the wet desulfurization device, decline of the removal rate due to reemission of mercury is suppressed. It is confirmed that such combination of improvement of the mercury oxidation rate and increase in the oxidized mercury removal rate realizes reduction of the amount of mercury emitted from the entire system to approx. one quarter as shown in Figure 6-1.

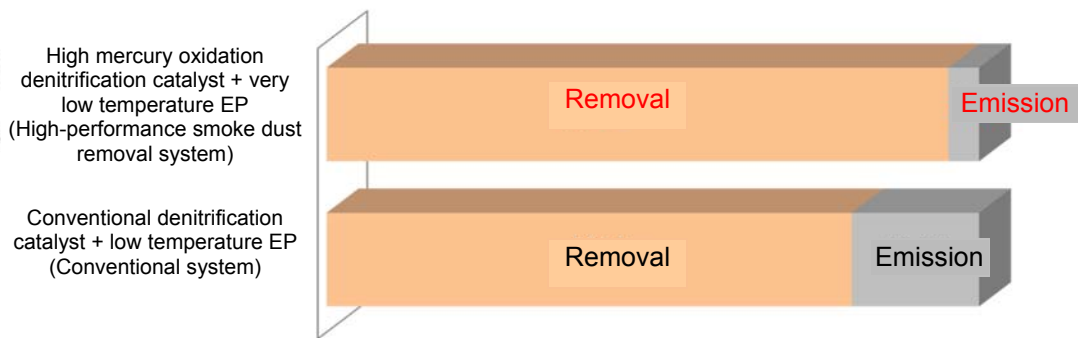
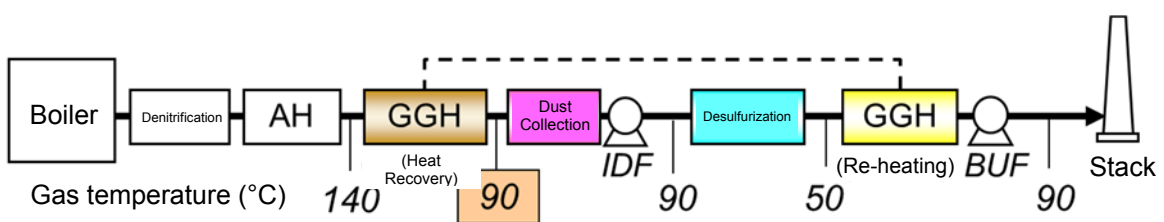


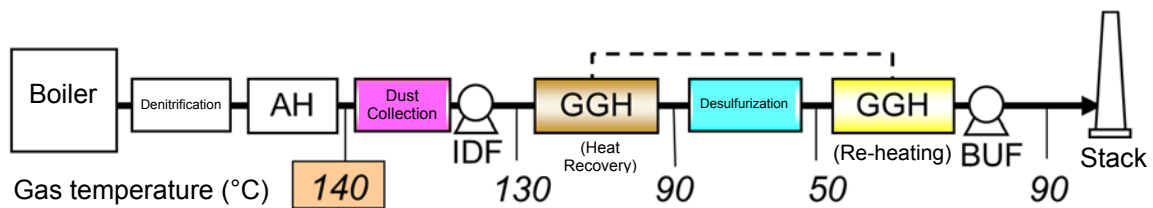
Figure 6-1 Comparison of mercury removal performance at a total system



For reference, the flow of the high-performance smoke dust removal system and the conventional system are shown in Figure 6-2. In the conventional system, a GGH heat recovery device is installed between an electrostatic precipitator and a desulfurization device, which results in the exhaust gas temperature of around 140°C at the electrostatic precipitator (low temperature EP). On the contrary, in the high-performance smoke dust removal system, installing a GGH heat recovery device before an electrostatic precipitator lowers the exhaust gas temperature at an electrostatic precipitator to around 90°C (very low temperature EP).



(a) Flow of the high-performance smoke dust removal system



(b) Flow of the conventional system

Figure 6-2. Comparison of the flow of exhaust gas treatment system

### 6.2.2 Addition of activated carbon to exhaust gas

In the U.S., as a measure to satisfy the very strict regulation for mercury in exhaust gas (MATS), a system in which powdered activated carbon is sprayed into exhaust gas to adsorb mercury and the powdered activated carbon is removed with smoke dust by DEP has been highly anticipated since before<sup>4),5)</sup>. The basic flow of the activated carbon addition system<sup>4)</sup> is shown in Figure 6-3. Although the exhaust gas treatment facility is only an electrostatic precipitator in this flow, some plants are equipped with denitrification catalyst and/or a desulfurization device.

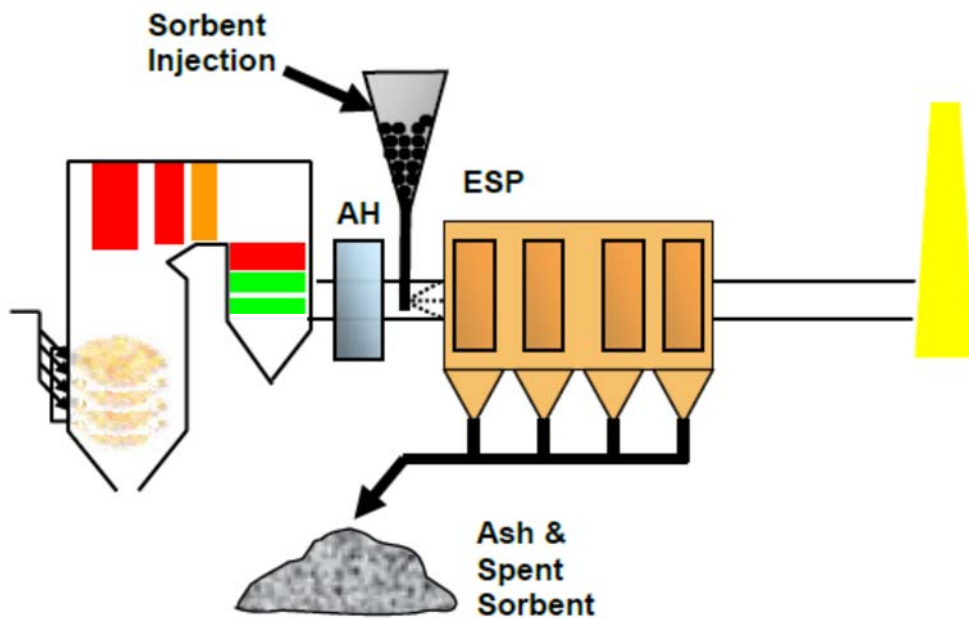


Figure 6-3 Basic flow of the activated carbon addition system<sup>4)</sup>

[Chapter 6 Reference]

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- 2) Kikkawa et al.: Highly-Efficient Removal of Toxic Trace Elements and Particulate Matter in Flue Gas Emitted from Coal-fired Power Plants by Air Quality Control System (AQCS): Mitsubishi Heavy Industries Technical Review Vol. 52 No. 2, 2015
- 3) T. Nakamoto et al.: Advanced AQCS technology for future emission control: VGB PowerTech, 11, 2014
- 4) T. J. Feeley et al.: Field testing of mercury control technologies for coal-fired power plants: DOE/NETL Mercury R&D Program Review, May, 2005
- 5) B. Looney et al.: The role of activated carbon in a comprehensive MATS strategy: POWER, March, 2014

## 7. MERCURY REMOVAL

### 7.1 Details of test

Coal from India (approx. 25 ton) provided by JCOAL was burned under the condition close to actual pulverized coal fired boilers (approx. 200 kg of coal was fed per hour) for one week (from Monday to Saturday) by using the “Combustion-AQCS Integrated Facility” held by MHPS to conduct test operation of exhaust gas treatment. Conducting component analysis of coal and combustion exhaust gas, etc., mercury removal performance of the conventional system (low temperature EP) and the high-performance smoke dust removal system (very low temperature EP) were compared. In addition, injecting activated carbon into exhaust gas, the following data with respect to mercury removal was obtained.

- Mercury concentration in coal
- Mercury concentration in exhaust gas in the case where activated carbon is not injected (after each device for dust removal and desulfurization)
- Mercury oxidation rate at the denitrification device
- Mercury concentration in exhaust gas in the case where activated carbon is injected (after each device for dust removal and desulfurization)

### 7.2 Main test operation conditions (plan)

(1) Combustion amount of coal: 185kg/h (ash content 40%)

(2) Gas temperature at inlet of the electrostatic precipitator:

90-100°C (high-performance smoke dust removal system),

140-150°C (conventional system)

(3) Electrostatic precipitator charge voltage: 25 to 45kV (3 conditions)

(4) Denitrification device: denitrification rate 90%

(5) Desulfurization device: desulfurization rate 95%

In order to support the result of mercury removal performance test conducted at the integrated facility (influence of lowering of DEP temperature to very cold and addition of activated carbon), laboratory basic test was also conducted and the result was closely reviewed.

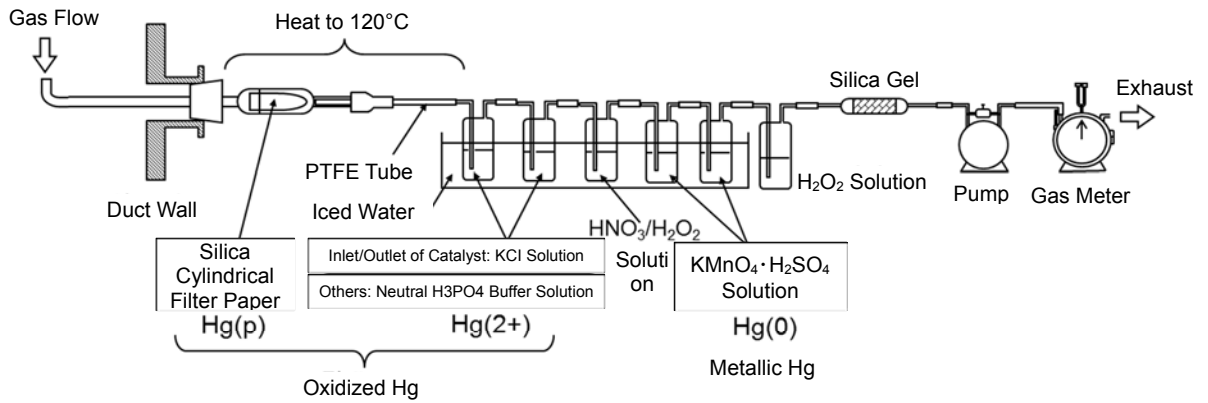
## 7.3 Measurement points

### 7.3.1 Mercury (Hg)

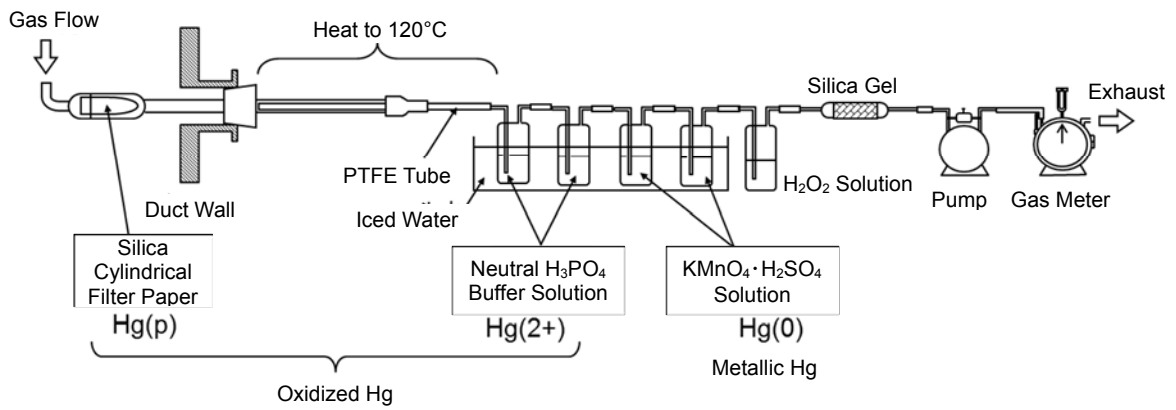
The sampling flow of Hg in exhaust gas is shown in Figure 7-1. (a) The method in accordance with EPA was used for the high temperature area from inlet of the denitrification catalyst (SCR) to outlet of the gas cooler and (b) the method in accordance with JIS was used for the low temperature area after inlet of DEP. In the method (a), silica cylindrical filter paper for particle collection is set outside the duct and heated to 120°C, and in the method (b), it is set inside the duct. Because a part of Hg is reduced by collected ash if the temperature of the filter paper is high, the method (a) is used for the high temperature area and dust is removed at low temperature (120°C) in order to avoid reduction of Hg by ash.

In both methods, the sampling nozzle was set as the port was opposite to the gas flow at the center of the duct and the exhaust gas was sampled by isokinetic sampling. Firstly, particulate Hg (p) was collected by the cylindrical filter paper and secondly, oxidized gaseous Hg (2+) was collected by KCl solution at inlet and outlet of the denitrification catalyst and by neutral phosphate buffer solution at other areas. Finally, metallic Hg (0) was collected by KMnO<sub>4</sub> solution and the analysis was conducted for each form. Inside of used sampling tube was cleansed by KMnO<sub>4</sub> solution and the cleaning liquid was blended with KCl solution or neutral phosphate buffer solution and counted as Hg (2+). The amount of Hg collected in the absorbing liquid was determined by reduction vaporizing atomic absorption method with a mercury analyzer (Nippon Instruments Corporation/MA-2000) shown in Figure 7-2. The filter paper was soaked in KMnO<sub>4</sub> solution just after sampling and heated for 4h at 70°C. Then, extraction treatment was made for the paper with ultrasonic wave for 1h and the amount of eluted Hg was determined as Hg (p).

Hg concentrations in the pulverized coal and EP ash recovered from the dry EP were determined by heating vaporizing atomic absorption method with the same Hg analyzer.



(a) Method in accordance with EPA (Ontario-Hydro Method) (inlet of denitrification catalyst - outlet of gas cooler)



(b) Method in accordance with JIS (EP inlet - FGD outlet)

Figure 7.1. Sampling flow of Hg in exhaust gas



Figure 7.2. Hg analyzer (Nippon Instruments Corporation/MA-2000)

### 7.3.2 Hydrogen chloride (HCl)

Since Hg oxidation in coal combustion exhaust gas mainly means generation of  $\text{HgCl}_2$  by combining with Cl, it is important to confirm the concentration of HCl in exhaust gas. The sampling flow of HCl in exhaust gas (in accordance with JIS K 0107) is shown in Figure 7-3. It was collected by absorbing liquid (pure water) after removing dust with cylindrical filter paper set inside the duct. The sampling probe was washed with pure water and the water was blended with the absorbing liquid. Chloride ion concentration in the liquid was determined with the ion chromatography device (former Dionex/ICS-2000) shown in Figure 7-4 and the HCl concentration in the gas was calculated.

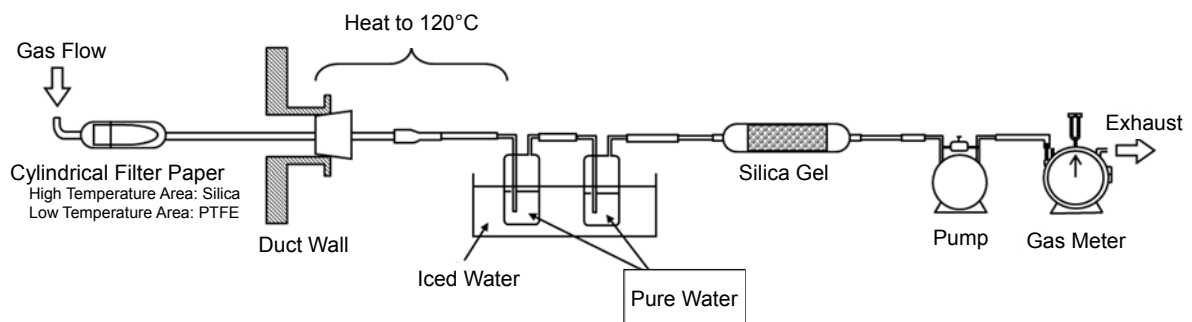


Figure 7-3. Sampling flow of HCl in exhaust gas (in accordance with JIS K 0107)

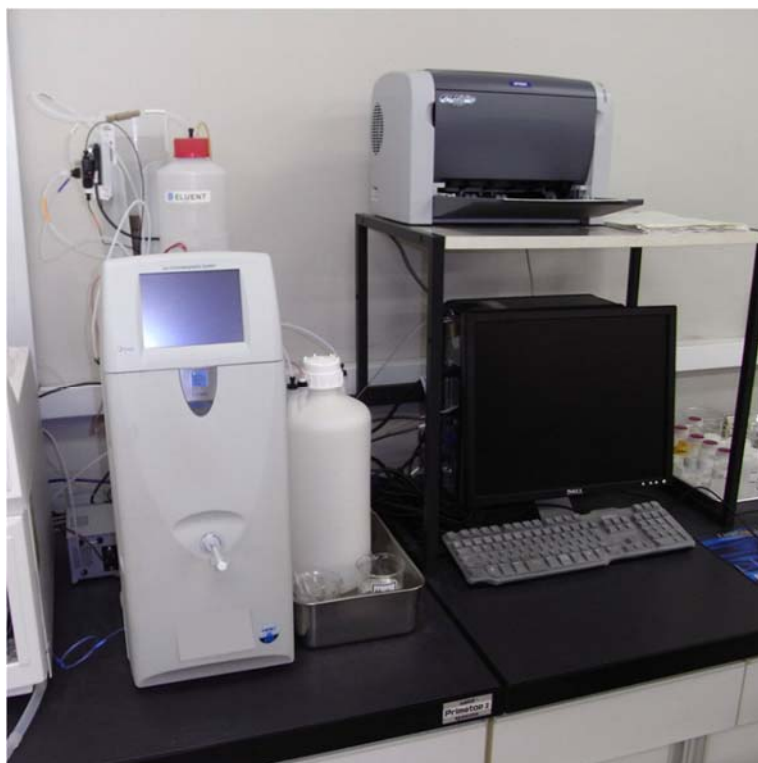


Figure 7-4. Ion chromatography device (former Dionex/ICS-2000)

### 7.3.3 Sulfur trioxide (SO<sub>3</sub>)

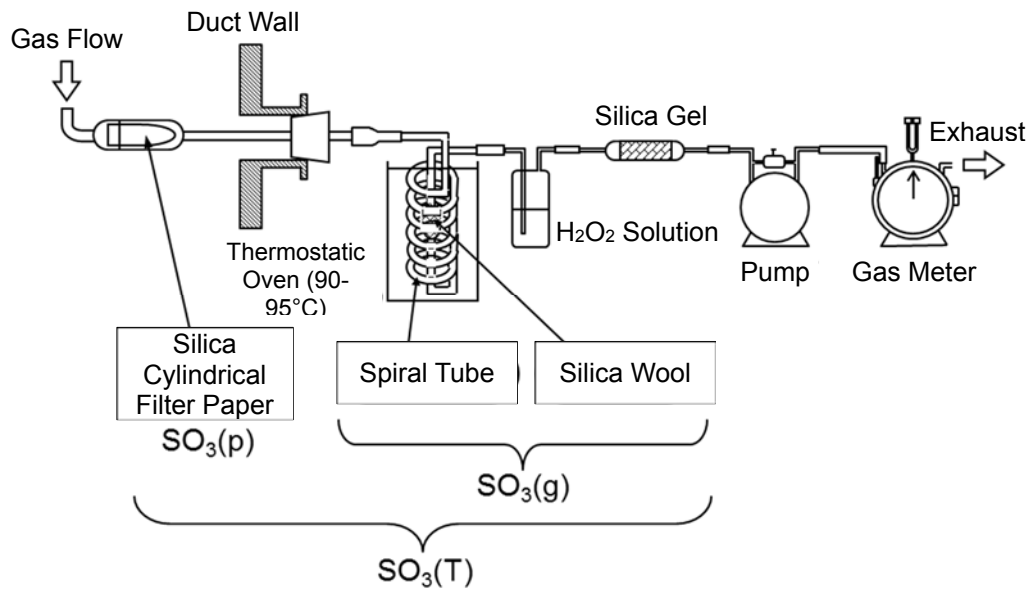
When SO<sub>3</sub> concentration in exhaust gas is high, surface of fly ash is covered by adsorbed SO<sub>3</sub> and Hg adsorption is disturbed, therefore, SO<sub>3</sub> was also measured and evaluated. The sampling flow of SO<sub>3</sub> in exhaust gas is shown in Figure 7-5. (a) The method in accordance with Japan Environmental Measurement and Chemical Analysis Association/note for environmental measurement and chemical analysis methods was used for the part from SCR inlet to DEP inlet, and (b) the method in accordance with EPA (NCASI Method 8A / ASTM 3226-73T) was used for the part after DEP outlet. In the method (a), silica cylindrical filter paper for particle collection is set outside the duct and heated to 120°C, and in the method (b), it is set inside the duct. In both methods, the sampling nozzle was set as the port was opposite to the gas flow at the center of the duct and the exhaust gas was sampled by isokinetic sampling.

The method (a) is an applicable method for a place with much dust content. After removing dust inside the duct by attaching silica cylindrical filter paper on the tip of the sampling probe, SO<sub>3</sub> was condensed and collected in the condition where SO<sub>2</sub> was vaporized by glass spiral tube

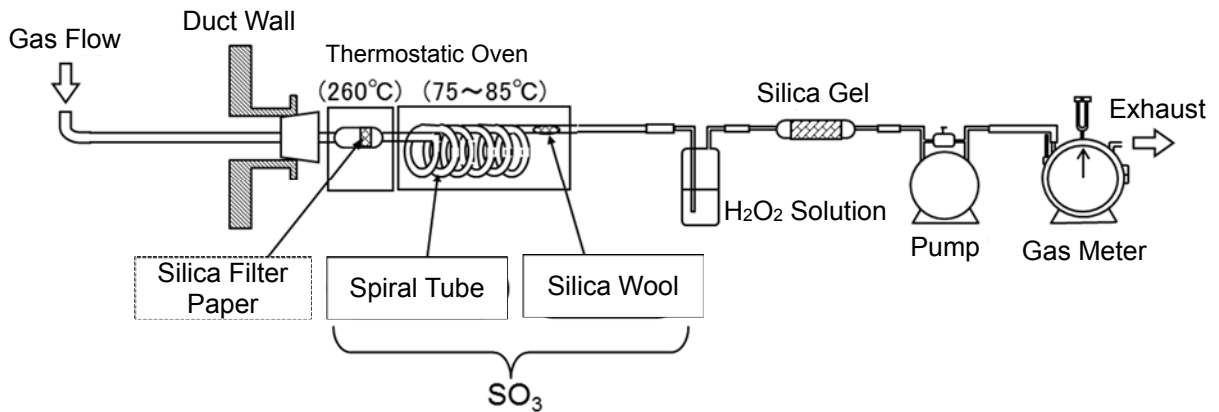
and silica wool that are heated to 90 - 95°C. The cylindrical filter paper was cleansed by ultrasonication (more than 1 hour) in a specified amount of pure water and the spiral tube and the silica wool were washed by pure water. The amount of sulfate ion in each cleaning liquid was determined with the same ion chromatography device as above and SO<sub>3</sub> concentration in the gas was calculated separately. Then, that of the filter paper and the spiral tube were represented as particulate SO<sub>3</sub> (p) and gaseous SO<sub>3</sub> (g) respectively, and the sum of them was represented as a total, SO<sub>3</sub> (T).

The method (b) is a method developed for exhaust gas from stack with small dust content and low temperature (popular name: heated filter paper method). After removing dust in the gas extracted from the duct by silica filter paper which is heated to 260°C, SO<sub>3</sub> is condensed and collected by spiral tube and silica wool that are heated to 75 - 85°C. In this method, SO<sub>3</sub> which was in the mist form inside the duct is vaporized on the heated filter paper and collected by the spiral tube together with originally gaseous SO<sub>3</sub>. Although the analysis method for the spiral tube and the silica wool is same as that of (a), SO<sub>3</sub> in the filter paper is not analyzed.





(a) Method in accordance with Japan Environmental Measurement and Chemical Analysis Association/note for environmental measurement and chemical analysis methods (SCR inlet to EP inlet)



(b) Method in accordance with EPA (NCASI Method 8A / ASTM 3226-73T) (EP outlet to FGD outlet)

Figure 7-5. Sampling flow of  $\text{SO}_3$  in exhaust gas

## 7.4 Evaluation for mercury removal performance

### 7.4.1 Test at the Combustion-AQCS Integrated Facility

#### (1) Evaluation for mercury behavior and removal rate

##### (a) Hg measurement points

As shown in Figure 7-6, mercury concentration in exhaust gas was measured by its form at 5 points that are catalyst inlet, catalyst outlet, EP inlet, EP outlet (desulfurization inlet) and desulfurization outlet, and its behavior and removal characteristics were evaluated. In addition, the Hg concentration in EP ash collected from the hopper of EP was also measured. In this paragraph, forms of mercury in exhaust gas are described as follows.

Metallic mercury (gaseous): Hg (0)

Oxidized Mercury (gaseous): Hg (2+)

Oxidized Mercury (particulate): Hg (p)

Oxidized Mercury: Oxidized Hg = Hg (2+) + Hg (p)

Total mercury: Hg (T) = Hg (0) + Hg (2+) + Hg(p)

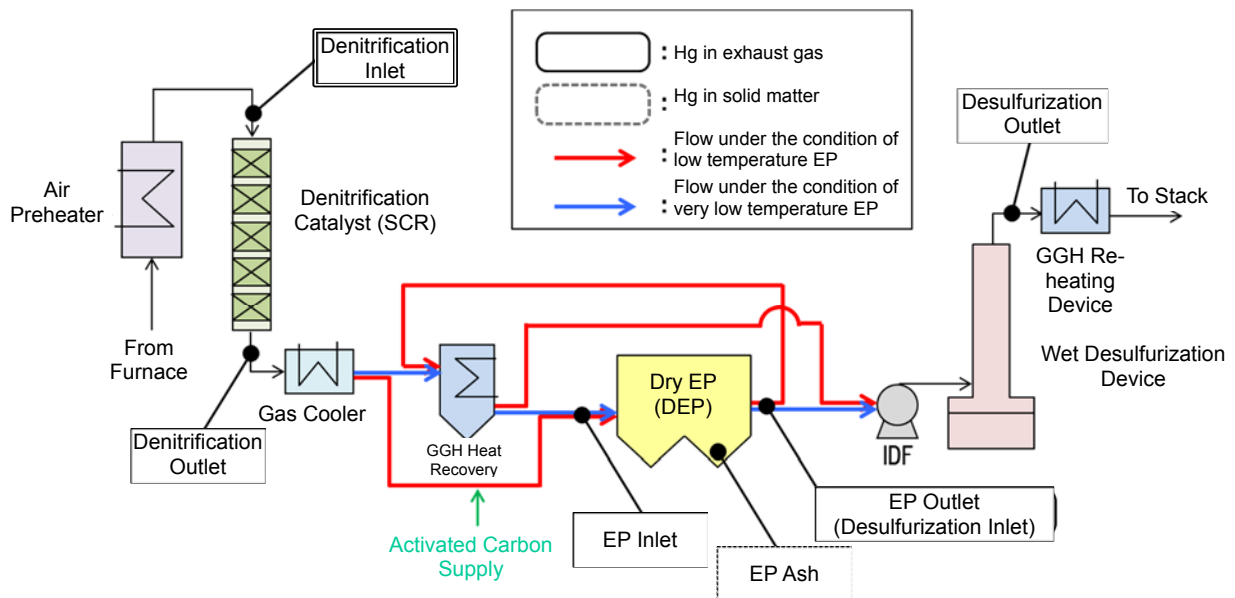


Figure 7-6. Hg measurement points

(b) Definition of Hg oxidation rate in catalyst

Since gaseous oxidized mercury has adsorptivity, there is a case where it adsorbs on sampling tools and cannot be collected completely or where it adsorbs on ash and partly drops and deposits inside the facility, which might cause errors of measurement values in exhaust gas. On the other hand, metallic mercury does not have adsorptivity and can be measured with high accuracy. Accordingly, mercury oxidation rate in the denitrification catalyst was defined as the reduction rate of metallic mercury from inlet to outlet of the denitrification catalyst by the formula 7-1 below.

$$\text{Mercury oxidation rate in catalyst (\%)} = 1 - \frac{\text{Denitrification outlet Hg(0)} \left( \frac{\mu\text{g}}{\text{m}^3\text{N}} \right)}{\text{Denitrification inlet Hg(0)} \left( \frac{\mu\text{g}}{\text{m}^3\text{N}} \right)} \times 100 \quad \dots\dots 7-1$$

(c) Definition of Hg removal rate in DEP

When the difference of Hg concentration in exhaust gas between inlet and outlet of DEP is small, there is a case where the Hg measurement value at the outlet is higher than that of the inlet and the Hg removal rate at the DEP which is calculated from the Hg concentration in exhaust gas becomes negative. Then, because almost all (more than 99%) of smoke dust in exhaust gas at DEP inlet is collected at the DEP, the removal rate was defined by the formula 7-2 below by assuming that Hg which is contained in ash (EP ash) recovered from DEP = Hg which was removed from exhaust gas.

$$\text{Mercury oxidation rate (\%)} \text{ in DEP} = \frac{\text{Smoke dust concentration at DEP inlet} \left( \frac{\text{g}}{\text{m}^3\text{N}} \right) \times \text{Hg in DEP ash} (\mu\text{g/g})}{\text{Hg(T) at DEP inlet} (\mu\text{g}/\text{m}^3\text{N})} \times 100 \quad \dots\dots 7-2$$

(2) Activated carbon addition test

Powdered activated carbon was added to exhaust gas before DEP and mercury removal performance was evaluated. Assuming actual situation of India, denitrification catalyst was not used by bypassing, and activated carbon was added under the low temperature EP condition. Outline of the method of injecting activated carbon and test conditions are shown in Figure 7-7 and Table 7-1 respectively. There was a sampling seat just before the DEP inlet and an activated

carbon injecting seat was set at approx. 13 m before that. The staying time to the DEP inlet was 1.7 sec. Since it is difficult to supply a little fixed amount of activated carbon as is, it was mixed with commercially available fly ash and diluted to 30 wt.%. This diluted activated carbon was quantitatively cut out by a table feeder and air-conveyed, then injected in parallel with exhaust gas from a nozzle (inner diameter 6 mm) inserted into the center of 300A duct. Because the additive amount of activated carbon to exhaust gas for the purpose of mercury removal is generally considered as around 0.05 - 0.1 g/m<sup>3</sup>N (around 1% of typical amount of smoke dust in exhaust gas of 5 - 10 g/m<sup>3</sup>N), the additive amount was varied in the range from 0 (no addition) to 0.2 g/m<sup>3</sup>N in this test. Although the smoke dust concentration in exhaust gas at EP inlet is 23.5 g/m<sup>3</sup>N which is lower than the smoke dust concentration at the denitrification inlet of 30~35 mg/m<sup>3</sup>N, it is because the smoke dust is partly lost from the exhaust gas by dropping and depositing on heat exchangers or ducts on the way. Actual additive amounts of activated carbon were 0.043, 0.085 and 0.184 g/m<sup>3</sup>N and activated carbon concentrations to smoke dust were 0.18, 0.36 and 0.78 wt.%.

Specifications of the activated carbon are shown in Table 7-2. "Darco-Hg" made by Norit Corporation which has successful results in the U.S. was used. It is made from lignite (brown coal) and not chemically-modified with Br, etc. Actual measurement value of ash content was high of 35.3 wt.%. The result of measurement for particle size distribution of activated carbon is shown in Figure 7-8. The average diameter (d50) was 17 μm. The BET specific surface area is 600m<sup>2</sup>/g.

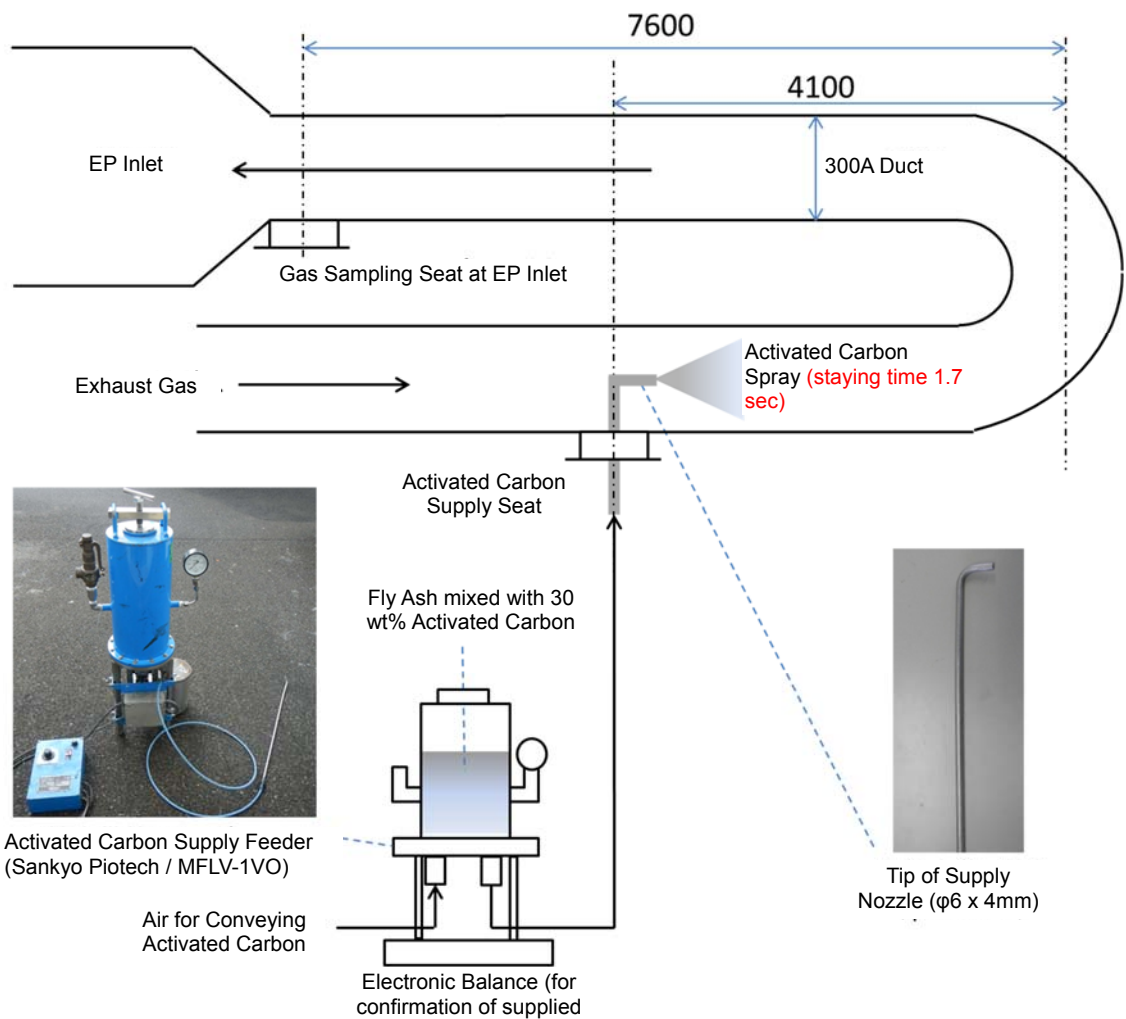


Figure 7-7. Method of injecting activated carbon

Table 7-1. Test conditions for addition of activated carbon

Item	Condition	Remarks
Denitrification catalyst	Bypass	
EP temperature (average)	Inlet:170°C, Outlet: 140°C	Low temperature EP condition
Staying time of activated carbon	1.7 Sec	Injecting seat - EP inlet
Additive amount of activated carbon (setting)	0.05, 0.1, 0.2 g/m <sup>3</sup> N	
Additive amount of activated carbon (actual)	0.043, 0.085, 0.184 g/m <sup>3</sup> N	
Smoke dust concentration at EP inlet	23.5 g/m <sup>3</sup> N	
Activated carbon concentration in smoke dust (actual)	0.18, 0.36, 0.78 wt.%	

Table 7-2. Specifications of powdered activated carbon

Item	Specifications	Remarks
Manufacturer / Product name	Norit / Darco-Hg	
Raw material	Texas Lignite	
Chemical modification	None	
Ash content	35.3 wt.% (dry)	Actual measurement
Average diameter	17 $\mu\text{m}$	Actual measurement
BET specific surface area	600 $\text{m}^2/\text{g}$	Specification

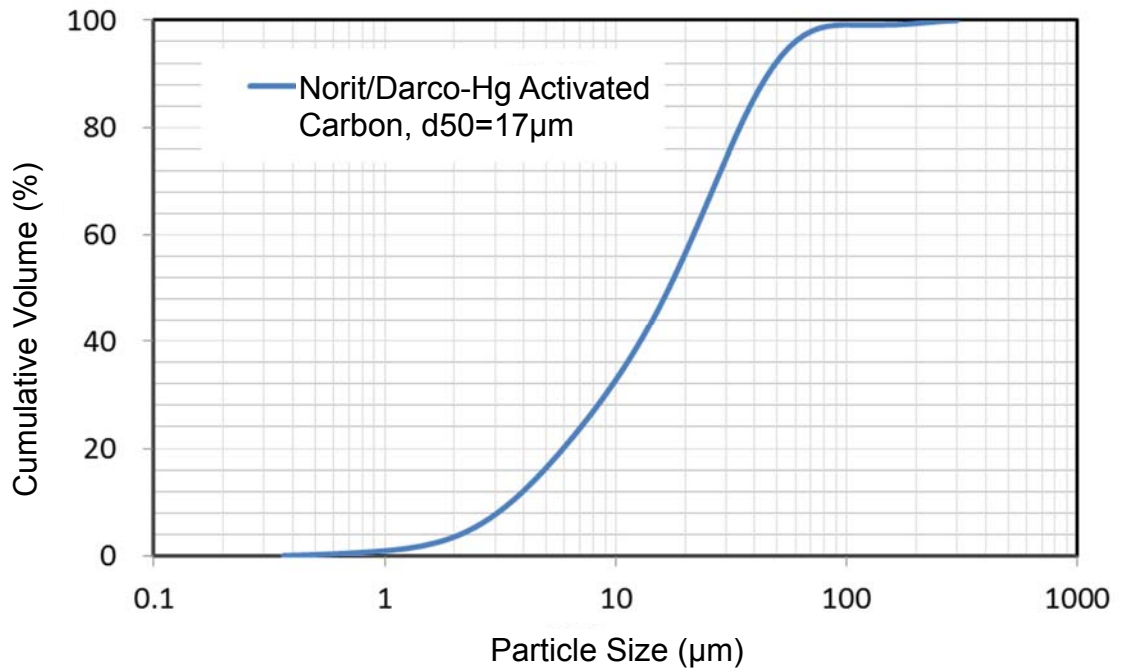


Figure 7-8. Particle size distribution of powdered activated carbon (actual measurement)

## 7.5 Basic test

In order to support the difference of DEP temperature (low temperature EP, very low temperature EP) and characteristics of Hg removal by adding activated carbon at the Combustion-AQCS Integrated Facility, laboratory basic test was conducted.

Outline of the device used for Hg removal basic test and experiment conditions are shown in Figure 3.3-4 and Table 3.3-3 respectively. Cylindrical reaction tube with inner diameter of 35 mm and length of 700 mm was heated from outside by an electric furnace, silica circular filter paper which was filled with ash of Talcher coal was fixed on an ash holder and the holder was inserted into the reaction tube, and then preheating simulated exhaust gas (5% of O<sub>2</sub>, 15% of CO<sub>2</sub>, 80% of N<sub>2</sub>) was supplied from the upper side of the reaction tube and made to pass through the ash holder. Both the reaction tube and the ash holder are made from quartz. EP ash recovered at the time of the test at the integrated facility was used as the ash after heating at 500°C for 3 hours and removing adsorbed Hg.

After controlling the temperature of liquid mercury at the thermostatic oven and generating specified concentration of Hg(0) saturated vapor, HCl gas was added. They were oxidized with oxidation catalyst and added to the simulated gas, then supplied into the reaction tube. The gas which passed through the ash holder was exhausted from the lower side. It was partly sampled and the concentrations of Hg(2+) and Hg(0) were measured. In addition, the ash was recovered after the experiment and Hg concentration in the ash was also measured. Both measurement methods of Hg in gas and in ash followed the method in the integrated facility. The temperature inside the reaction tube was 250 °C around the inlet and the outlet in order to prevent Hg adsorption, and 160°C or 90°C at the ash holder part to simulate low temperature EP and very low temperature EP respectively. However, since this is a method in which the gas passes through a layer of ash, contact conditions of ash and the gas are closer to bag filter than EP.

The supplied amount of gas, the filling amount of ash, and the time of supplying gas were set so that the proportion of the amount of ash to the amount of gas was equivalent to that at EP inlet in the test at the integrated facility of 25 g/m<sup>3</sup>N. In addition, when activated carbon is added, the amount of 0.4 wt.% to the heat-treated ash was mixed so that the concentration in the gas was the standard condition of 0.1 g/m<sup>3</sup>N. As with the test at the integrated facility, Darco-Hg made by Norit Corporation was used as the activated carbon.

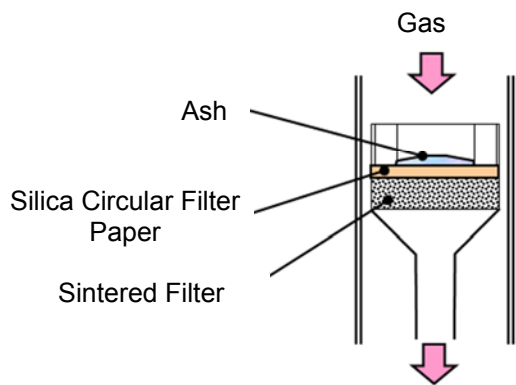
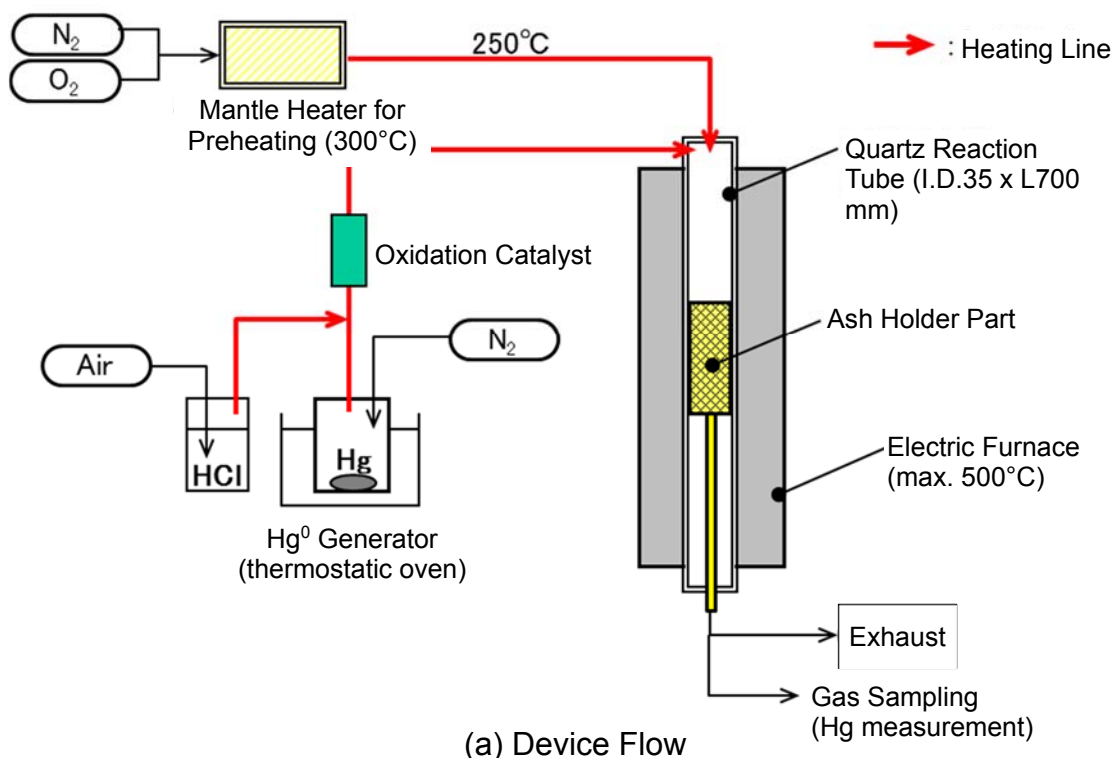


Figure 7-9. Mercury removal basic experiment device



Table 7-3. Mercury removal basic test conditions

Item	Condition	Remarks
Size of reaction tube	Inner diameter: 35 mm Length: 700 mm	
Simulated exhaust gas composition	O <sub>2</sub> : 5%, CO <sub>2</sub> : 15%, N <sub>2</sub> : 80%	
Hg additive concentration	35 µg/m <sup>3</sup> N	
Temperature of ash holder part	160°C, 90°C	
Type of ash	EP ash of Talcher coal at the integrated facility	Heat-treated at 500°C for 3 hours
Supplied amount of gas	0.4 L/min	Conversion of the concentration in exhaust gas Ash: 25 g/m <sup>3</sup> N Activated carbon: 0.1 g/m <sup>3</sup> N
Filling amount of ash	0.2 g	
Thickness of ash layer	2 mm	
Time of supplying gas	20 min	
Additive amount of activated carbon to ash	0.4wt%	
Type of activated carbon	Norit / Darco-Hg	

## 8. MERCURY REMOVAL, RESULTS

### 8.1 Mercury oxidation performance by catalyst

Relation between gas temperature at inlet of the denitrification catalyst and Hg oxidation rate (reduction rate of metallic Hg) in the test at the Combustion-AQCS Integrated Facility is shown in Figure 8-1 together with the past results of coals under test (public data). The concentration of containing Cl is different depending on coal and they are compared in a range of 0.8-46 ppm (dry) of HCl concentration in exhaust gas. Hg oxidation performance of catalyst became higher as the temperature was lower and the HCl concentration in exhaust gas was higher. Hg oxidation rate drops more sharply at high temperature side as the HCl concentration is lower, which strongly shows the effect of HCl concentration.

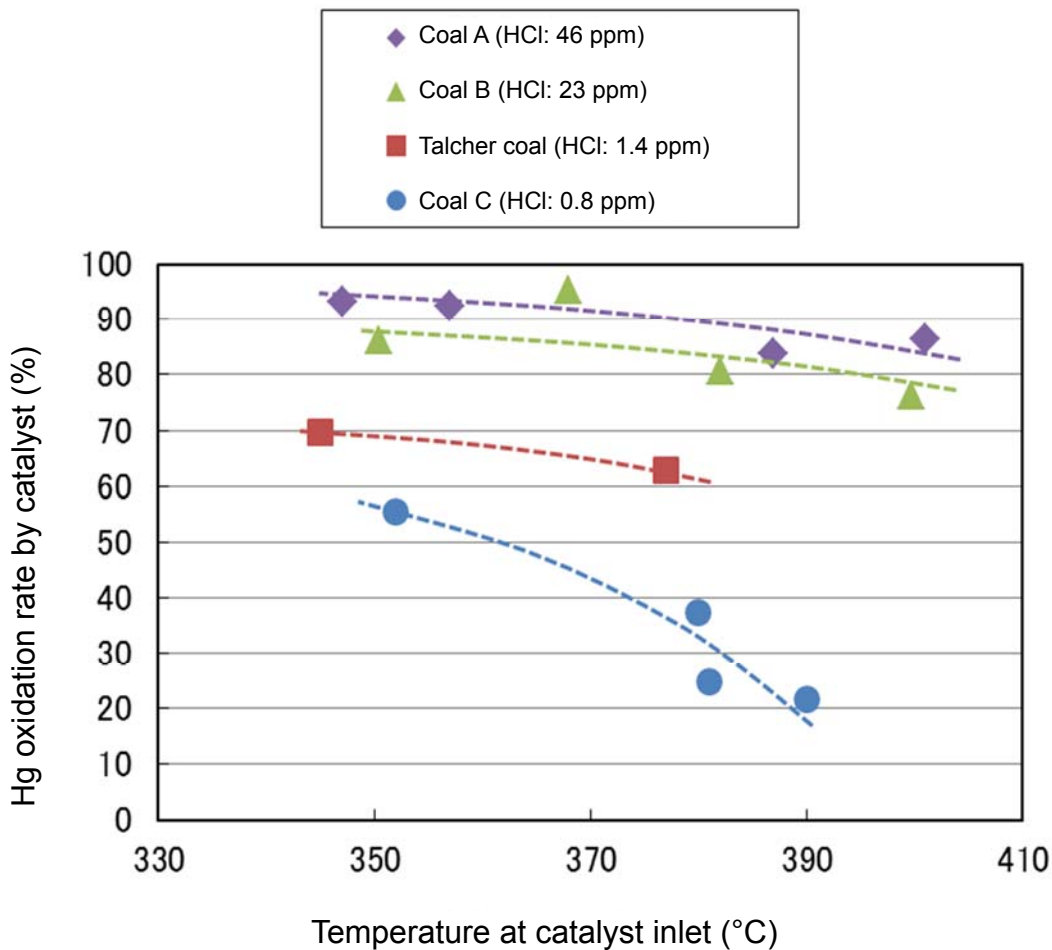


Figure 8-1. Effect of temperature on Hg oxidation rate in denitrification catalyst

Relation between HCl concentration in exhaust gas and Hg oxidation rate is shown in Figure 8-2 by classifying temperature at catalyst inlet into 350-360°C and 380-390°C. Hg oxidation rate is sharply increased as HCl concentration is higher when the HCl concentration is around 5 ppm or less, and reaches the ceiling when the HCl concentration is around 20 ppm or more. Since the HCl concentration of Talcher coal is low of 1.4 ppm, the Hg oxidation rate in catalyst was low such as 70% at around 350°C of inlet temperature and 63% at around 380°C of that. However, it was confirmed that it was reasonable level by comparing with other coals in both terms of temperature and HCl concentration.

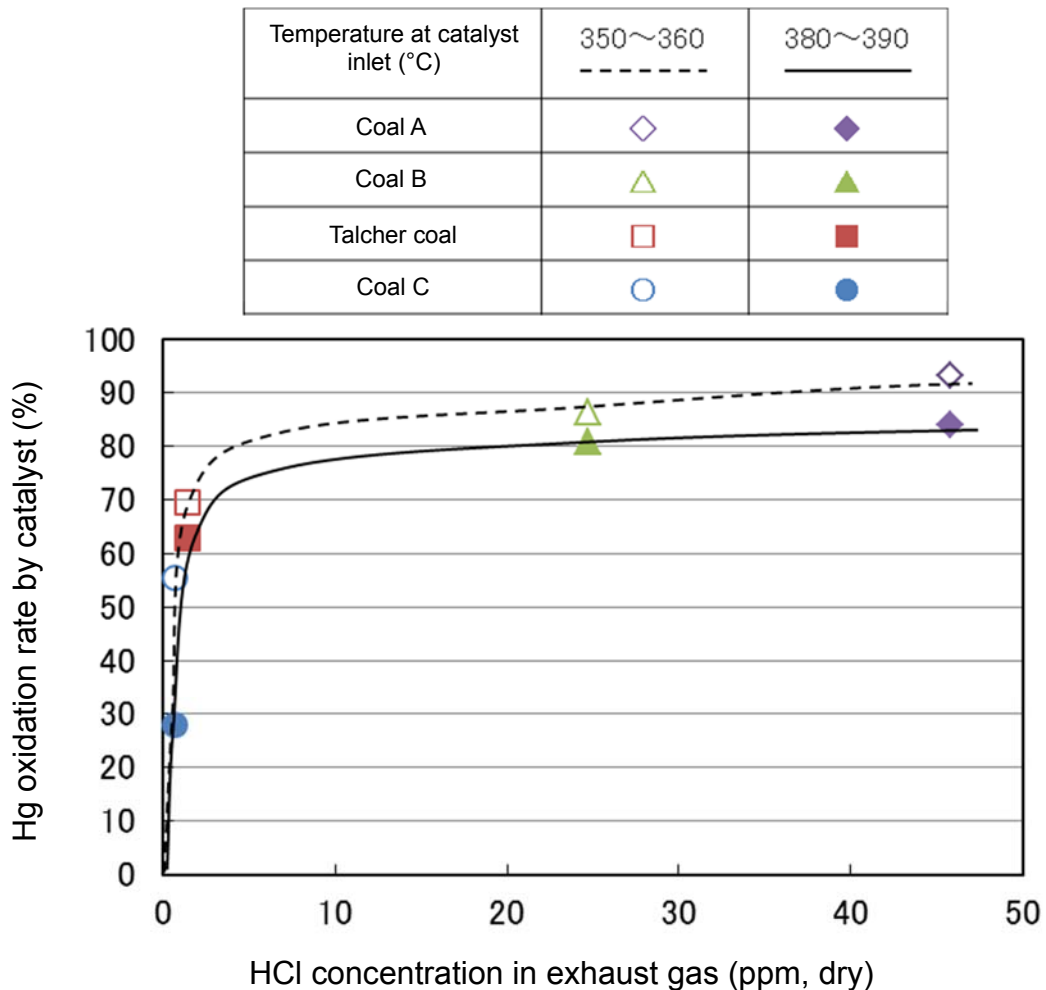


Figure 8-2. Effect of HCl concentration in exhaust gas on Hg oxidation rate in denitrification catalyst

## 8.2 Effect of temperature of dry EP on mercury removal performance

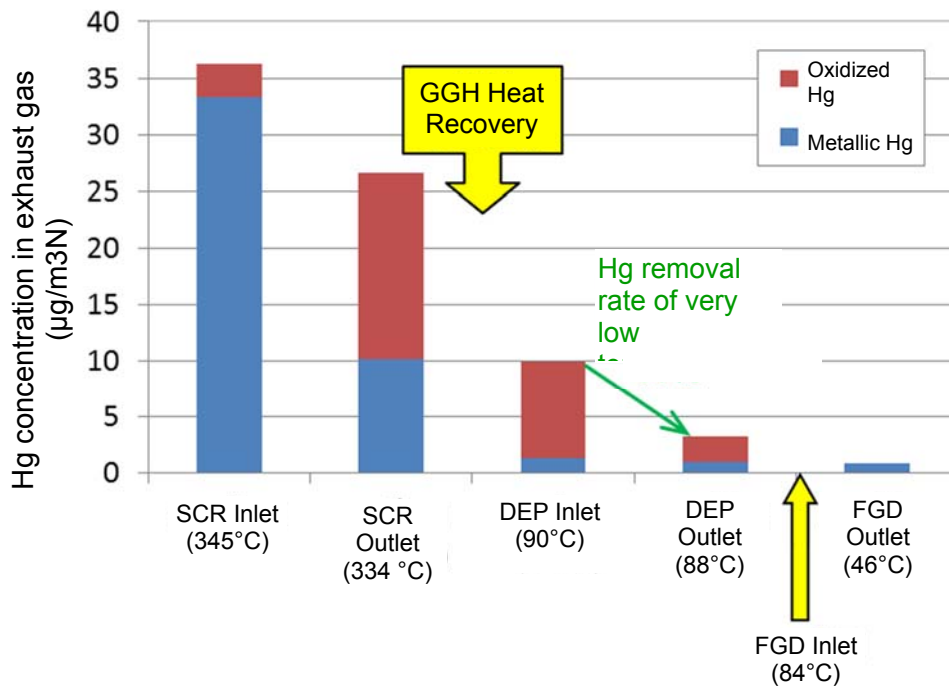
### 8.2.1 Test at the Combustion-AQCS Integrated Facility

Behavior of Hg in exhaust gas from inlet to outlet of denitrification is shown in Figure 8-8 as to (a) the high-performance smoke dust removal system (very low temperature EP conditions) and (b) the conventional system (low temperature EP conditions). The formula of oxidized Hg =  $Hg(2+) + Hg(p)$  is applied to the figure. Total Hg concentration is gradually decreased from inlet of the denitrification catalyst to EP inlet. This is because gaseous oxidized Hg has adsorptivity and a part of it which adsorbed ash drops and deposits inside the facility and is lost from the gas.

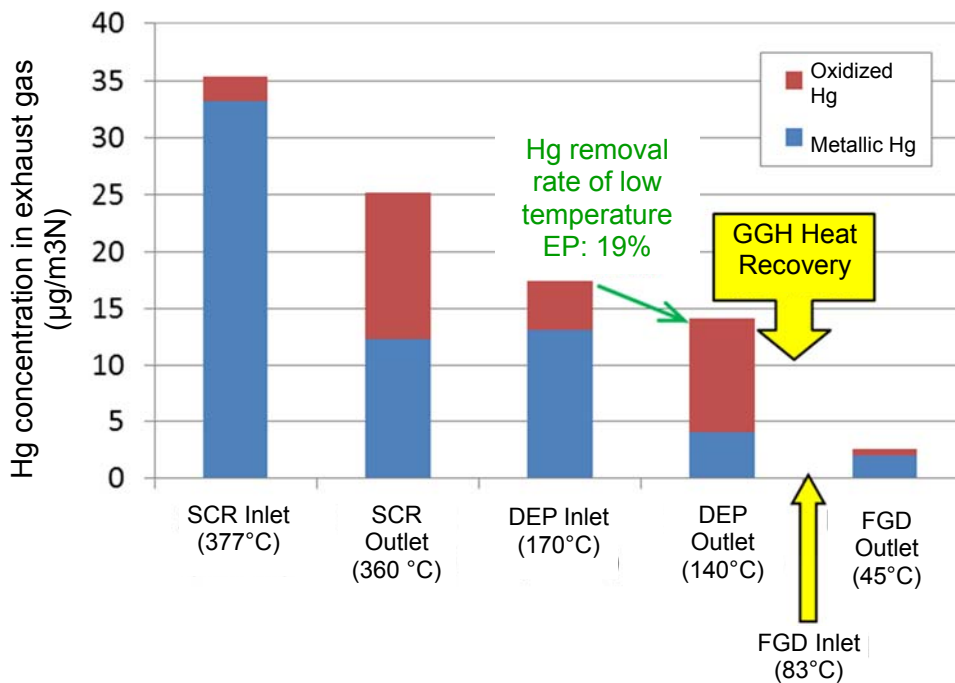
Hg removal rate in DEP calculated from Hg concentration in exhaust gas at inlet and outlet of DEP was 68% for the high-performance smoke dust removal system and 19% for the conventional system, then, it was confirmed that very low temperature EP is effective for Hg removal. This is an effect of lowering operation temperature of DEP which promotes Hg adsorption on smoke dust and raises smoke dust removal rate in DEP.

Considering about metallic Hg (measurement accuracy is high because it does not have adsorptivity), under the very low temperature EP condition, the amount of metallic Hg sharply dropped from SCR outlet to DEP inlet, but hardly changed at DEP inlet, DEP outlet and FGD outlet. On the other hand, under the low temperature EP condition, the amount of metallic Hg hardly changed from denitrification outlet to DEP inlet and dropped from inlet to outlet of DEP and from DEP outlet to FGD inlet. This difference of Hg behavior is considered to be effected by the position of GGH heat recovery device which is installed between catalyst outlet and DEP inlet in the high-performance smoke dust removal system and installed between DEP outlet and FGD inlet in the conventional system. Due to the difference of the layout, the exhaust gas temperature at DEP inlet dropped to 90°C in the high-performance smoke dust removal system, while it dropped only to 170°C in the conventional system. On the other hand, from DEP outlet to FGD inlet, the temperature hardly changed (88 → 84°C) in the high-performance smoke dust removal system, while it dropped (140 → 83°C) in the conventional system. In addition, heat dissipation from the test facility is large because it is smaller than actual equipment and, when using low temperature EP, it caused temperature difference (170 → 140°C) between inlet to outlet. Like this, since the place where metallic Hg was reduced (oxidized) corresponded to the

place where the exhaust gas temperature dropped, it was suggested that Hg oxidization is promoted by lowering the exhaust gas temperature.



(a) High-performance smoke dust removal system



(b) Conventional system (low)

Figure 8-8. Hg behavior throughout the entire exhaust gas treatment (when using SCR, effect of EP temperature)

With respect to Hg concentration at FGD outlet, in the high-performance smoke dust removal system, it was mostly accounted for by metallic Hg and low level of 1  $\mu\text{g}/\text{m}^3\text{N}$  or less, and most of oxidized Hg remaining in outlet of very low temperature EP was removed in FGD. On the other hand, Hg concentration at FGD outlet in the conventional system was rather high of 2.5  $\mu\text{g}/\text{m}^3\text{N}$ . However, since metallic Hg does not dissolve in desulfurization absorbing liquid, metallic Hg remaining in EP outlet is usually exhausted as is from FGD outlet, while 4  $\mu\text{g}/\text{m}^3\text{N}$  of metallic Hg which existed at outlet of low temperature EP in the conventional system was decreased to approx. half at FGD outlet. This also suggests that Hg oxidization was promoted by lowering temperature from EP outlet to FGD inlet and as a result, it is considered that Hg was removed by dissolving in FGD absorbing liquid as oxidized Hg. In addition, oxidized Hg remained much more at outlet of low temperature EP than outlet of very low temperature EP. This flows into FGD and it is inferred that Hg concentration in desulfurization absorbing liquid in the conventional system is much higher than that in the high-performance smoke dust removal system. When Hg concentration in desulfurization absorbing liquid becomes high, there is a risk that Hg which once dissolved is reduced and reemitted depending on liquid conditions including pH and concentration of sulfurous acid, and Hg concentration at FGD outlet is highly raised<sup>1),2)</sup>. Accordingly, high-performance smoke dust removal system using very low temperature EP can reduce the final amount of exhaust Hg more reliably.

### 8.2.2 Basic test

In the test at the Combustion-AQCS Integrated Facility, the difference of Hg removal rate in DEP between the conventional system and the high-performance smoke dust removal system was considered to be caused by the difference of exhaust gas temperature in DEP. In order to verify this, using the basic test device, the amount of Hg which adsorbed on coal ash was evaluated by making the temperature of the holder part which holds coal ash be 2 conditions of low temperature EP (160°C) and very low temperature EP (90°C). The results are shown in Figure 8-9. Hg concentration by chemical form under each condition was obtained by measuring Hg concentration in the gas at outlet of the reaction tube and in coal ash after supplying gas.

Under the very low temperature EP condition, out of Hg detected at outlet of the device, the amount of Hg which adsorbed on ash was 43% of the total Hg and higher than 2% of that under

the low temperature EP condition. From this, it was able to be confirmed that adsorption of Hg oxidized by denitrification catalyst on smoke dust is promoted by lowering exhaust gas temperature in DEP. However, comparing the results of the test at the Combustion-AQCS Integrated Facility and the basic test, the amount of Hg which adsorbed on smoke dust was smaller in the basic test. This is considered to be caused by the difference of contact conditions of the gas containing Hg and smoke dust. In the basic test, a method in which the gas passes through the ash layer was used and the contact condition of the gas and smoke dust was close to bag filter. Although the contact efficiency was better than DEP, the contact time of the gas and the ash layer in the basic test was extremely shorter of 0.06 seconds than the staying time of exhaust gas in DEP (approx. 7 seconds) in the test at the Combustion-AQCS Integrated Facility and it caused the small amount of adsorption. In addition, Hg(0) ratio is different between the low temperature EP condition and the very low temperature EP condition. This is probably because, since the temperature of the holder part was set lower under the very low EP condition, Hg was oxidized by low temperature in addition to by catalyst as shown in the test at the Combustion-AQCS Integrated Facility.

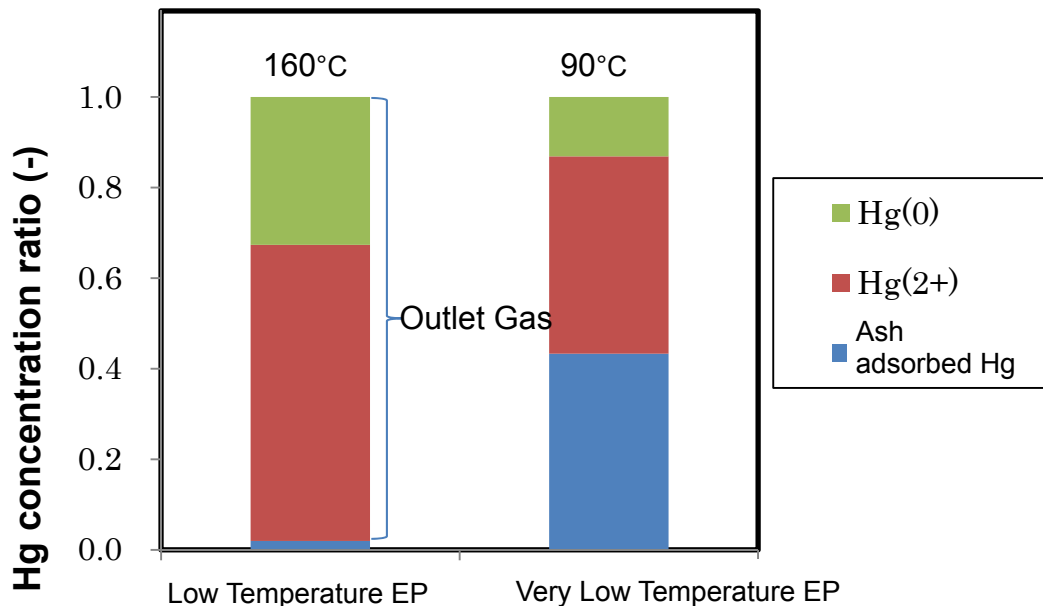


Figure 8-9. Characteristics of Hg adsorption on coal ash (results of basic test)



### 8.3 Mercury removal performance when adding activated carbon

#### 8.3.1 Test at the Combustion-AQCS Integrated Facility

Hg (T) concentrations in exhaust gas at DEP outlet and FGD inlet when adding powdered activated carbon to exhaust gas before DEP are shown in Figure 8-10. Assuming actual conditions of India, the activated carbon addition test was conducted without denitrification catalyst (SCR) (bypass) and in the conventional system (low temperature EP).

Although Hg concentration in exhaust gas at EP outlet was 29  $\mu\text{g}/\text{m}^3\text{N}$  without activated carbon and gradually dropped as more amount of activated carbon was added, it was still high of 21  $\mu\text{g}/\text{m}^3\text{N}$  after adding the maximum amount of 0.18  $\text{g}/\text{m}^3\text{N}$ . The reason why Hg removal effect by activated carbon was small in this test is considered later together with evaluation of Hg removal rate in DEP.

Hg concentration in exhaust gas at FGD outlet was around 10  $\mu\text{g}/\text{m}^3\text{N}$  whether or not activated carbon was added to exhaust gas. This is probably because Hg concentration at DEP outlet was not reduced significantly by adding activated carbon.

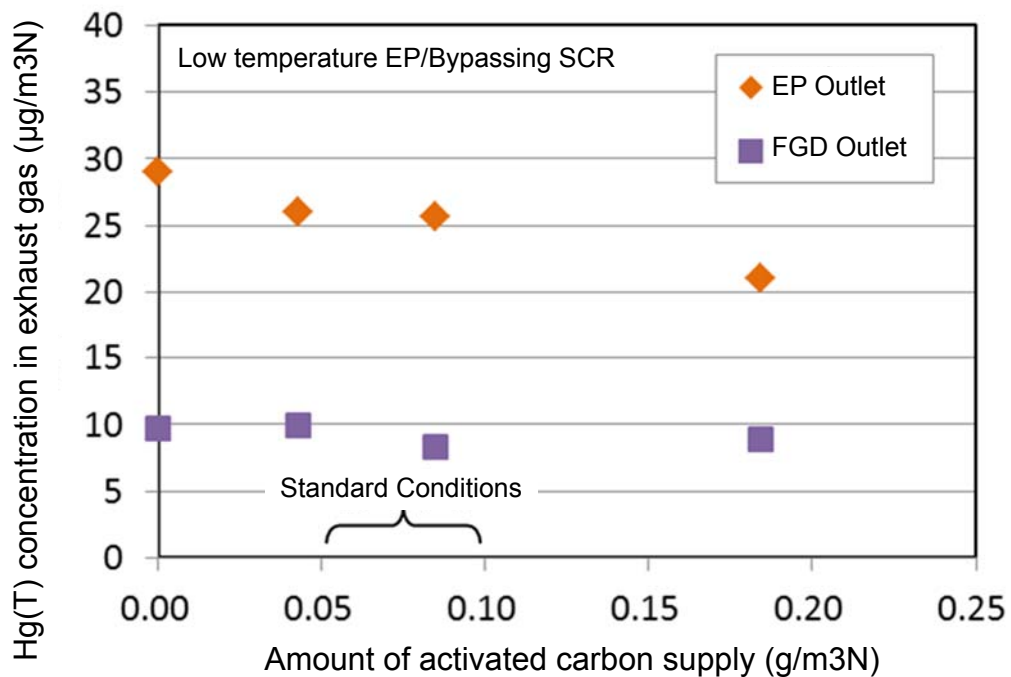


Figure 8-10. Hg (T) concentration in exhaust gas at EP outlet and FGD outlet at the activated carbon addition test (SCR bypass, low temperature EP condition)

Hg removal rate in low temperature EP at the activated carbon addition test is shown in Figure 8-11 by comparing with other systems. Hg removal rate without activated carbon is 13% when using low temperature EP and bypassing catalyst, 35% when using low temperature EP and catalyst and 70% when using very low temperature EP and catalyst, then, it is able to be confirmed that use of catalyst and lowering the temperature of DEP to very cold is effective on Hg removal. When using low temperature EP and bypassing catalyst, although the Hg removal rate became higher as more amount of activated carbon was added, it was only 33% when adding the maximum additive amount (0.18 g/m<sup>3</sup>N) and the Hg removal performance was less than that of the case where low temperature EP and SCR were used without activated carbon. It is considered that, since the coal ash has reserve capacity of Hg adsorption because the smoke dust concentration in exhaust gas of Talcher coal is very high as well as Hg is difficult to be oxidized without catalyst because the HCl concentration is very low, the promotion of Hg oxidization by catalyst more contributes to improvement of Hg removal rate in DEP than increase in adsorption site by adding activated carbon.

In addition, the Hg removal rate in very low temperature EP with catalyst was good, approx. twice as great as that of low temperature EP. In very low temperature EP, the adsorption amount of SO<sub>3</sub> on smoke dust is increased because the exhaust gas temperature is lower than the sulfuric acid dew point. Therefore, if SO<sub>3</sub> concentration is high, Hg adsorption is usually disturbed and the Hg removal rate declines<sup>3),4)</sup>. In fact, the gaseous SO<sub>3</sub> concentration was high of 15 ppm at inlet of low temperature EP, while it was 1 ppm or less at inlet of very low temperature EP, then, most of SO<sub>3</sub> seems to adsorb on ash within the GGH heat recovery device. However, it is considered that, since the ratio of the smoke dust concentration to the SO<sub>3</sub> concentration is very high, adsorption site of ash was not occupied by SO<sub>3</sub> and the Hg removal rate did not decline.

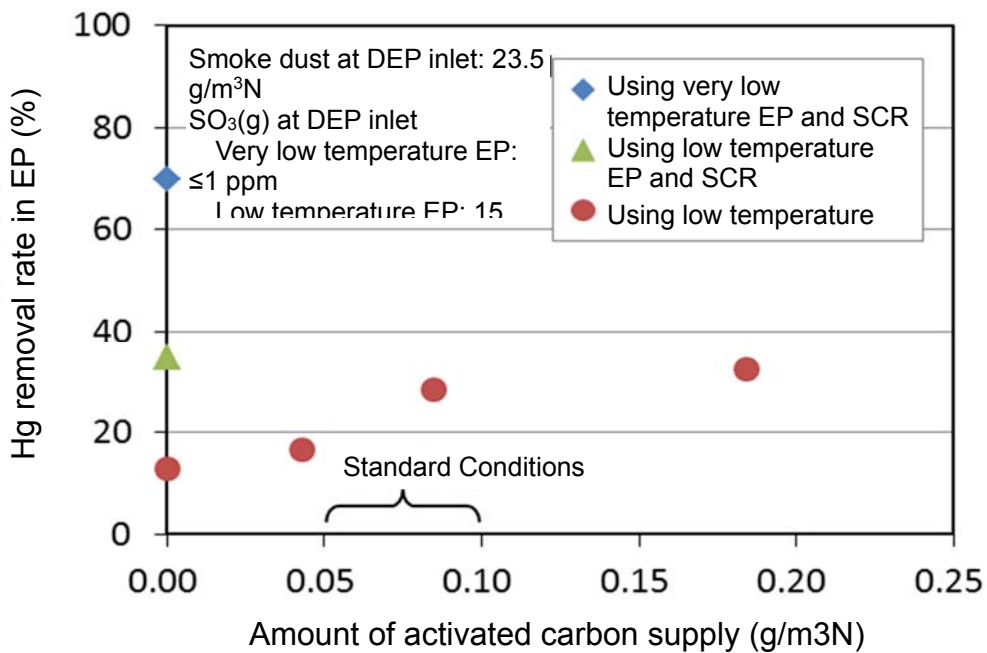


Figure 8-11. Effect of activated carbon, catalyst and EP temperature on Hg removal rate in DEP

### 8.3.2 Basic test

The Hg removal rate by addition of activated carbon in the test at the Combustion-AQCS Integrated Facility was verified with the basic test device. In this consideration, the amount of adsorbed Hg on coal ash including activated carbon with and without Hg oxidization by catalyst was evaluated. As shown in Table 7-3, the amount of mixed activated carbon was 0.4 wt% of coal ash.

The result is shown in Figure 8-12. When Hg was not oxidized by bypassing denitrification catalyst under the low temperature EP condition, Hg adsorption on coal ash including activated carbon was a little. This is a similar trend to the result of the test at the Combustion-AQCS Integrated Facility in which Hg removal effect by adding activated carbon was low, and supports that the promotion of Hg oxidization by catalyst is more effective on improvement of Hg removal rate in DEP than increase in adsorption site by adding activated carbon. In addition, when Hg was oxidized by denitrification catalyst, the amount of Hg adsorption on coal ash including activated carbon was increased even in low temperature EP, but the effect was higher in very low temperature EP.

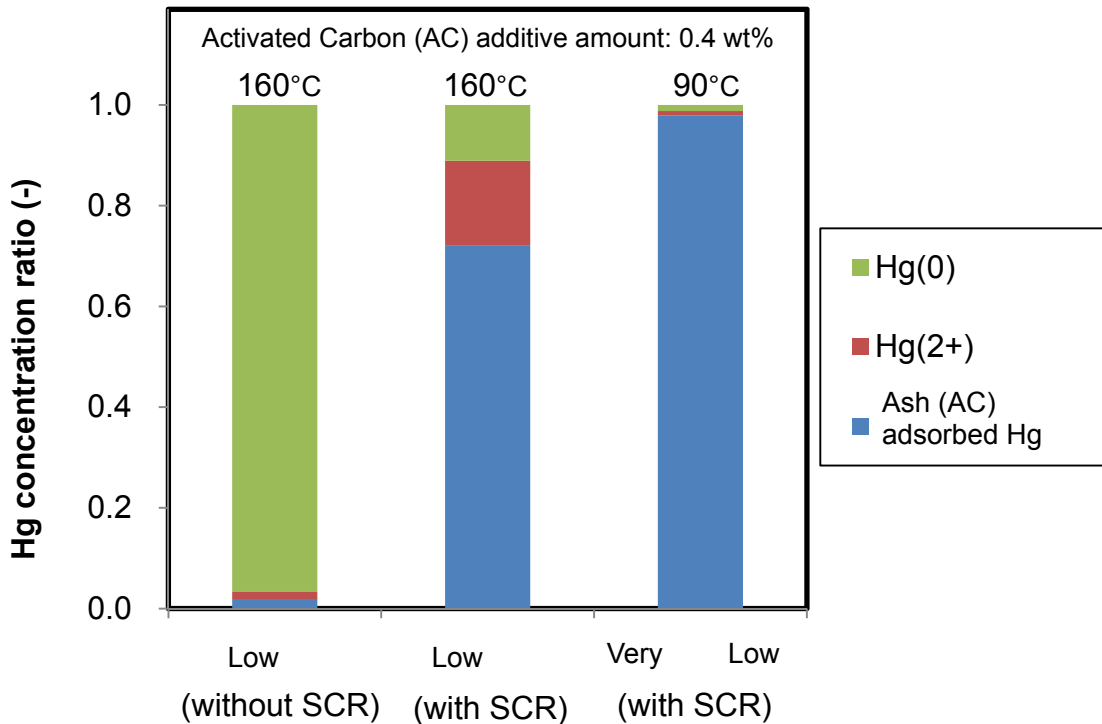


Figure 8-12. Characteristics of Hg removal by activated carbon (results of basic test)

### 8.3.3 Consideration of cost

Assuming that 0.2 g/m<sup>3</sup>N of activated carbon is supplied in an actual equipment equivalent to 600MW (process gas amount: 2,000,000 m<sup>3</sup>N/hr) and the price of activated carbon is \$1/kg, required annual cost is calculated as approx. \$3,200,000.

As a result of this test, when using low temperature EP and bypassing catalyst, the Hg removal rate in DEP with addition of approx. 0.2 g/m<sup>3</sup>N of activated carbon remained only 33%. On the other hand, when activated carbon was not added, the Hg removal rate in DEP was 35% in the case of using low temperature EP and catalyst and 70% in the case of using very low temperature EP and catalyst. Accordingly, it can be said that it is possible to obtain higher Hg removal effect in DEP than activated carbon by applying the high-performance smoke dust removal system consisting of very low temperature EP and catalyst.

[Chapter 4 Reference]

- 1) C. Senior, Review of the role of aqueous chemistry in mercury removal by acid gas scrubbers on incinerator systems: Environ Eng Sci 24(8), 2007
- 2) N. Omine et.al., Study of elemental mercury re-emission in a simulated wet scrubber: Fuel, Vol.91, Issue 1, 2012
- 3) J. Jervis & F. Meselole: SO<sub>3</sub> Effect on Mercury Control : Power Engineering, January, 2008
- 4) N. Imada et.al., Development of Mercury and SO<sub>3</sub> Control Technology using Gas-Gas Heater: The 35rd International Technical Conference on Coal Utilization & Fuel Systems, 2010

## 9. SUMMARY OF MERCURY REMOVAL

Since Talcher coal from India contains high concentration of mercury (Hg) and very low concentration of chlorine (Cl), there was a possibility that the oxidation rate and the removal rate of mercury fell to the low level. In view of the aforesaid, under the Study, mercury behavior and removal characteristics were evaluated with the Combustion-AQCS Integrated Facility and the basic testing equipment in the laboratory.

Main results are described below.

### (1) Mercury oxidization performance by catalyst

Although Hg oxidization rate in denitrification catalyst (high mercury oxidation-type catalyst manufactured by MHPS) was rather low of 70% at around 350°C of the temperature at catalyst inlet and 63% at around 380°C of that, considering Talcher coal contains low concentration of HCl, it is considered as reasonable oxidation performance by comparing with other types of coal.

### (2) Mercury removal performance in DEP

Hg removal rate in DEP was 70% in the high-performance smoke dust removal system (using very low temperature EP and catalyst) and 35% in the conventional system (using low temperature EP and catalyst), then, it was confirmed that very low temperature EP is effective on Hg removal.

### (3) Mercury removal performance at the time of adding activated carbon

Hg removal rate becomes higher in the order of using very low temperature EP and catalyst > using low temperature EP and catalyst > using low temperature EP and bypassing catalyst (with the maximum amount of activated carbon) > using low temperature EP and bypassing catalyst (without activated carbon), then, catalyst had more Hg removal effect than addition of activated carbon. It is probably because the ash has reserve capacity of Hg adsorption even without activated carbon due to the high smoke dust concentration and Hg is hardly oxidized without catalyst due to the very low HCl concentration. Also in the basic test with a

small electric furnace, it was confirmed that the amount of Hg which adsorbs on coal ash including activated carbon is significantly increased by installing catalyst (Hg oxidization).

#### (4) Economic evaluation

Assuming that 0.2 g/m<sup>3</sup>N of activated carbon is supplied in an actual equipment equivalent to 600MW (process gas amount: 2,000,000 m<sup>3</sup>N/hr) and the price of activated carbon is \$1/kg, required annual cost is calculated as approx. \$3,200,000. In addition, the Hg removal rate in DEP when adding approx. 0.2 g/m<sup>3</sup>N of activated carbon was equal to that of the conventional system with low temperature EP and SCR. Furthermore, when applying the high-performance smoke dust removal system consisting of very low temperature EP and SCR, the Hg removal rate was significantly higher than that of the case where 0.2 g/m<sup>3</sup>N of activated carbon was added.

## 10. TECHNICAL INFORMATION, DESULPHURIZATION AND DENITRIFICATION

10.1 Desulfurization performance depending on the difference of desulfurization method (dry, semi-dry and wet)

Flue gas treatment technologies used in thermal power plants, especially in coal-fired power plants are classified into “wet treatment” and “dry treatment” as showed in Figure 10-1.

Since flue gas from coal-fired boilers contains nitrogen oxides, sulfur oxides and smoke dust in large quantities, denitrification device, desulfurization device and electrostatic precipitator are installed. Especially the smoke dust causes blocking and pressure loss by adhesion to the inside wall or deposit. It is therefore required to construct a system and design each facility by taking into account for them. In Japan, wet treatment is mainly used.

Although heavy oil has been mainly fired in thermal power plants until the oil shock and an electrostatic precipitator (EP) was once installed before denitrification device in consideration of adhesion/corrosion due to  $\text{SO}_3$  in the exhaust gas and acid ammonium sulfate generated by chemical reaction with  $\text{NH}_3$  used for denitrification, after the oil shock, as coal-fired power has become main-stream, the operation temperature of EP has been lowered. This is because, in the case of coal-fired boilers, the smoke dust concentration in the exhaust gas is very high of 10-20  $\text{g}/\text{m}^3\text{N}$  and the dust collection performance of EP is more efficient at lower temperature. In a flow in the second column, the smoke dust concentration at the stack outlet becomes around 15-25  $\text{mg}/\text{m}^3\text{N}$  by providing a dust removing tower called cooling tower to the desulfurization device (FGD).

In addition, a flow in the third column enables reduction of the smoke dust concentration at the stack outlet to 5  $\text{mg}/\text{m}^3\text{N}$  or less by adding a dry EP to it.

Currently, by use of “very low temperature EP” in which EP is installed after a gas-gas heater (GGH), called high-performance system, there is a process that achieves the smoke dust concentration at the stack outlet of 5  $\text{mg}/\text{m}^3\text{N}$  or less without a wet EP. This high-performance system can remove  $\text{SO}_3$  in the exhaust gas without a wet EP.



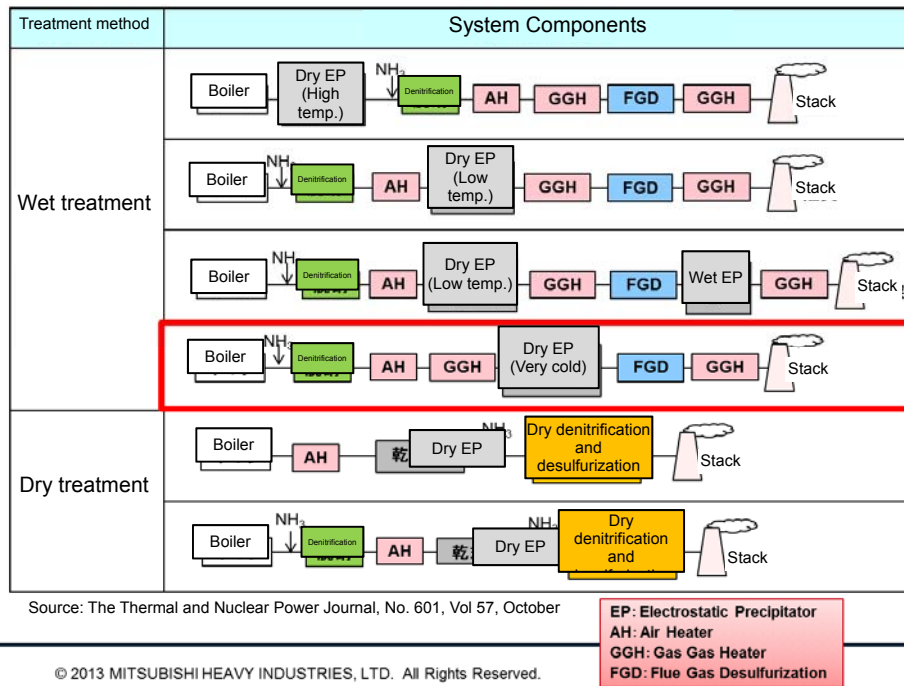


Figure 10-1 Comparison of flue gas treatment of “Wet” and “Dry” process

Furthermore, flue gas desulfurization processes are also roughly classified into “wet method,” “dry method” and “semi-dry method.” Under the current situation, the great majority adopts wet methods and, especially as a large-volume exhaust gas treatment process for thermal power plants, one of the wet methods, “lime-gypsum process” becomes main-stream around the world. Typical processes are shown in Tables 10-1 and 10-2.

Table 10-1. Types of flue gas desulfurization processes

	Process Name	Outline of the Process	Implementation Status
Wet method	Lime-gypsum process	<ul style="list-style-type: none"> <li>Absorb SO<sub>2</sub> by alkaline aqueous solution or slurry</li> <li>Oxidize generated sulfite and add it to sulfate as necessary</li> </ul>	Implemented in many large-to-medium scale plants
	Magnesium hydroxide process	<ul style="list-style-type: none"> <li>Recover and utilize or dispose the product material</li> <li>A process is also proposed in which generated sulfite is dissolved and converted into high-concentration SO<sub>2</sub> gas, and then, sulfuric acid, etc. for recovery.</li> </ul>	Implemented in many small scale plants
	Soda process	<ul style="list-style-type: none"> <li>There are several processes depending on the type of alkali used.</li> </ul>	Applied to glass and pulp industries and small scale plants

Dry method	Activated carbon adsorption process	<ul style="list-style-type: none"> <li>• Adsorb SO<sub>2</sub> by activated carbon</li> <li>• Heat and desorb adsorbed SO<sub>2</sub>, recover high-concentration SO<sub>2</sub> and convert it into sulfuric acid or sulfur, etc.</li> </ul>	Operated in some plants
	Electron beam process	<ul style="list-style-type: none"> <li>• Irradiate with electron beam in the presence of ammonia</li> <li>• Catch the product material by dust collector</li> </ul>	Demonstration test is implemented in the past
	Coal ash utilization process	<ul style="list-style-type: none"> <li>• Utilize pellets made by mixing coal ash, calcium hydroxide and used absorbent as an absorbent</li> <li>• It is also an effective utilization method of coal ash</li> </ul>	The study is promoted in Hokkaido where the proportion of coal-fired power generation is high and 1 plant is under operation therein.
	Furnace desulfurization process	<ul style="list-style-type: none"> <li>• Use limestone as the bed material of the fluidized bed boiler and perform furnace desulfurization.</li> <li>• Mix limestone with coal and remove SO<sub>2</sub> in the high-temperature furnace.</li> </ul>	Adopted by pressurized fluidized bed boilers of power plants inside and outside Japan
Semi-dry method	Spray drying process	<ul style="list-style-type: none"> <li>• Convert SO<sub>2</sub> into powder of calcium sulfite, etc., by spraying slaked lime slurry into the reaction tower</li> <li>• Catch them by dust collector and dispose the collected materials.</li> </ul>	Many implementations in Europe and the U.S.

Source: National Institute for Environmental Studies, Japan, Description of environmental engineering, Flue gas desulfurization technology

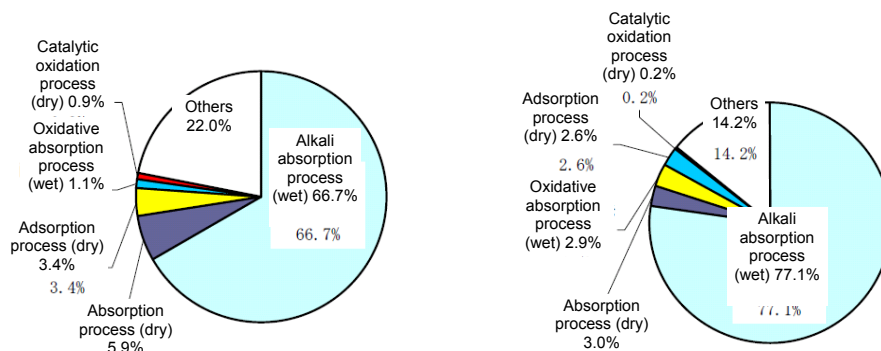


Figure 10-2. Processing method/capacity of flue gas desulfurization device

Source: Ministry of the Environment, Investigation of fixed sources concerning the atmospheric environment for FY 2004

Table 10-2. Characteristics of flue gas desulfurization processes

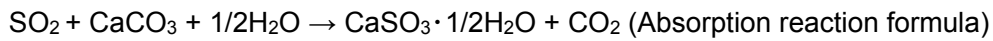
Classification	Desulfurization process	Absorbent or Adsorbent	By-product (Treatment)	Characteristics (Desulfurization rate, cost, etc.)
Wet	Lime slurry absorption process (such as lime-gypsum process)	Limestone, slaked lime, dolomite, fly ash	Gypsum (recovery), sludge (including calcium sulfite) (disposal)	Desulfurization rate: 90% or more Cost of equipment: Expensive
	Magnesium hydroxide slurry absorption process	Magnesium hydroxide	Gypsum (recovery), magnesium sulfate (disposal)	Desulfurization rate: 90% or more
	Alkali solution absorption process	Sodium hydroxide, sodium sulfite, ammonia water, etc.	Sodium sulfite, sulfur/sulfuric acid, ammonium sulfate (recovery)	Desulfurization rate: 90% or more
	Double alkali process	Soda, ammonia, aluminum sulfate	Gypsum (recovery)	Desulfurization rate: 90% or more
	Oxidative absorption process	Catalyst added dilute sulfuric acid	Gypsum (recovery)	Desulfurization rate: 85 to 90%
Semi-dry	Spray dryer process	Slaked lime, sodium bicarbonate, soda ash hydrothermal curing agent (using coal ash)	Calcium sulfite, gypsum (disposal or use for landfill)	Desulfurization rate: 70 to 85% The amount of water used is less than wet method
Dry	Furnace desulfurization process	Limestone, slaked lime, steam curing agent (using coal ash)	Calcium sulfite, gypsum (disposal or use for landfill)	Desulfurization rate: Around 80%
	Activated carbon absorption tower process	Activated carbon (activated coke)	Sulfuric acid (sulfur, fluid SO <sub>2</sub> ) (recovery)	Desulfurization rate: 80% Activated carbon is expensive
	Electron beam process	Ammonia	Ammonium sulfate (recovery)	Desulfurization rate: 80 to 95% Expensive Simultaneous desulfurization and denitrification

Source: Environmental Conservation Simulation in Tianjin City (III) - Introduction of environmental /energy technology suited to urban and rural area

Additional explanations about typical desulfurization processes are provided below.

(a) [Wet method] Lime-gypsum process

In this process, limestone (CaCO<sub>3</sub>) which is alkaline component is converted into slurry and reacted with SO<sub>2</sub> within the absorption tower, then, SO<sub>2</sub> is absorbed and gypsum (CaSO<sub>4</sub> · 2H<sub>2</sub>O) is recovered as the by-product. Recovered gypsum is sold as gypsum board or cement additive. It is therefore adopted by large-sized boilers including thermal power plants.



As specific processes, there are spray process in which absorption solution is sprayed to exhaust gas to make it react with SO<sub>2</sub>, grid process in which absorption solution is flowed on the surface of grid-like filler, and liquid column process in which the agent is sprayed upward, etc.

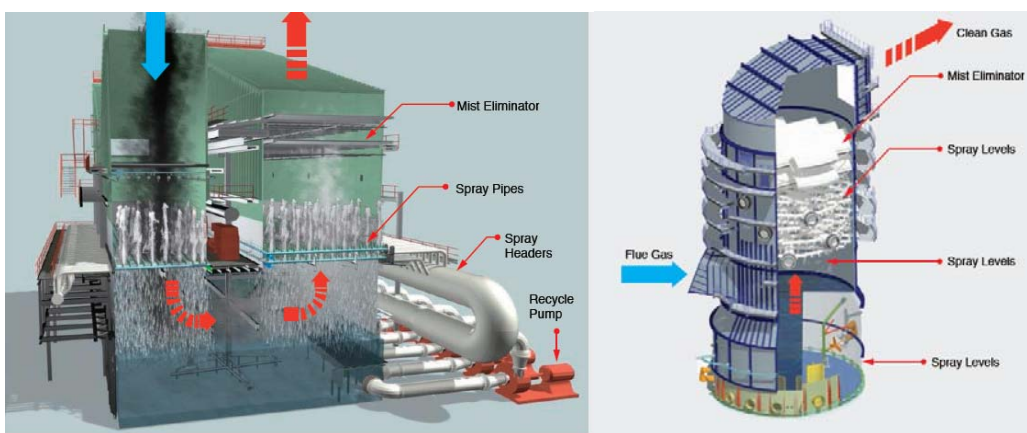


Figure 10-3. Liquid column tower (concurrent two-phase flow) Figure 3. Spray tower

Source: Brochure of MITSUBISHI HITACHI POWER SYSTEMS, LTD.

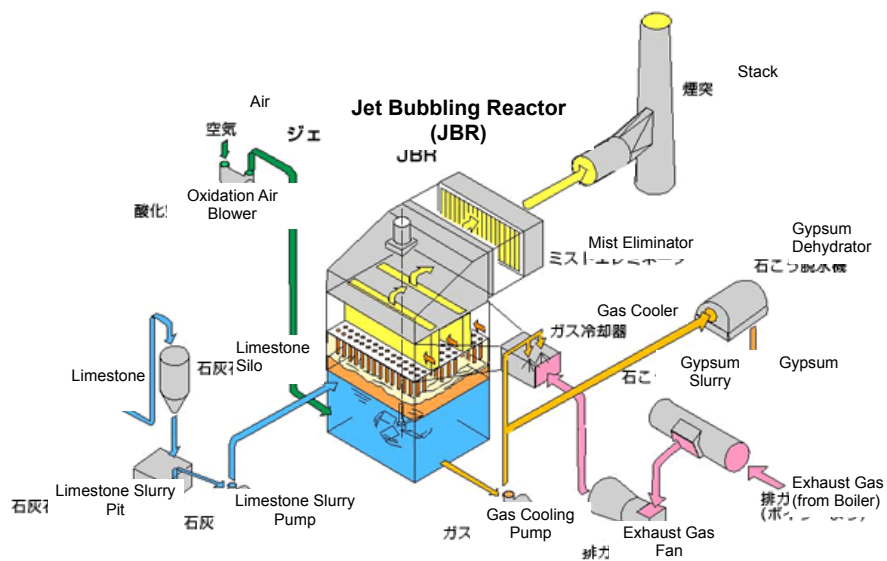


Figure 10-4. Jet bubbling type absorption tower

Source: Chiyoda Corporation website

(b) [Wet method] Magnesium hydroxide process

Since lime-gypsum process requires complicated gypsum recovery process and wastewater treatment process, many small-sized boilers adopt “magnesium hydroxide process” using magnesium hydroxide which is small-scale and the cheapest alkali second to lime. The flow of magnesium hydroxide process is almost same as that of lime-gypsum process except for gypsum recovery process.

By-product of this process is soluble magnesium sulfate and facilities are therefore simplified.

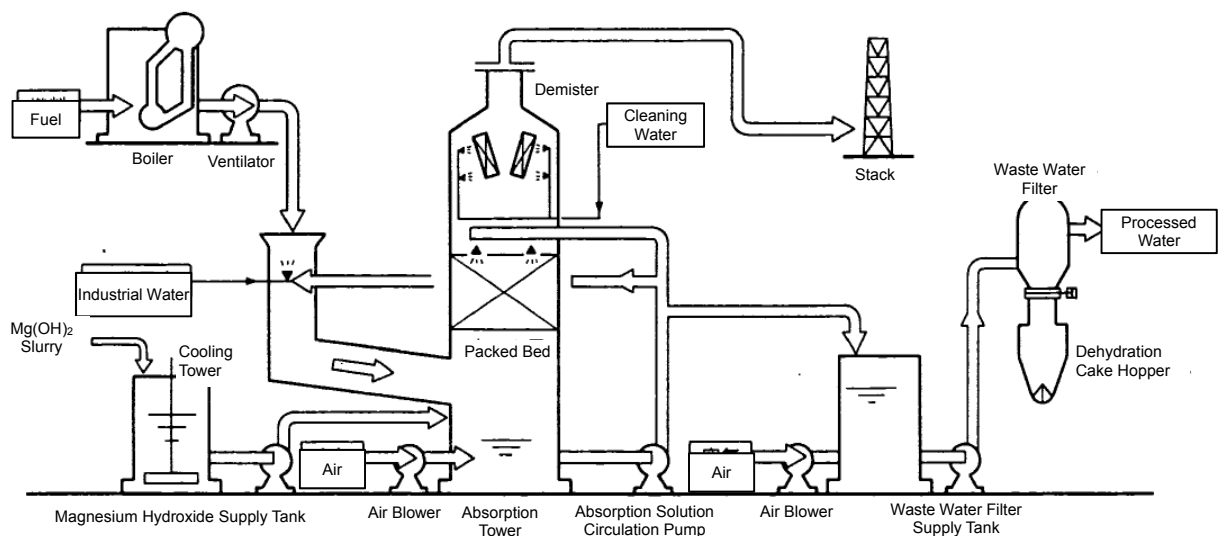
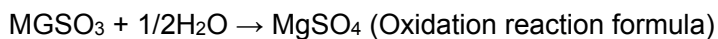
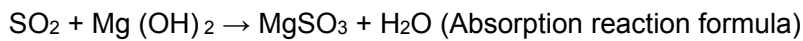


Figure 10-5. Process flow of magnesium hydroxide process

Source: Mitsubishi Heavy Industries Technical Review, vol.31 No.4 (1994-7)

(C) [Wet method] Soda process

In this process, caustic soda (NaOH) or sodium carbonate (Na<sub>2</sub>CO<sub>3</sub>) is used as the absorbent and reacted with SO<sub>2</sub> and sodium sulfite (Na<sub>2</sub>SO<sub>3</sub>) is generated. Na<sub>2</sub>SO<sub>3</sub> can be used as-is for

digestion of paper pulp. In addition, there is also a process which oxidizes  $\text{Na}_2\text{SO}_3$  into sodium sulfate ( $\text{NaSO}_4$ ) and discharges it as-is. Although this process was used by pulp factories or small-scale facilities in the late 1960's, it is replaced by cheaper magnesium hydroxide process because caustic soda as the absorbent is expensive and the operating cost is increased.

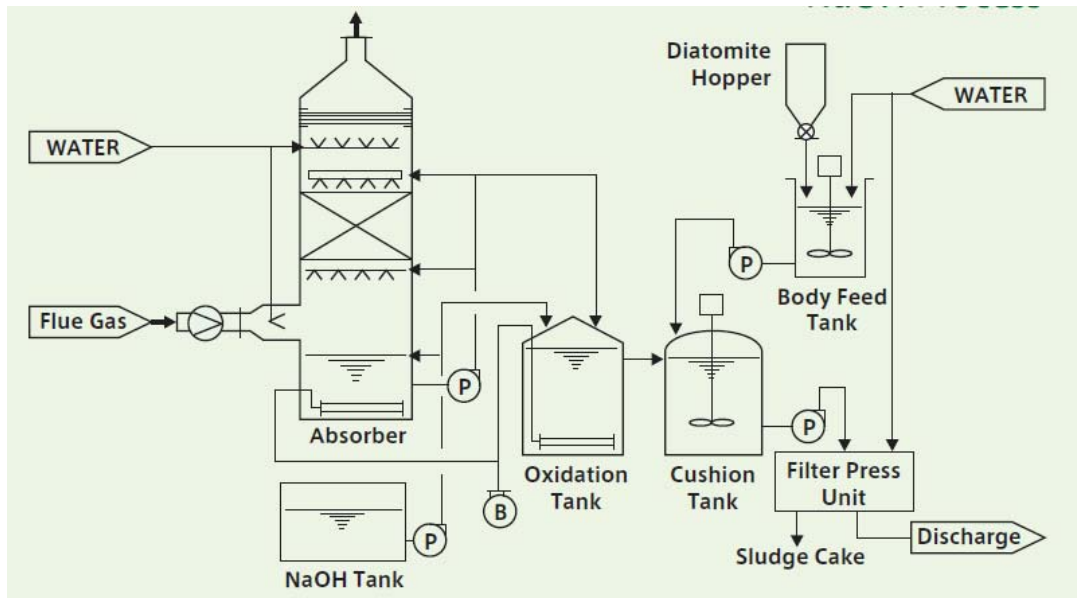


Figure 10-6. Process flow of caustic soda process

Source: Brochure of KUBOTA KASUI Corporation

(d) [Dry method] Activated carbon adsorption process

In this process, SO<sub>2</sub> is absorbed by activated carbon. In addition, this process is used as simultaneous desulfurization and denitrification technology. Furthermore, this technology can remove dioxin and heavy metal elements, etc.

The process flow of dry desulfurization and denitrification technology (called ReACT) is shown in Figure 6 and its reaction mechanism is shown in Figures 10-7 and 10-8.

In addition, ReACT has been delivered to Isogo Thermal Power Plant and meets the emission standard\*<sup>1</sup>).

\*<sup>1</sup>) Emission standard for Isogo Thermal Power Plant

Item	Unit	No.1 Unit	No.2 Unit
Sulfur oxides	ppm	20	10
Nitrogen oxides	ppm	20	13
Smoke dust	mg/m <sup>3</sup> N	10	5

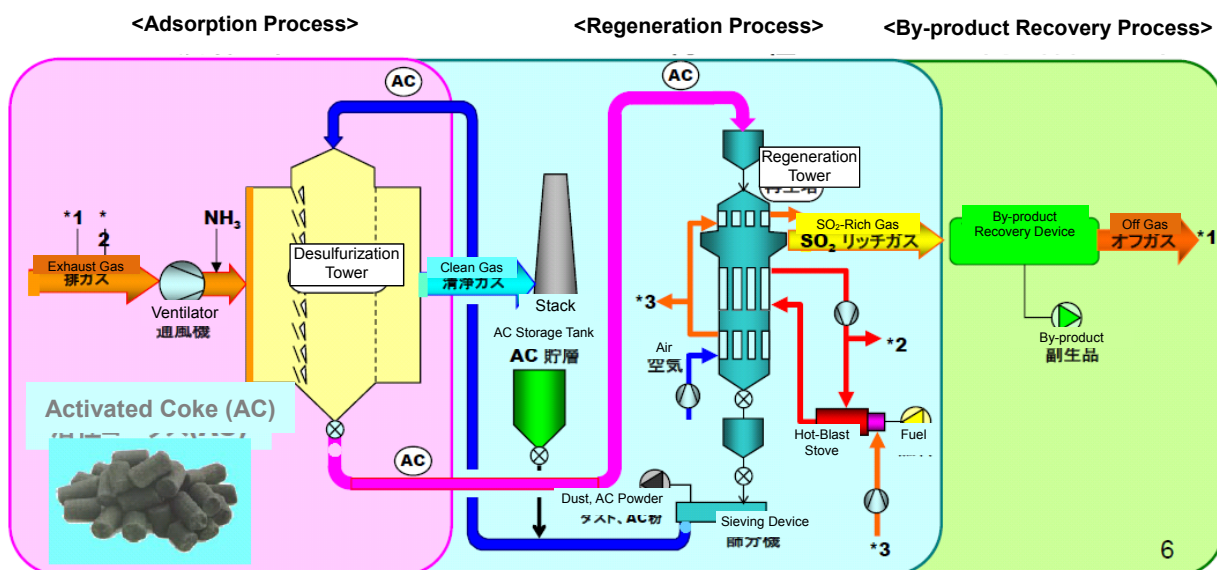
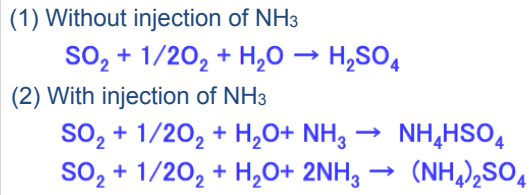


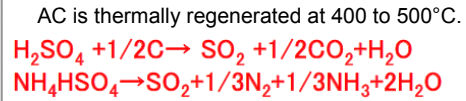
Figure 10-7. ReACT (Regenerative Activated Coke Technology)

Source: Dry desulfurization and denitrification technology (JCOAL first study meeting for FY 2014)

### Desulfurization Reaction Mechanism



### Regeneration Reaction



### Denitrification Reaction Mechanism

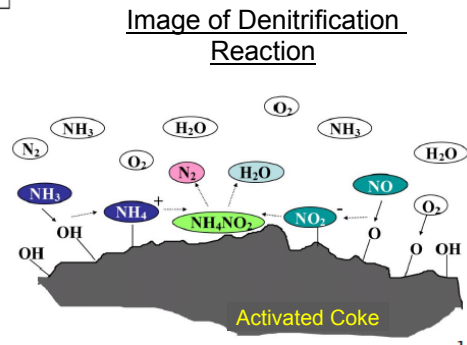
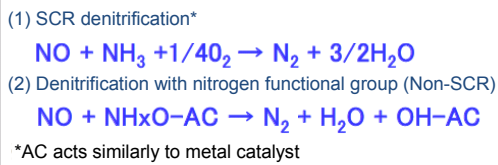
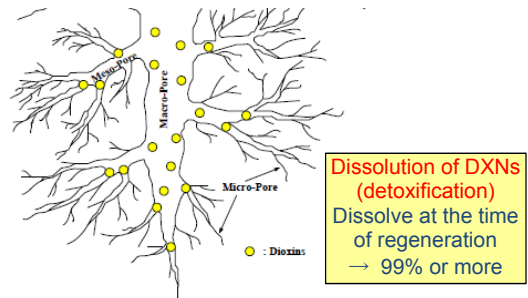


Figure 10-8. ReACT reaction mechanism (desulfurization/denitrification)

Source: Dry desulfurization and denitrification technology (JCOAL first study meeting for FY 2014)

### Dioxin Removal

Dioxins are adsorbed by AC in the adsorption tower and 99% or more of them are dissolved at the time of thermal regeneration in the regeneration tower at 400 to 500°C.



### Mercury Removal

Mercury is adsorbed by AC in the adsorption tower. The reaction formula is described at the right.

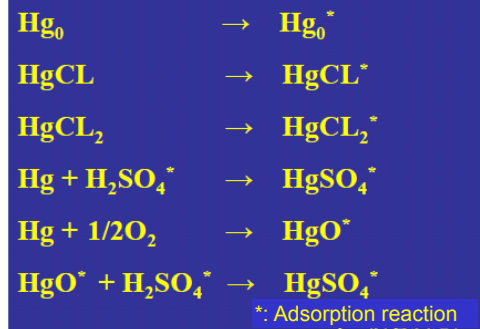


Figure 10-9. ReACT reaction mechanism (dioxin removal/mercury removal)

Source: Dry desulfurization and denitrification technology

(JCOAL first study meeting for FY 2014)



(e) [Dry method] Electron beam process

This is a process in which NO<sub>x</sub> and SO<sub>x</sub> in the exhaust gas and injected ammonia are irradiated with electron beam to be reacted and converted into particulates of ammonium sulfate or ammonium nitrate, then, they are recovered by dust collector. Ammonium sulfate, etc., which are the by-products can be used as fertilizer (Figure 10-9). Although there are such advantages that waste water treatment is not necessary and ammonium sulfate can be used as fertilizer, it remains in the step of demonstration test because the special facility to generate electron beam is required<sup>\*2)</sup>.

In addition, characteristics of the performance are that it achieves 98% or more of desulfurization rate and 80% of denitrification efficiency where NH<sub>3</sub>/NO molar ratio is around 1 at 70 to 120°C, and although the desulfurization performance does not effect on the inlet concentration of SO<sub>2</sub>, the denitrification efficiency is increased as the SO<sub>2</sub> concentration is higher.

<sup>\*2)</sup> In Japan, a pilot plant (gas treatment capacity: 12000 m<sup>3</sup>N/h) was constructed at the Shin-Nagoya Power Plant of Chubu Electric Power Co., Inc., and the technology was verified (1991 to 1994). Furthermore, a plant (Photo-2) with gas treatment capacity of 300 thousand m<sup>3</sup>N/h (90 thousand kW) was installed at the Chengdu Thermoelectric Plant (cogeneration power plant) in Sichuan, China and its demonstrated operation was made under the condition of 80% of desulfurization rate.

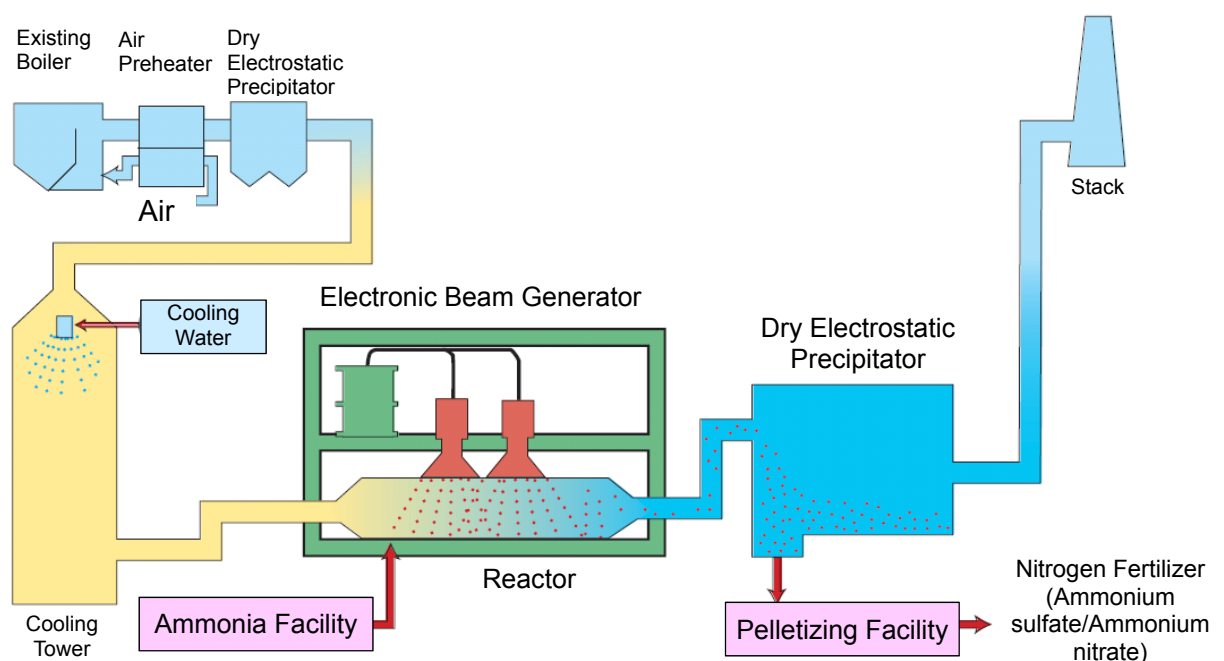


Figure 10-10. Process flow of electron beam process

Source: New Energy and Industrial Technology Development Organization/Japan Coal Energy Center, "Japanese Clean Coal Technologies (5B3. Simultaneous desulfurization and denitrification technology)"

## 10.2 Economy depending on the difference of desulfurization method (dry, semi-dry and wet)

There are few documents in which economy depending on the difference of desulfurization method is quantitatively evaluated and, in this research study, the description is only in “Preliminary research of desulfurization cost” written by Yoshitaka Nitta, et al. (Keio Economic Observatory) showed in Figure 10-10. In such document, assuming that desulfurization device for coal combustion becomes common in developing countries, its cost data is investigated based on information in existing main literature and organized. Specifically, it is reported that the cost of wet desulfurization is, if it is manufactured in Japan and installed in China, approx. 15 thousand yen/kW for the cost of equipment and 0.5 yen/kWh for the operating cost, and by simplifying the system, they become approx. 10 thousand yen/kW and around 0.1 yen/kWh respectively. In addition, electron beam process is also reported as a dry method and it costs approx. 15 thousand yen/kW for the cost of equipment and 0.4 yen/kWh for the operating cost.

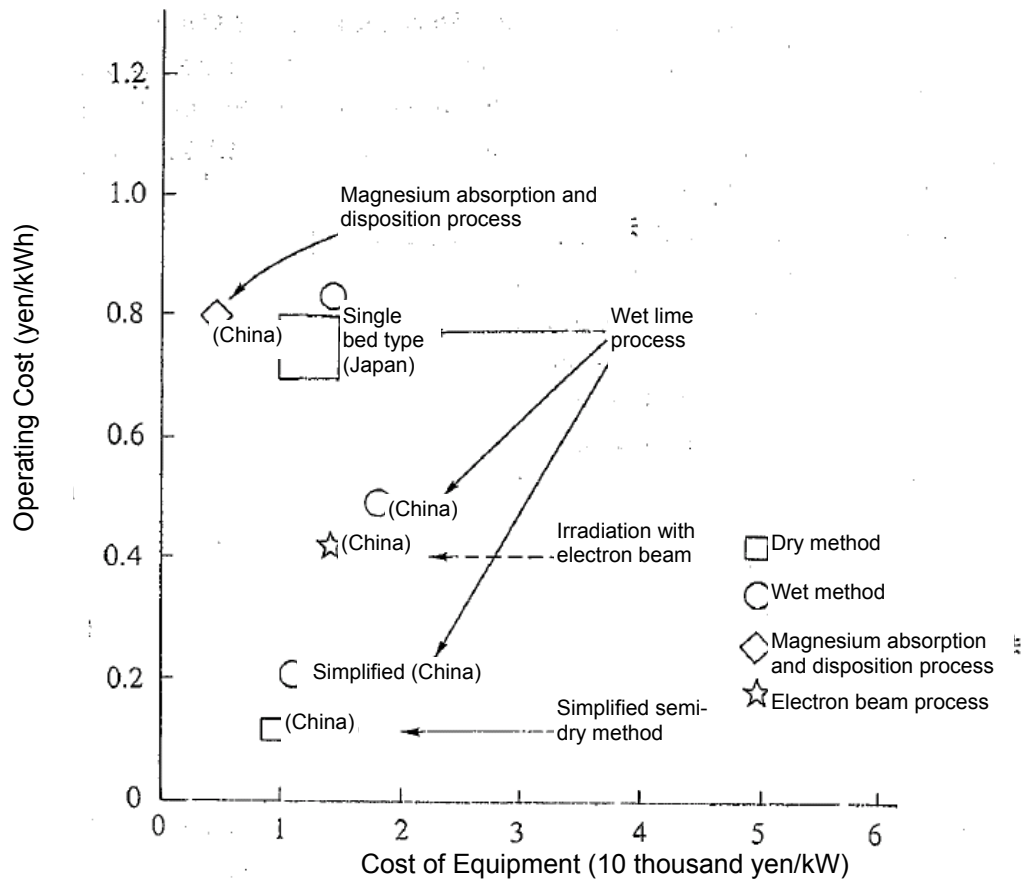


Figure 10-11. Comparison of desulfurization cost

Source: Yoshitaka Nitta, et al. from Keio Economic Observatory, "Preliminary research of desulfurization cost"

### 10.3 Relationship between limestone property (purity) and gypsum property and effective utilization method of gypsum

The reaction formula in lime-gypsum process is represented as  $\text{SO}_2 + \text{CaCO}_3 + \text{H}_2\text{O} \rightarrow \text{CaSO}_4 \cdot 2\text{H}_2\text{O} + \text{CO}_2$ .  $\text{CaCO}_3$  (limestone) reacts to absorbed/removed  $\text{SO}_2$  in equimolar ratio (1:1) and equimolar  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  (gypsum) is generated, the gypsum purity therefore depends on the limestone purity.

Furthermore, the gypsum purity is affected by “limestone utilization rate (reaction rate)” in addition to the limestone purity.

Accordingly, the relationship between limestone purity and gypsum purity under the following conditions is as Figure 11.

The amount of exhaust gas : 1,000,000 m<sup>3</sup>N/h

Inlet concentration of  $\text{SO}_2$  : 1,000 ppm

Desulfurization rate : 95%

Limestone utilization rate : 97%

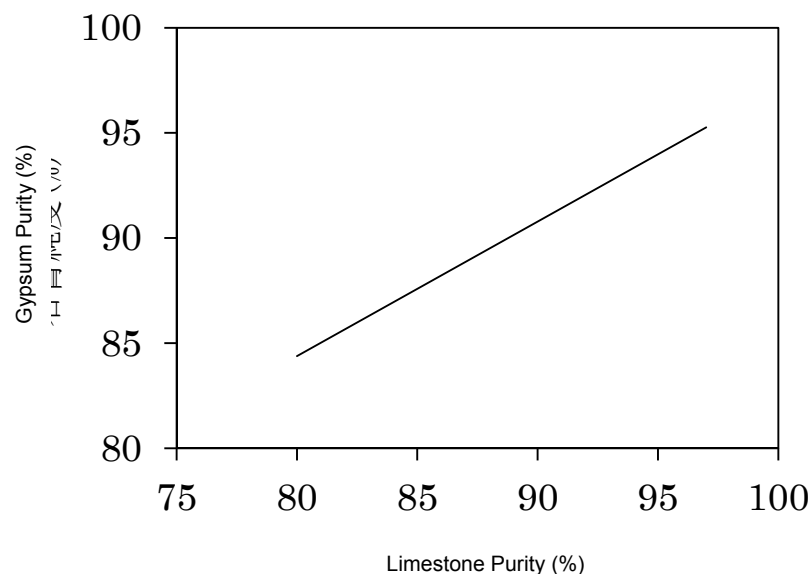


Figure 10-12. Relationship between limestone purity and gypsum purity

Gypsum is classified into gypsum dihydrate, gypsum hemihydrate and anhydrous gypsum depending on the existence form of its crystal water. Gypsum dihydrate and anhydrous gypsum

exist even in nature and gypsum hemihydrate is obtained generally by firing gypsum dihydrate. Since gypsum has characteristics of incombustibility and fireproof property as an inorganic material and also possesses sound insulation which is one of requirements in the case of being used for a parting wall, etc., and dimensional stability by which volume change after molding is little, it makes substantial contribution to durability of buildings. Furthermore, it is used for very wide range of purposes including cement, civil engineering, agriculture, and food in addition to building materials because it has properties required for various industries (Table 10-3).

In addition, gypsum used for these purposes is mainly chemical gypsum because currently natural gypsum is not produced in Japan. A shortage is supplied by import of natural gypsum from other countries.

Chemical gypsum includes the one that is made as a by-product of each industry (by-product gypsum), that is made by catching sulfurous acid gas in flue gas from thermal power plants by lime (flue gas desulfurization gypsum), and that is made by neutralizing sulfuric acid with lime (neutralized gypsum). Recently, recovered waste gypsum board is also utilized.

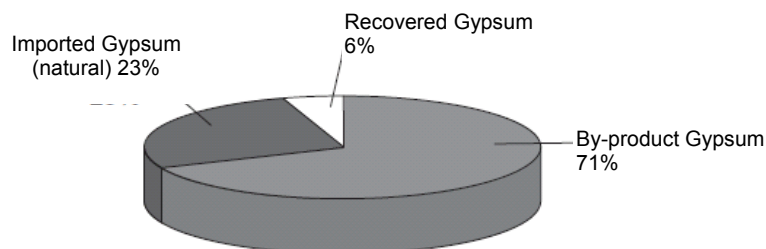


Figure 10-13. Amount used of gypsum for gypsum board in Japan (approx. 4,076 thousand ton/year)

Source: Census of Ministry of Economy, Trade and Industry for FY 2010

Table 10-3. Purpose of use and required properties of gypsum

Industry	Purpose of use	Form of gypsum	Required properties
Gypsum board	Building material	$\beta$ ·hemihydrate dihydrate	High adhesive property
Plaster	Building material Top coat Under coat	$\alpha$ ·hemihydrate $\beta$ ·hemihydrate	Whiteness, Particulate, High workability No stain, No efflorescence, High workability
Pottery	{ Model Working mold	$\alpha$ ·hemihydrate $\beta$ ·hemihydrate	Little coloring impurities at high temperature, High strength of hardening body, Small expansion High abrasion resistance, Small amount of air bubbles, Smooth surface
Glass	{ Polish Crucible	$\alpha$ ·hemihydrate $\beta$ ·hemihydrate	No coarse grain, High strength, Small expansion, Long casting time
Medical care	{ Dental model Surgery General Plaster cast	$\alpha$ ·hemihydrate $\beta$ ·hemihydrate	{ High strength, Small expansion Appropriate casting time
Machinery	{ Model Mold	$\alpha$ ·hemihydrate	Long casting time, High strength, Small expansion Long casting time, High strength, Small expansion
Cement	Setting adjustment Expansive cement	dehydrate anhydrous	No impurity which blocks hydration of cement is contained
Craft	Plastic statue	$\beta$ ·hemihydrate	Whiteness, High workability, No stain, No efflorescence
Food	Soybean curd	dehydrate	High purity, Fineness, No deleterious material is contained
Agriculture	Special fertilizer	dehydrate	Neutral, dissolved in water and easy to be absorbed by plants
Civil engineering	Soil improvement material	$\beta$ ·hemihydrate	Neutral and can represent strength when mixing with soil

Source: Gypsum Board Association of Japan, Chapter 1 Materials

In addition, use of flue gas desulfurization gypsum is restricted mainly to building materials and cement. Engineering properties which become a problem in those fields are listed below.

(Source: Journal of the Mining and Metallurgical Institute of Japan/98)

a) Gypsum for cement

Although flue gas desulfurization gypsum is generally powder, it contains attached water due to its refining process and its handling ability (transportation, storage, and supply) become a problem when using it. The problem of handling ability indicates generation of bridge or scale and dust scattering, and it is said that, in order to prevent them, it is desirable to make the attached water be 5 to 10%.

In addition, when mixing and grinding gypsum with clinker, in the case of natural gypsum, the grinding power is reduced because clayey impurities contribute as a grinding aid, but in the case of flue gas desulfurization gypsum which contains the amount of SO<sub>3</sub> close to the theoretical value, the power consumption is expected to be increased because ball coating or flake is generated like phosphogypsum. Furthermore, it is necessary to be careful because the flue gas desulfurization gypsum which contains more than a certain amount of various impurities causes quality deterioration of the cement.

Problematic substances as impurities are carbon which comes to the surface of cement and concrete and calcium sulfite which causes setting retardation of cement if it remains more than a certain amount. In addition, it is required to prevent mixing of metals including zinc, lead, tin, and copper because they adversely affect the setting efficiency and also are harmful.

#### b) Gypsum for building materials

Grain diameter of gypsum is important in order to make grain size of calcined gypsum suitable for each purpose when manufacturing gypsum building materials. Standard water-carrying capacity is increased and strength of hardening body is decreased as the grain size of calcined gypsum is smaller.

In addition, too much CaO does not always adversely affect gypsum building materials, but it could affect them when flue gas desulfurization gypsum is used as a raw material of gypsum board. If there is around 0.5% of CaO as Ca(OH)<sub>2</sub>, bonding of thick paper for board and gypsum core is disturbed, it is therefore a requirement for gypsum for board not to contain CaO. Existence of large amount of calcium sulfite is not desirable for manufacturing of light-weight hardening body. Furthermore, it generates pungent odor at the time of kneading of calcined gypsum after mixing with phosphogypsum, it is therefore undesirable in terms of work environment.

Moreover, although impurities in flue gas desulfurization gypsum include few various soluble salts such as Na, Mg, Al, Fe, and NH<sub>3</sub>, if they are mixed, they move to near the surface layer during its molding and dry processes and cause efflorescence phenomenon or generate double salt with calcium sulfate. If extremely large amount of them are contained, it could cause decrease in strength of hardening body and quality deterioration of gypsum building materials.



On the other hand, because pH of most gypsum and gypsum products is near neutral and there is no direct relation to the quality, the pH value is only a reference in many cases.

c) Gypsum for soil improvement

It is said that, when using flue gas desulfurization gypsum for soil improvement, it is desirable to make its grain diameter be 2 to 5 mm by granulating operation and provide it with properties including 500 g/pellet or more of crushing strength and disintegration in water.

In addition, it is also reported that Central Research Institute of Electric Power Industry makes an effort to develop environmental cleanup materials (apatite hydroxide) made from desulfurization gypsum and waste gypsum board. (Source: CRIEPI REPORT V05011)

Apatite hydroxide is one of the calcium phosphate minerals which has a composition of  $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ . CRIEPI performed an elution test (Environment Agency notification No. 46) for a synthesized apatite hydroxide sample as a soil environment cleanup material and got a result that all of the elution amount of lead, cadmium, fluorine, arsenic, selenium and hexavalent chromium are less than their soil environmental standard values. CRIEPI says, in the future, optimization considering the cost and long-term adsorption evaluation, etc., are necessary.

#### 10.4 Correlation between the denitrification rate at the time of using Indian coal and the amount of ammonia injection

Generally, the denitrification rate and the amount of ammonia injection do not depend on the type of coal. The amount of ammonia injection can be calculated by the theoretical formula below using the denitrification rate and other conditions.

$$Q = G_d \times C_{\text{inlet NO}_x} \times 10^{-6} \times \alpha$$

where

Q: The amount of ammonia injection [Nm<sup>3</sup>/h]

G<sub>d</sub>: The amount of dry gas [Nm<sup>3</sup>/h,dry]

C<sub>inlet NO<sub>x</sub></sub>: Inlet concentration of NO<sub>x</sub> [ppmvd@actual O<sub>2</sub>]

α: Molar ratio (Inlet concentration of NH<sub>3</sub>/Inlet concentration of NO<sub>x</sub>)[-]

Examples of exhaust gas conditions of denitrification device for a coal-fired boiler is showed in Table 10-4.

Table 10-4. Examples of exhaust gas conditions of denitrification device for a coal-fired boiler

Item	Unit		Remarks
The amount of processed gas	Nm <sup>3</sup> /h,dry	2,000,000	
O <sub>2</sub> concentration	vol%,dry	3.5	
Inlet concentration of NO <sub>x</sub>	ppmvd@6%O <sub>2</sub>	400	466.7ppmvd@actual O <sub>2</sub>
Outlet concentration of NO <sub>x</sub>	ppmvd@6%O <sub>2</sub>	41.7	*3
Denitrification rate	%	89.6	
Leakage concentration of NH <sub>3</sub>	ppmvd@6%O <sub>2</sub>	5	
Molar ratio	-	0.909	= 89.6/100 + 5/400

\*1 These are examples of exhaust gas conditions of denitrification device for a coal-fired boiler and different from the actual plan.

\*2 Reference concentration of O<sub>2</sub> is assumed to be 6%.

\*3 According to the "GOVERNMENT OF INDIA MINISTRY OF ENVIRONMENT, FOREST AND CLIMATE CHANGE NOTIFICATION (New Delhi, \_November, 2015)," NO<sub>x</sub> limit value of 100mg/Nm<sup>3</sup> is applied which could be applied to power plants from January 1, 2017.

In this case, the amount of ammonia injection, Q is obtained by the formula below.

$$Q = 2,000,000 \times 466.7 \times 10^{-6} \times 0.909 = \underline{\underline{848.5[\text{Nm}^3/\text{h}]}}$$

## 10.5 Considerations for the design of denitrification device when combusting high ash content Indian coal.

As showed in Table 10-5, Indian coal is characterized by higher smoke dust concentration of 50 to 100g/Nm<sup>3</sup> than other types of coal. Because of this, there are considerations for design of denitrification device as follows.

### (1) Abrasion

Due to increase in the amount of smoke dust in the exhaust gas, it is required to take measures against abrasion of instruments such as a duct, inside structure of duct, ammonia injection nozzle, guide vane, and denitrification catalyst. Especially, since the denitrification catalyst is a key component of denitrification device, abrasion of the denitrification catalyst could cause deterioration of denitrification performance. It is therefore necessary to take measures by designing of the denitrification reactor according to the appropriate flow velocity as well as by uniformizing the flow velocity distribution at the inlet of the denitrification catalyst. In order to confirm that the flow velocity distribution at the inlet of the denitrification catalyst is appropriate, CFD (Computational Fluid Dynamics) analysis and model test are considered for utilization.

### (2) Ash deposit

Due to increase in the amount of smoke dust in the exhaust gas, ash deposit on a horizontal part of the duct or on the catalyst layer and blocking of the denitrification catalyst are concerned. In order to avoid the blocking of the denitrification catalyst, as with the measures against abrasion of the catalyst, it is important to design the denitrification reactor according to the appropriate flow velocity and to uniformize the flow velocity distribution at the inlet of the denitrification catalyst. In addition, installation of a dust removal device including a steam soot blower and a sonic horn (sonic soot blower) for each catalyst layer is cited as one of the measures to prevent ash deposit.

(3) Catalyst deactivation

Performance of the denitrification catalyst deteriorates with time. In the case of denitrification device for a coal-fired boiler, the main factor of the deterioration is adhesion of poisoning components in ash to the catalyst. Since the amount of poisoning components is increased due to increase in the amount of smoke dust in the exhaust gas, it is required to make a plan for denitrification device with due consideration for the deterioration of denitrification performance.

Table 10-5. Property comparison between Indonesian coal and Indian coal

Ash Analysis	Indonesian Coal	Indian Coal
SiO <sub>2</sub> , %	30-55	55-66
Al <sub>2</sub> O <sub>3</sub> , %	22-30	15-28
Fe <sub>2</sub> O <sub>3</sub> , %	3-10	3-10
CaO, %	2-8	0.5-2.5
MgO, %	1.5-2.0	0.1-1.0
Na <sub>2</sub> O, %	0.2-1.5	0.1-1.5
K <sub>2</sub> O, %	0.5-2.3	0.0-1.2
TiO <sub>2</sub> , %	0.9-1.6	1.0-1.8
SO <sub>3</sub> , %	2.8-5.0	0.0-1.4
P <sub>2</sub> O <sub>5</sub> , %	0.3-2.0	0.1-2.6
Dust Loading, g/Nm <sup>3</sup>	10-40	<b>50-100</b>

10.6 Denitrification catalyst geometry (plate and honeycomb); characteristics of each geometry and how to select it

Titanium oxide-based catalysts are used as the denitrification catalyst of denitrification device for a coal-fired boiler. Titanium oxide-based denitrification catalysts developed in Japan in the 1960's are highly reliable catalysts which are currently adopted as catalysts of denitrification device for industrial boilers all over the world. Honeycomb and plate titanium oxide-based catalysts are adopted for a lot of denitrification device for industrial boilers not only in Japan, but also in Europe, the U.S., and China, etc.

Titanium oxide-based denitrification catalysts are classified by their geometry into honeycomb and plate. Characteristics for each are showed in Table 10-6. They have different properties by

the difference of geometry and manufacturing process and are selected according to conditions including operational conditions, design conditions of the denitrification device, cost, and taste of the customer. However, since optimal design conditions for denitrification reactor are different depending on the geometry, it is required to select the catalyst geometry by taking into account not only for the geometry itself, but also for the entire denitrification device.

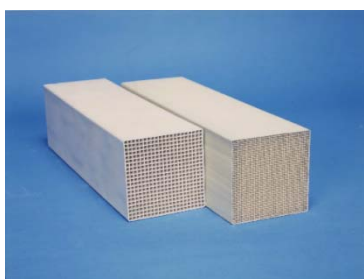


Figure 10-14. Honeycomb catalyst



Figure 10-15. Plate catalyst

Table 10-6. Comparison of catalytic properties by geometry

	Honeycomb	Plate	Remarks
1. Comparison of geometry/structure			
Surface area/Openings	Generally, a honeycomb catalyst has larger specific surface area and a plate catalyst has larger openings.		
2. Comparison of properties			
Resistance to abrasion due to dust	○	○	Although theoretically a plate catalyst which has larger openings is superior in blocking resistance, in the case of a system that is planned with proper selection of catalyst specifications including the pitch and appropriate flow velocity and rectifier, their resistance to abrasion/blocking due to dust are equal.
Resistance to blocking due to dust	○	○	
Pressure loss	○	◎	Under the same conditions, pressure loss of a plate catalyst is lower.
Catalyst quantity	◎	○	Catalyst volume of a honeycomb catalyst which has larger specific surface area is smaller.
Catalytic activity, lifetime	○	○	Their chemical durability are equal because they are titanium oxide-based catalysts as well.

Note: “○” and “◎” represent relative evaluation. When one is “○” and the other is “○,” it means both are equal, and when one is “○” and the other is “◎,” it means “◎” is superior.