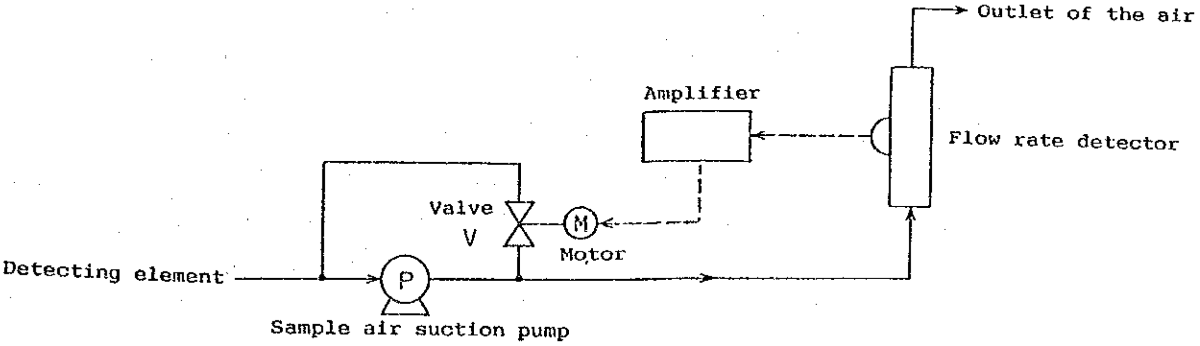
The flow rate stabilizer detects the deviation of the sample air flow rate from the set flow rate value, amplifies the detected signal to the electric signal, actuates flow rate adjusting devices such as the needle valve, and automatically feeds back the flow rate to the set value with its feedback control function. In this way, the stabilizer always maintains the sample air flow rate at the set value securely, preventing blinding of the filter paper in the one-hour measuring period and long period that do not rely on daily maintenance.

A diagram of a flow rate stabilizer is indicated in Explanation Figure 7. For the detection of the deviation of sample air's flow rate from the set value and the generation of the electric signal, a mass flow controller is used or the float position of the flow meter is detected optically. When the sample air flow rate fluctuates and deviates from the set flow rate, the signal detected is amplified to the electric signal. The electric signal adjusts the valve, revolving the motor. In this way, the flow rate is controlled and fed back to the set value.



Explanatory Figure 7 Diagram of a Flow Rate Stabilizer

10. Test Methods of Monitors

(1) **Empty Test:** This test is similar to the zero drift test which uses the zero gas of the gas analyzer. In this test, instead of zero gas, air containing no particulate matter is used, air purified and dried with two sheets of filter medium with the A1 collection efficiency specified by JIS K

0901.

(2) **Flow Rate Stability of Sample Air:** The fluctuation characteristic of the sample air flow rate differs with the monitor type. Test methods, therefore, are classified and specified by the monitor type.

(a) **Monitor of the Piezoelectric Balance Method:** As the section of the monitor which collects suspended particulate matter does not cause differential pressure, there is no cause for the sample air flow rate to fluctuate in a short period. The method to test the stability in a long run is, therefore, specified.

(b) **Monitors using Beta-Ray Absorption Method and the Light Absorption Method:** When suspended particulate matter is collected on the filter paper, differential pressure is caused by the resistance of the filter paper. With the collection of particles, the differential pressure increases and the flow rate of sample air reduces. A flow rate stabilizer is, therefore, introduced to prevent fluctuation in the flow rate. As the filter paper advances forward every measuring period, the sample air flow rate is read at the start and at the end of the one-hour measuring period in the calibration aerosol introducing test. The test method is specified for the case when blinding of the filter paper is caused by particles.

(c) **Monitor using the Light Scattering Method:** Because there is no area in the passage of sample air which causes differential pressure, and because as a rule the sensitivity of the detector does not change even if the flow rate of sample air fluctuates, it is not necessary to perform tests.

IV. MEASURING METHOD FOR PARTICLE-SIZE DISTRIBUTION OF DUSTS IN FLUE GAS

1. Scope

This Standard, besides being applicable to the soot and dust that is specified by the Air Pollution Control Act, may also be applied to the measuring of particle size distribution of particulates in gas caused by processes in the chemical, foodstuffs and other industries in which powder is widely used.

The measuring of particle size distribution of dust is necessary for calculating the diffusion of particulates in exhaust gas containing dust or for analysing the chemical components by particle size of SPM (suspended particulate matters) in the atmosphere required to determine the source of the particulates. It is also necessary for the selection, designing and evaluation of the performance of dust collection devices for the prevention of air pollution, and for the evaluation of such unit processes in the powder-related industries as pulverization, classification and sorting. This Standard therefore is applicable to a wide range of fields.

3. Meanings of Terminology

As some of the main terminology used in this Standard is already defined in JIS B 9909 (How to Express the Specifications of Dust Collecting Devices), JIS Z 8808 (Procedure for Measuring Dust Concentrations in Exhaust Gas) and JIS Z 8901 (Test Dust), unnecessary duplication has been avoided. However, on terminology for which a different expression was deemed necessary to be used, it has been taken up without avoiding duplication.

Note that JIS B 7954 (Automatic Devices for Measuring Suspended Particulate Matters in the Atmosphere) and JIS Z 8814 (Low Volume Air Sampler and Procedure for Measuring Suspended Particulate Matters in Air Using Low Volume Air Sampler) also have definitions of terminology, but these pertain to particulates in the atmosphere and differ in meaning to the terminology in this

Standard which specifies the source of the dust, so they have not be particularly mentioned.

(1) **Dust:** JIS B 9909 defines it as being "Solid particulates contained in gas normally of a particle size of 1μm or more, but in this Standard the term shall also include solid particulate fume of a size under 1μm".

And in JIS Z 8808 it is defined as being "Soot, dust and other solid particulates, with free water eliminated by drying. Combined and other water that is weighed by measuring based on this Standard shall also be considered to be dust". It thus plainly defines the relationship of dust with water content. In this Standard too, the collected dust sample is dried for 1 hour at 105 - 110°C, so the thinking is fundamentally the same as that of the two standards.

With regard to particulates in the atmosphere, such definition for "suspended particulate matters" as is used, for example, in JIS B 7954, is "solid or liquid particulates suspended in the atmosphere", so it clearly differs from the dust in this Standard with respect to the evaluation of liquid particulates and the drying temperature of the sample.

(2) **Particle Size:** This is an expression in a one-dimensional numeric value of the size of a particle. If the particle was spherical, it would be simple to express its size, but as the particle is usually of a complex form, particle size also has various definitions. Here, since it is necessary to know the size of the particles moving in air (or gas), the density (Pp) of the particulate against the geometric particle size (Dp) has been taken into consideration, and particle size has been expressed hydromechanically as:

$$Dpa = Dp\sqrt{Pp}$$

This is called aerodynamic particle size (Dpa) or aerodynamic diameter.

Note that JIS Z 8814 applies and uses the same definition as this Standard.

4. Types & Principles of Measuring Methods

Measuring methods for particle size distribution in ducts can be largely divided into the method of measuring particles flowing inside the duct (in-situ measurement) and the method of measuring the dust collected with a dust collecting device. The latter makes measurements of a certain quantity of the collected dust sample by such methods as screening, liquid phase subsidence and microscope, but it has the disadvantage of not measuring dust that has escaped being caught by the dust collector. Accordingly, the former measuring method is now generally being used.

There are various ways of measuring particle size of dust flowing through a duct such as the measuring by separation utilizing the inertia force of particulates (the inertia impact method -- cascade impacter method), measuring by separation utilizing the centrifugal force of particulates (the centrifuge separation method -- multi-stage cyclone method), measuring by separation by cyclone force after subjecting the particulates to an electric charge (the electrostatic separation method -- electrical mobility method), measuring from the light that is scattered when it irradiates the particulates (the optical method -- scattered light method), and others. When these methods are compared, the results are as per Explanatory Table 1.

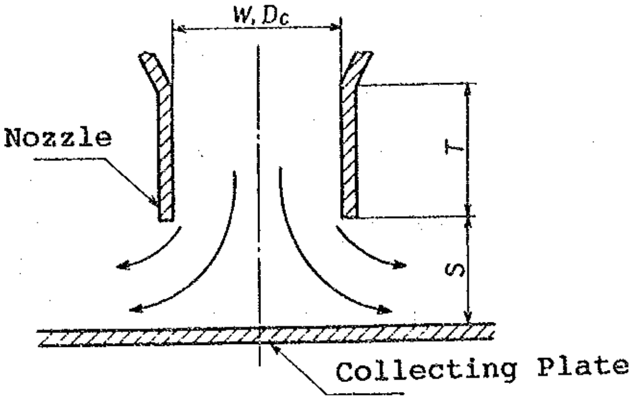
In Explanatory Table 1, particle size distribution to be obtained on the basis of quantity is when the dust concentration is extremely low and calculation of distribution is based on the particle size of each individual particulate. When the purpose is for evaluating the performance of a dust collector or a powder process, since a very much higher concentration than this is, in many cases, the object of measurement, usually a measuring method based on mass is employed.

For this purpose, the multi-stage cyclone was developed relatively recently in the United States) and examples of measurements have been reported, but considering that the device in not sold on the Japanese market and from the fact that the cascade impacter method is widely employed, it was decided to take up only the cascade impacter method in this Standard.

Explanatory Table 1 METHODS OF MEASURING PARTICLE SIZE DISTRIBUTION OF DUST IN DUCTS

Measuring Method	Measuring Range (μm)	Particle Size Distribution	Dust Concentration
Cascade Impacter	0.05 - 30	Based on Mass	Medium to Large
Multi-Stage Cyclone	0.1 - 20	Based on Mass	Medium to Large
Scattered Light	0.1 - 20	Based on Qty.	Small
Electrical Mobility	0.01 - 1	Based on Qty.	Small

The principle of the cascade impacter method, as shown in Explanatory Figure 1, is that the sample gas is blown from a small nozzle at high velocity towards a collecting plate, and the particulates in the gas are separated and collected by striking them against the collecting plate by the force of inertia. The measuring apparatus consists of several stages of impacters with nozzle diameters of increasingly smaller size. The particle size distribution is measured by gradually increasing the flow velocity of the gas, and the further downstream in the flow, the smaller the particles that are separated and collected. This type of device is known as a cascade impacter.



Dc, W: Nozzle diameter or slit width
T: Length of nozzle
S: Distance between tip of nozzle and collecting plate

Explanatory Figure 1 IMPACTER NOZZLE

The size of the particles that are separated and collected at the impacter is determined by the inertia force of the particles that are blown out from the nozzle, that is to say, by the dimensionless inertia parameters (Y) shown in the following equation:

$$Y = \frac{C \times Pp \times Dp^2 \times v_0}{18 \times \mu \times Dc} \quad \dots\dots\dots\dots (1)$$

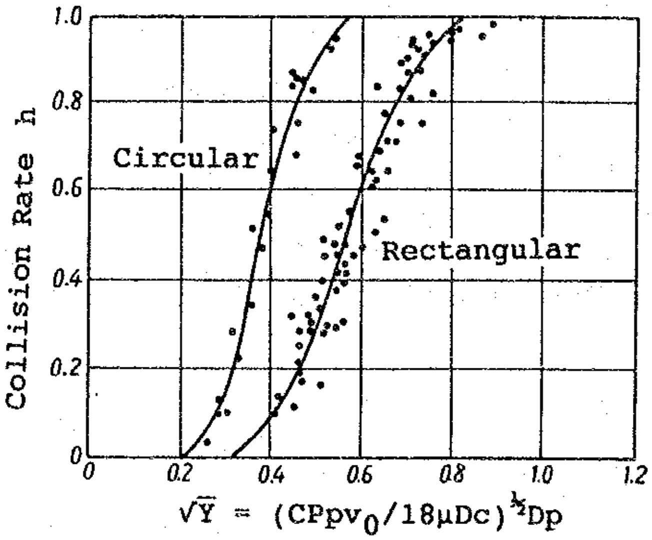
Here, C is Cunningham's correction factor, Pp the particle density, Dp the particle size, v_0 the velocity of the discharge from the nozzle, μ the coefficient of viscosity of the gas, and Dc the diameter of the nozzle (when the nozzle is a rectangular one, this is replaced with the slit width W).

Note that Stk $[=CPpDp^2v_0/18\mu(Dc/2)]$ is also used for inertia parameters, in which case the relationship is Stk = 2Y.

Cunningham's correction factor is a coefficient for correcting the lowering of resistance, due to gas molecules, of the movement of particles in the fine particle size range of less than 1μm. It is expressed by the following equation employing the mean free path of gas molecules (n):

$$C = 1 + 2.514 \times \frac{n}{Dp} + 0.80 \times \frac{n}{Dp} \exp\left[-0.55\times\left(\frac{Dp}{n}\right)\right] \quad \dots\dots (2)$$

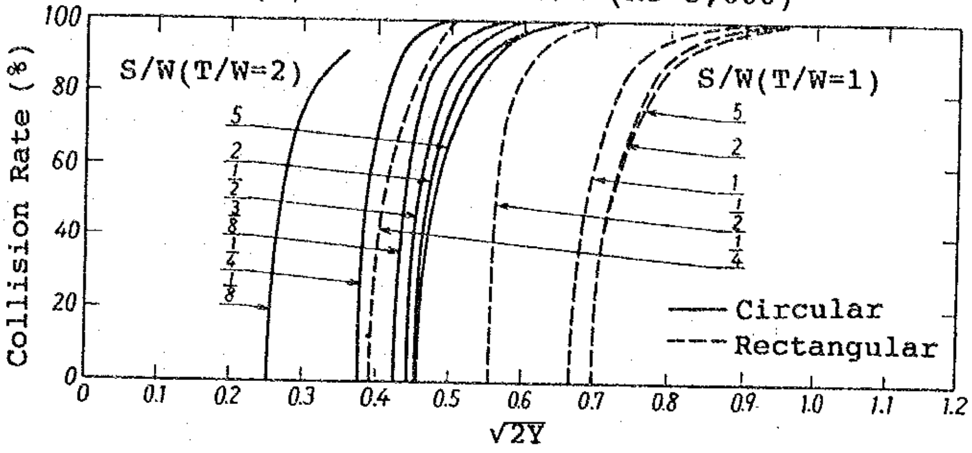
The relationship of Y to the rate of collision, exists also in the S/Dc value (clearance ratio, that is, the distance between the nozzle tip and the collecting plate/nozzle diameter) and the Re number value, but in circular nozzles, in the range of Re = 100 - 3,000, it is practically uniform, and Ranz and Wong have obtained the results of Explanatory Figure 2 with S/Dc = 3. Here, the collection rate has been treated in the same sense as collision rate.



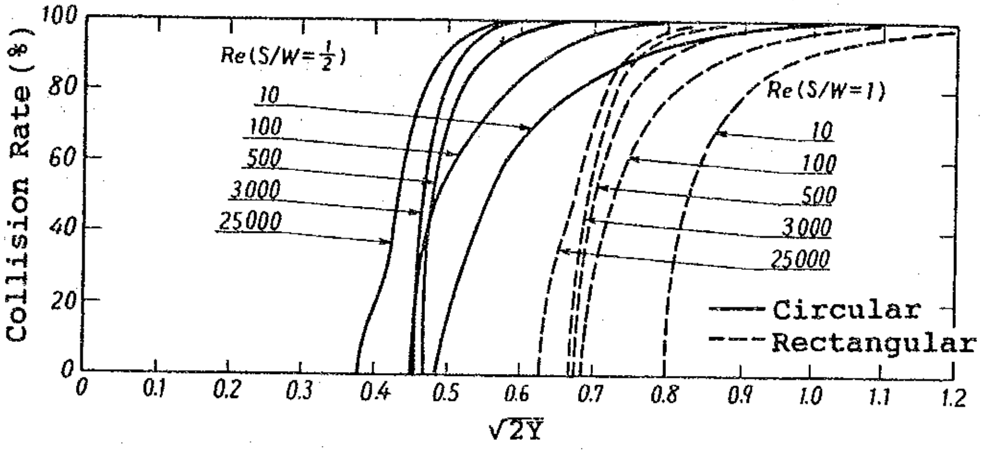
Explanatory Figure 2 COLLISION RATE FROM CIRCULAR AND RECTANGULAR NOZZLES

On the other hand, Marple has expressed, by theoretical calculation, the effect of S/W (= S/Dc) when Re = 3,000, the effect of Re when T/W (nozzle length/nozzle diameter) = 1, and the effect of T/W when Re = 3,000, as in Explanatory Figure 3. The solid line is when the nozzle is circular and the broken line, when the nozzle is rectangular. It can be seen that with Re = 3,000, the curves become practically the same when S/W = 2 - 5, and with circular nozzle T/W = 1, there is almost no change in the collection rate of 50% with Re = 100 - 3,000.

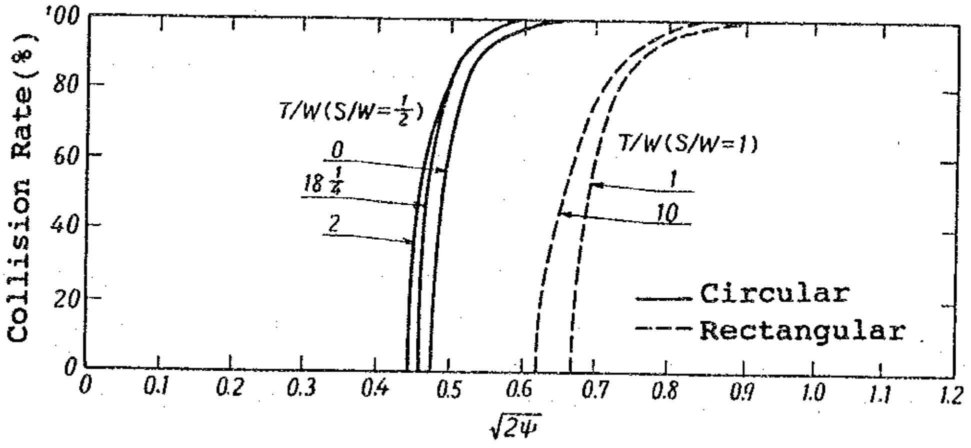
(a) Effect of S/W (Re=3,000)



(b) Effect of Re Number (T/W=1)



(c) Effect of T/W (Re=3,000)



Explanatory Figure 3 COLLISION RATE OF CIRCULAR AND RECTANGULAR NOZZLE IMPACTERS

From these Figures, the particle size, of which the collection rate becomes 50%, is called 50% separation size or ECD (effective cut-off diameter) and the Y at that time is expressed as Y_{50}. This value is shown in Explanatory Table 2.

Explanatory Table 2 Calculated Value of $\sqrt{2Y_{50}}$

S/Dc. S/W	0.25	0.50	1.0	2 - 5
Circular Nozzle (Re=3,000)	0.39	0.45	0.48	0.48
Rectangular Nozzle (Re=1,500)	0.42	0.57	0.70	0.73

The research and development of the cascade impacter was started by K.R. May in 1945, after which a number of variations were submitted by many researchers and put into practical use. When these are classified, they are either nozzles of circular shape or slit-shape (rectangular, oblong, or some such shape) varying in the number of jet nozzles in one stage from 1 to 200 or more, as shown in Principal Table 1. As these are all based on the same principle, it was decided to approve all of them as being applicable to this Standard. However, considering that, in actuality, the circular, multi-nozzle type is widely used, it was decided to assume this type when describing the sampling device and the measuring method.

Note that in Remarks it is stated that "the particle size range to be measured with the measuring method described in this Standard shall generally be 0.05 to 30μm". These values were used because, although the range that can be measured with a normal cascade impacter is approximately 0.3μm and above, when the low pressure impacter described later is used, the lower limit can be expanded to about 0.05μm.

Also, although, when sampling, there is a possibility of coarse particles undergoing inertia separation or gravitational subsidence at the suction nozzle prior to the gas being introduced into the impacter, the upper limit of 30μm was used because it becomes possible to make this the upper limit if the pre-separator described later is employed and by the relationship to gas flow velocity or particle density.

5. Outline of Measuring Method

This Standard covers the determining of particle size distribution by inserting a classifying and collecting device based on the inertial impact method or a suction nozzle into a duct through which exhaust gas containing dust is flowing, equidistantly sucking up part of the exhaust gas, and, after drying the dust that has been collected at each stage of the classifying and collecting device, measuring its mass.

An extremely important condition when measuring particle size distribution is, as in the case of JIS Z 8808, collecting dust samples by the "equidistant sucking up" of dust. In other words, the sample gas should be collected by passing the suction nozzle through the measuring point at the same distance as the flow velocity of the exhaust gas. If equidistant sucking up is not properly executed, not only will there be an error in the concentration obtained by the measurement, but the results of the particle size distribution will also be distorted. This is clear from the relationship between the flow of the gas and the loci of the particles due to inertial force. When measuring dust concentrations in accordance with JIS Z 8808, a balanced type sampling device can be used which makes it possible to carry out equidistant suction in accordance with the changes in the velocity of flow of the exhaust gas, but when measuring particle size distribution, since it is a prerequisite of the measuring principle that the gas flow passing through the classifier-collector be uniform, it is not possible to change the suction quantity in accordance with fluctuation of the exhaust gas flow velocity. In conclusion, it is necessary to take into account the point that measuring is limited to a stable condition in which the flow velocity of the exhaust gas is uniform and does not change.

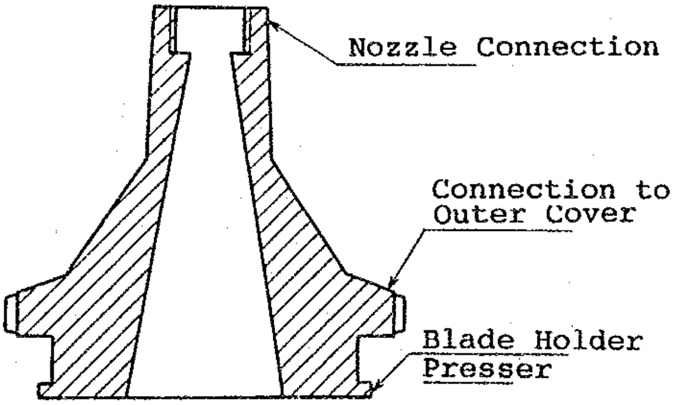
6. Sampling Device

6.1 Composition of Sampling Device: In Principal Figure 2, atype of sampling device that is inserted into the duct is shown. This type of classifier-collector requires no heating or heat insulation, operation is simple and so is widely used. Besides this, there is the type where the classifier-collector is placed outside the duct. When this type is employed, heating or heat insulation is necessary in order to prevent condensation in the suction pipe and classifier-collector due to temperature drop. Also in this case, the material and construction of the suction pipe from the nozzle to the classifier-collector should be such that adherence of particles is minimized. During measuring, unless the temperature in the classifier-collector is maintained at a uniform level, the gas flow velocity in the device is liable to change, so careful attention must be paid to temperature control. When the temperature of the exhaust gas in the duct and the gas in the heated classifier-collector is different, consideration must be given to the fact that suction flow rate at the classifier-collector must be used in place of the suction flow rate Qs at the suction nozzle. When part of the classifier-collector must of necessity be placed outside the duct due to the measuring hole being too small, heat insulation or heating in accordance with the foregoing should be carried out.

6.2 **Classifier-Collector Unit:** The example of a circular,multi-nozzle type cascade impacter shown in Principal Table 2, shows the construction of an Andersen stack sampler, and the inertia parameter $Y_{50}=0.14$ was calculated from a monograph based on the maker's data. In an impacter of the construction shown in Principal Table 2, S/W value is 2 - 10 and Re number is 100 - 500. In Explanatory Figure 3 the relationship between $\sqrt{2Y_{50}}$ and the collision rate is shown; on the circular impacter graph of Explanatory Figure 3 (a), if the S/W value increases, the tendency is for the separation and collection rate curve to move to the right. If $\sqrt{2Y_{50}}=0.14$ was applied to this, it would become $\sqrt{2Y_{50}}=0.53$, but in Explanatory Figure 3 (b), if the circular impacter's curves of Re number 100 and 500 were moved slightly to the right, $\sqrt{2Y_{50}}$ would become approximately 0.5 at a collection rate value of 50%. In accordance with this, from Explanatory Figure 3, it is possible to estimate to a certain degree the inertia parameter of the impacter shown in Principal Table 2.

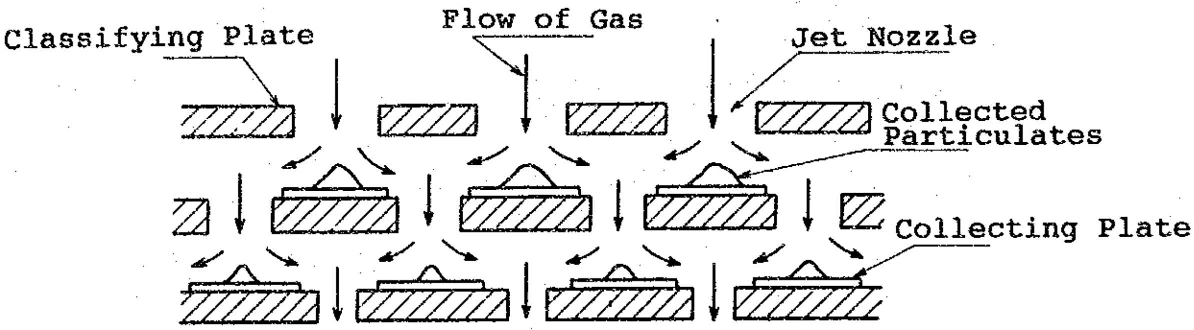
6.2.1 **Suction Nozzle:** The configuration of the suction nozzle comes in the L-shape or goose-neck shape shown in Principal Figure 5. When the measuring hole is small and the diameter of the nozzle is too large, the goose-neck shape is easier to use.

6.2.2 **Diffusion Unit:** The construction of the diffusion unit must be such that vortex and drift does not occur in it, when guiding the gas flow from the suction nozzle to the classifying plate of the uppermost stage. For that, a unit of a conical shape with an appropriate incline internally is most often used. As the diffusion unit, by being connected with screws, has the purpose of clamping together the collecting plate, classifying plate and support ring, normally the construction shown in Explanatory Figure 4 is used.



Explanatory Figure 4 EXAMPLE OF DIFFUSION UNIT

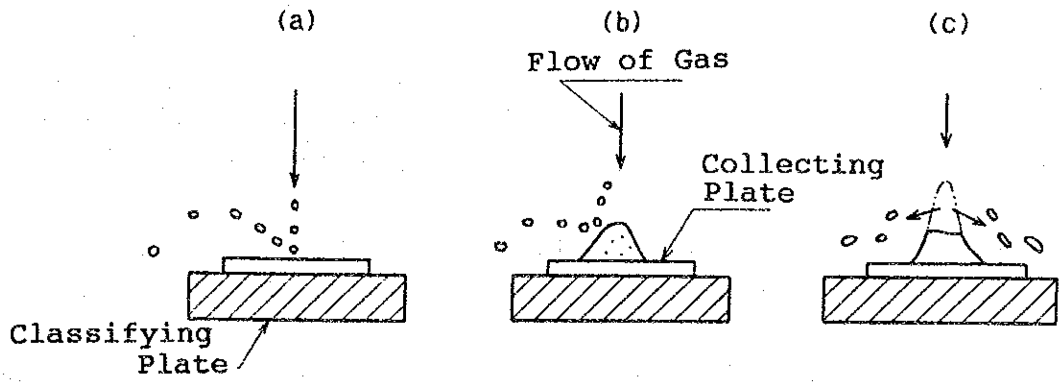
6.2.3 **Classifying Plate:** The attached positions of the classifying plate and the collecting plate and the flow of the gas between them are as shown in Explanatory Figure 5. The jet nozzles opened in the classifying plate are important to the classifying performance of the impacter and, at the same time, are subjected to high velocity gas the lower the stage becomes, so are liable to become corroded. Therefore, it is necessary that material with the best anti-corrosion properties in the collector be used; the use of stainless steel and other material with equal or better properties than SUS (316) is desirable. After use, the classifying plate should be thoroughly cleaned in an ultrasonic washer or some such device to keep its nozzles free of clogging at all times.



Explanatory Figure 5 **LOCATION OF CLASSIFYING PLATE AND COLLECTING PLATE AND FLOW OF GAS**

Depending on the characteristics of the particulates, wall loss may occur because of the adherence of the particulates to the reverse side of the classifying plate. An effective means of minimizing wall loss, is to hold down as much as possible the re-scattering of the particles at the collecting plate. With regard to deformation of the jet nozzles due to use for long durations, there are some in which the tops and bottoms of the nozzles become corroded increasing the inside diameter of the nozzles and there are some in which the tops corrode and accumulate at the bottom of the bore of the jet nozzles causing the nozzles to become clogged. Accordingly, the shape of the jet nozzles should be regularly checked with a stereoscopic microscope. A simpler method would be hold up a well-cleaned classifying plate to a suitable light source. If the jet nozzles on the classifying plate do not appear to be of the same brightness and there are some that appear brighter or darker than the others, there is a possibility that the jet nozzles are deformed or clogged.

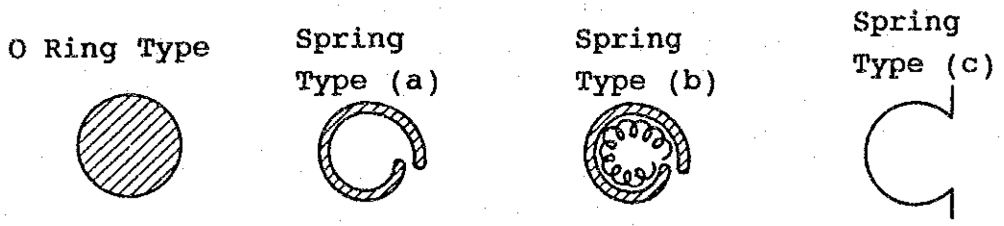
6.2.4 Collecting Plate: When the particulates inertially collide against the collecting plate, they are liable to rescatter depending on the their nature and the construction of the collecting plate. The re-scattering of particulates on the collecting plate, as shown in Explanatory Figure 6, may be due to the particulates (a) bouncing off the surface of the collecting plate, (b) secondary bouncing off collected particulates, (c) scattering of accumulated particles, and other factors. So, in order to minimize (a), thought should be given to the selection of the collecting plate, and to minimize (b) and (c), the taking of excessive samples should be avoided, it being best to keep the accumulated amount at each stage to a maximum of 10mg. As collecting plates with little re-scattering, filter paper of glass fiber coated with grease or other agents is used, but this is not suitable for inserting in high temperature exhaust gas and in the horizontal direction in classifier-collectors. Normally, filter paper, stainless steel plate, roughened stainless steel plate or other materials are used, but depending on the temperature and moisture content of the exhaust gas and the characteristics of the particulates, it is necessary to select an appropriate material with a proper surface finish.



Explanatory Figure 6 **CONCEPTUAL DRAWINGS OF RE-SCATTERING OF PARTICULATES AT THE COLLECTION PLATE**

6.2.5 Support Ring: Support rings are for the purpose of maintaining the gap between the classifying plate and the collecting plate and to keep the T/W value mentioned in 4.

at a uniform level. As the support ring is always removed before and after a measuring operation, gas leaks are likely to occur. Because of that, various types of rings to minimize gas leaks have been devised, examples of their cross-sections being as shown in Explanatory Figure 7. For materials, there are stainless steel, inconel steel, teflon, etc., so an appropriate one should be selected as occasion demands. Particularly, when filter paper is used as the collecting plate, material and construction of a kind which would not damage the filter paper should be selected. If the mounting of the support ring is poor, a ring-like adherence of particles due to gas leakage will be found on the inside of the plate holder. In order to prevent this a material or construction with elasticity and close contact properties should be used and it should always be cleaned before it is installed.



Explanatory Figure 7 **EXAMPLES OF CROSS-SECTIONS OF SUPPORT RINGS**

6.2.6 **Back-up Filter:** As material for back-up filters, normally, filter paper made of glass fiber or silica fiber is widely used, but silica fiber filter paper, in particular, has large moisture absorption properties so care is required. Silica fiber filter paper is generally superior when used in sour gas or in high temperatures and when used for chemical analysis. For measuring exhaust gas with a high moisture content, the pressure loss of the filter paper increases and the filter paper is likely to be damaged. In such a case, filter paper of higher strength, such as paper with wire mesh reinforcement and double layer paper, should be used. The shape of the back-up filter is usually circular but a cylindrical filter paper may be used at the back of the classifier-collector.

7. Measuring Method

7.1 Measuring Location, Hole and Point

7.1.2 Measuring Hole: It is desirable that the measuring hole have an inside diameter of about 150mm to allow the classifier-collector and the suction nozzle to be inserted. However, when the classifier-collector shown in Principal Figure 3 is used, its diameter is approximately 80mm, so if the suction nozzle (goose-neck type) shown on the right of the Principal Figure 5 is employed, a measuring hole with an inside diameter of about 100mm may also be used. Great care should be taken when inserting, as dirt and rust on the internal walls of the measuring hole can easily enter the suction nozzle.

7.1.3 Measuring Point: With this measuring method, the classifier-collector, compared to that for measuring dust concentrations, is much larger and the necessary quantity of sample is also greater. So if sampling was to be done in each sectionalized area specified in JIS Z 8808, the operation would become very troublesome, and the collected amount of samples cannot be expected to be too great. Accordingly, it was decided to employ the collection method of sampling from a representative point that is specified in Remark 1. or Remark 3. of 4.3 of JIS Z8808. In this case, a point where the dust concentration is average at a place where variations in the flow velocity, temperature, and other factors in the duct is the smallest, should be selected as the representative point.

7.5 Sampling Method

7.5.2 Calculation of Suction Flow Rate:

(1) Equal Velocity Suction & Suction Flow Rate at Suction Nozzle: Equality velocity suction flow rate (Qm) at the gas meter should be calculated by the formula given in 7.5.2 of the Principal Text and the suction flow rate (Qs) at the suction nozzle in the duct should be obtained by the equation (3).

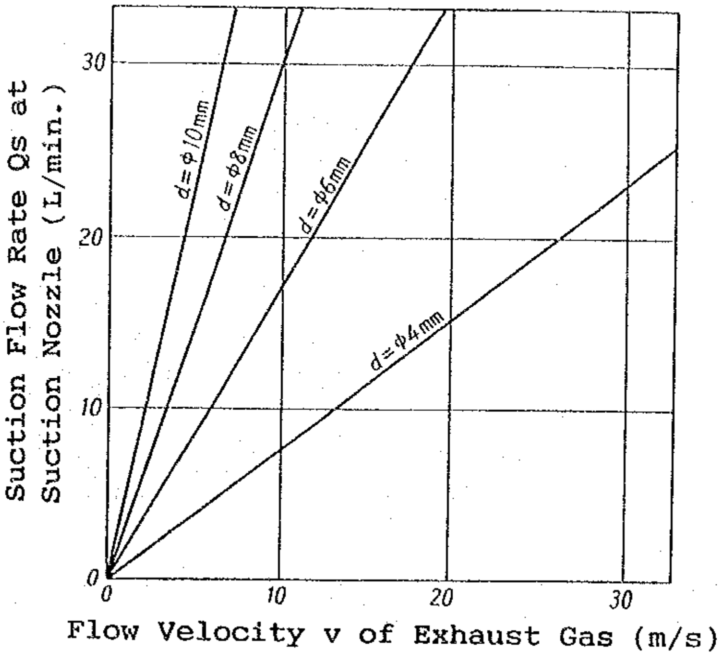
$$Qs = \frac{\pi}{4} d^2 \times v \times 60 \times 10^{-3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Where, Qs : Suction flow rate at suction nozzle (l/min.)
d : Inside diameter of suction nozzle (mm)
v : Flow velocity of exhaust gas (m/s)

The suction flow rate at the main body of the classifier-collector (which may be judged to be the same as the suction flow rate at the suction nozzle), has a certain allowable range and also, as shown in Principal Figure 8, the classification width obtained by measurement changes depending on Qs. Accordingly, when calculating Qs, from results obtained by preliminary measurement, d is selected in advance in accordance with equation (3) so that Qs falls within the allowable range, and then Qs is calculated.

When suction is carried out at the optimum suction flow rate of the classifier-collector and also when an appropriate classification width is obtained from Principal Figure 8, a suitable d can be selected with equation (3). However, as Qs varies when d changes, care must be taken with the scope of use of the gas meter and pump and the suction time.

(2) **Selection of Suction Nozzle Bore:** As both the suction flow rate (Qs) at the gas meter and the suction flow rate (Qs) at the suction nozzle are proportionate to the square of the bore (d) of the suction nozzle, while the more suction nozzles of different bores that are readied the better, normally it is desirable to have ready bores ranging from $\phi 4$ to 12mm at increments of about 2mm. Accordingly, the relationship between d and Qs depending on the flow velocity (v) of exhaust gas is shown in Explanatory Figure 8.



Explanatory Figure 8 **FLOW VELOCITY OF EXHAUST GAS WITH SUCTION NOZZLE BORES AS PARAMETERS**

(3) **Range of Suction Flow Rate:** The cascade impacter, by the nature of its principle, is able to measure at whatever classification width that matches any changes which occur in the suction flow rate (Qs) at the suction nozzle. However, with an actual impacter, if Qs is made too small or, conversely, too big, the re-scattering at the collecting plate increases, resulting in the possibility of the results of particle size distribution obtained being different. In such a case, re-scattering is greatly effected by both Qs and the material and construction of the collecting plate. Accordingly, with the measuring method employing the impacter of the structure shown in Principal Table 2, considering the construction of the collecting plate currently being used, the usable range of suction flow rate was decided at about 5 - 30 l/min. However, since the optimum suction flow rate of this impacter is normally 20 l/min., when carrying out suction at a considerably different suction flow rate than this optimum suction flow rate, consider using a collecting plate with little re-scattering properties as described in 6.2.4.

7.5.3 Sampling

(1) **Amount and Duration of Sampling:** When a large quantity of particles is collected at each stage, re-scattering increases and furthermore, as shown in Explanatory Figure 6 (c), the nature of the classification itself will be changed. Because of that, it is necessary to finish the sampling before such a phenomenon occurs. Since this sort of phenomenon is liable to occur when a sample of dust in exhaust gas from a heavy oil burning boiler of more than 10mg is taken at any stage, it was decided that the sampled quantity at each stage should be a maximum of 10mg.

As guidelines for the amount and duration of sampling, using the anticipated dust concentration of the facilities to be measured as reference, the average estimated sample quantity (M_e) can be obtained from equation (4).

$$M_e = \frac{Cn \times Qn \times T}{n + 1} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (4)$$

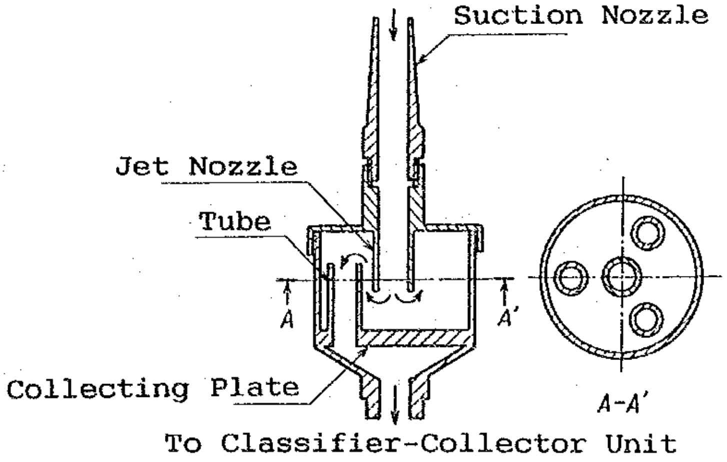
Where, Me : Estimated quantity of sample to be collected from each stage (mg)
Cn : Anticipated dust concentration ($g/m^3{}_n$)
Qn : Suction flow rate converted to 0°C, 1 atmosphere (l_n/min.)
T : Duration of suction (min.)
n : No. of stages in impacter

When the exhaust gas concentration is not too high, Qn in equation (4) may be replaced with the suction flow rate at the gas meter (Qm). Set M_e at an appropriate weight between 1 and 5mg and determine the guideline for the sampling duration using equation (4).

(2) **Pre-Separator:** If coarse particles exist in great numbers in the exhaust gas, the collected amount at the uppermost stage of the classifier-collector will increase, causing rescattering of coarse particles and resulting in the possibility of the classification characteristics of the

lower stages changing.

In such a case, it would be best if a pre-separator for capturing coarse particles of 30μm or more be installed immediately behind the suction nozzle. The pre-separator must not be such that it affects the collecting characteristics of the classifier-collector. Explanatory Figure 9 shows an example of a pre-separator of the inertial impact method.



Explanatory Figure 9 EXAMPLE OF PRE-SEPARATOR

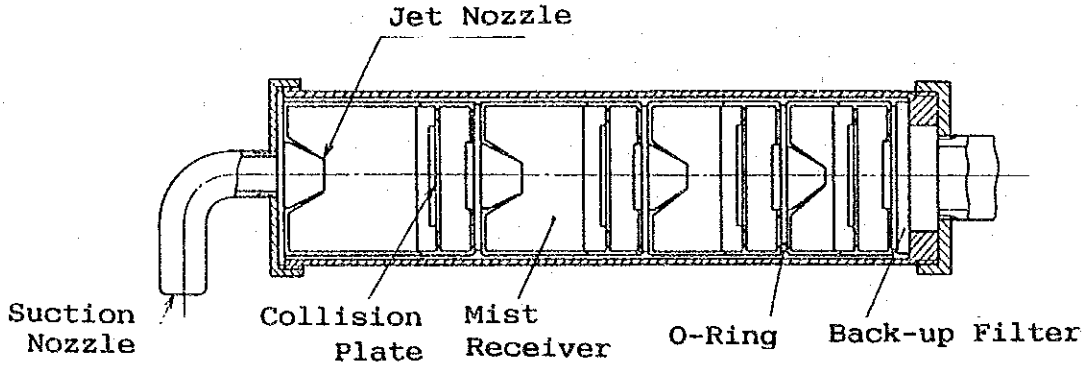
(3) **Method of Taking Out Sample:** As the specimens collected on the collecting plate are in a state where they are extremely likely to scatter when a shock is imparted to from the outside, the greatest of care should be exercised when taking out the classifier-collector from the measuring hole.

Since, depending on the particulates, even the worker's breath could cause them to scatter when removing the collecting plate from the classifier-collector, the plate should be removed under windless conditions in a room or some such enclosure.

When it is necessary to remove and attach the collecting plate on the spot in order to carry out repeated measurements at the site, do so inside an automobile or other enclosure near the site.

(4) **Weighing Quantity:** Depending on the collected particulates, there are those which have great moisture absorption properties and reactivity. In such a case, if the particulates are left standing for a long time, they are liable to adsorb the moisture and gases in the air or undergo oxidation, or corrosion may occur on the collecting plate. With particulates that are liable to incur such phenomenons, weigh them promptly before such phenomenons have a chance to occur.

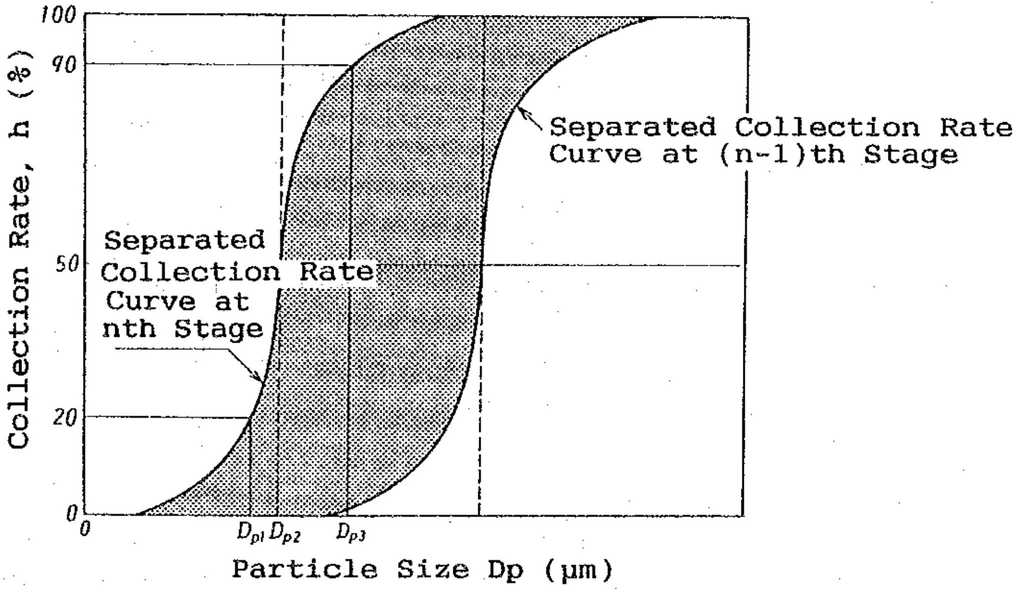
(5) **Measuring Inside Exhaust Gas Containing Mist:** When the exhaust gas contains a large quantity of mist, the mist is liable to adhere to the inner walls of the classifier-collector, in turn causing particulates to adhere. Moreover, the collected particulates are liable to be washed away by the mist. In such a case, an impacter with a built-in mist receiver, as shown in Explanatory Figure 10, is employed and, after collection, the mist is dried and only the particulates are weighed.



Explanatory Figure 10 **EXAMPLE OF IMPACTER WITH MIST SEPARATOR ATTACHED**

7.6 **Method of Calculating Particle Size:** With regard to the method of calculating the particle size, the following describes the 50% separation size concept and the calculation process shown in 7.6.1 (1) and 7.6.2 of the Principal Text.

(1) **50% Separation Size Concept:** With regard to the impacting of particulates against the collecting plate of the impacter, theoretically the relationship shown in Explanatory Figure 3 holds true. As shown in the Figure, all particulates of a given particle size or more are not captured on a certain collision plate -- there are some particulates that are collected at about that particle size and some that are not. This is called the separated collection characteristics at the nth stage and inscribes a peculiar collection rate curve of its own. The separated collection rate curve at the nth stage takes the form shown in Explanatory Figure 11, the broken line being the Dp_{50} calculated by applying Y_{50} in equation (1).

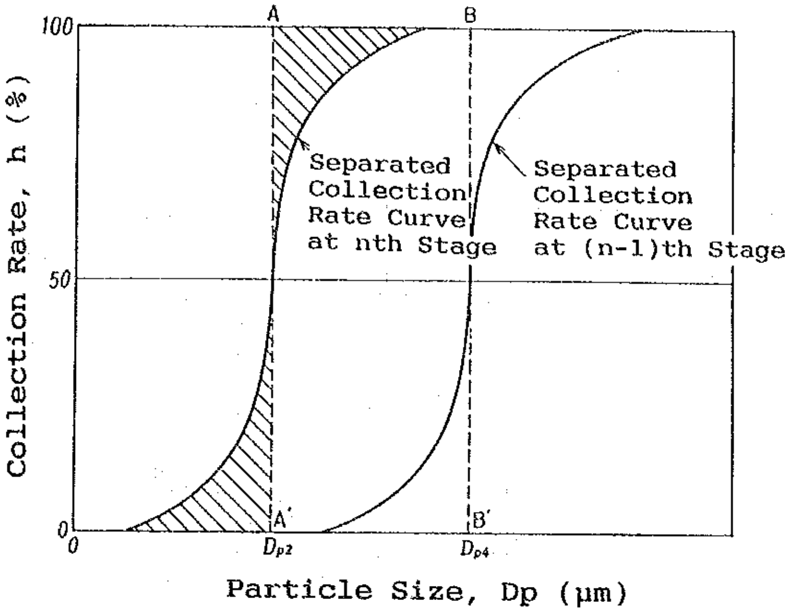


Explanatory Figure 11 RELATIONSHIP BETWEEN SEPARATED COLLECTION RATE AND PARTICLE SIZE (1)

The above shows that actually, although with particle size Dp_1, 20% of the particulates are captured, 80% of the particulates are not, and, similarly, with Dp_3, although 90% of the particulates are captured, 10% of the particulates are not. The Figure shows that with Dp_2, 50% of the particulates are captured and 50% are not. Generally impacters have been designed so that the particle size showing this 50% capture rate coincides with the particle size calculated by equation (1). On the other hand, a similar curve can also be obtained at the next upper stage, [the (n-1)th stage], and the particulates in the area surrounded by the separated collection rate curves of the nth stage and the (n-1)th stage are captured on the collecting plate of the nth stage.

Accordingly, as shown in Explanatory Figure 12, if the impacter has been designed so that the shaded area above the 50% collection rate (the part that is not collected) and the shaded area below the 50% collection rate (the part that is collected) cancel each other out, it can be said that the particulates of and above the particle size at the 50% collection rate will all be captured. This is called the 50% separation particulates and are the particulates collected at the nth stage. And then, with the same thinking for the (n-1)th stage, it can be considered that, in the end, the area surrounded by points A, B, B' and A' are the particulates that will be captured at the nth stage. Therefore, at the nth stage, all the particulates between the 50% separation particulates Dp_2 and Dp_4 will be collected. This is called the classification width of the particulates at the nth stage.

From the foregoing, attention should be paid to the fact that, when actually using an impacter, the particulates collected on its stages have a certain physical size distribution.



Explanatory Figure 12 RELATIONSHIP BETWEENSEPARATED COLLECTION RATE AND PARTICLE SIZE (2)

(2) **Steps in Particle Size Calculation Equations:** Equation (1)' holds true for the collision of particulates against the collecting plate.

$$Y_{50} = \frac{C \text{ x } Pp \text{ x } v_0 \text{ x } Dp_{50}^2}{18 \text{ x } \mu \text{ x } Dc} \text{ x } 10^{-7} \text{ .... (1)'}$$

Where, Y_{50} : Inertia parameter for 50% separation size

C : Cunningham's correction factor

Pp : True density of particulates (g/cm^3)

v_0 : Flow velocity at jet nozzle (cm/s)

Dp_{50} : 50% separation size (μm)

μ : Viscosity coefficient of gas (g/cm·s)

Dc : Bore of jet nozzle (mm)

If the impacter is designed so that Y_{50} becomes an appropriate value, Dp_{50} can be obtained from equation (1)'. When equation (1)' is arranged with respect to particle size (Dp_{50}), it becomes equation (5).

$$Dp_{50} = \sqrt{\frac{18 \times \mu \times Dc \times Y_{50}}{C \times Pp \times v_0} \times 10^7} \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

Although equation (5) holds true of one circular jet nozzle as shown in Explanatory Figure 1, with a multi-nozzle type impacter with N number of jet nozzles, particle size is expressed as equation (6) using the suction flow rate (Qs) of the impacter.

$$Dp_{50} = \sqrt{\frac{18 \times \pi \times N \times \mu \times Y_{50} \times 60 \times Dc^3}{4 \times C \times Qv_2} \times 10^2} \ldots\ldots \quad (6)$$

Where, N : Number of jet nozzles
Qs : Suction flow rate at suction nozzle (1/min.)

Here, the particle size (Dp_{50}) obtained by equation (6) is expressed, from the principle of the impacter, as the 50% separation size. Equation (6) is the equation shown in 7.6 of the Principal Text.

7.6.1 Method of Calculating Particle Size Not Requiring Cunningham's Correction Factor

(1) **Method by Calculation:** This calculation method is used when the particle size is 1μm or more. Since the viscosity coefficient of gas (μ), when the gas is combustion exhaust gas, etc., can be said to be equal to the viscosity coefficient of air, μ is obtained by the following equation (7).

$$\mu = 10^{-6} \times (172 + 0.4 \times \theta s) \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

Where, θs : Exhaust gas temperature (°C)

Here, making Cunningham's correction factor C = 1, from equations (6) and (7), the particle size at each stage is obtained by equation (8).

$$Dp_{50} = \sqrt{\frac{2.70 \times \pi \times N \times Y_{50} \times Dcn^{3} \times (172+0.4 \times \theta s) \times 10^{-2}}{C \times Pp \times v_{0}}} \quad \ldots. (8)$$

Where Dcn : Bore of jet nozzle at nth stage (mm)

Equation (8) is the same equation as is shown in 7.6.1 (1) of the Principal Text.

Also, Qs is obtained by equation (3).

(2) **How to Obtain Physical Size by Graph:** Equation (8) is quite complicated and the calculation is somewhat troublesome. If this could be obtained by graphs, it would be extremely easy to determine the particle size. Accordingly, in 7.6.1 (2) of the Principal Text, a simple method of determining the particle size by graph instead of by calculation is described based on the impacter show in Principal Table 2 with number of jet nozzles (N), jet nozzle bore (Dc), and inertia parameter (Y_{50}). Since, from Table 2, N, Dc and Y_{50} are defined for each stage, if the suction flow rate at the suction nozzle (Qs) and the exhaust gas temperature (θs) are known, then from equation (8), the particle size (Dp_{50}) can easily be obtained by graph as a function of Qs and θs. Here, the temperature correction in Principal Figure 9 is, as can be seen from equation (7), mainly a correction due to the viscosity coefficient of the gas.

Also, the majority of the usual powder-related processes is carried out at ordinary temperature. Accordingly, Principal Figure 8, in consideration of use at ordinary temperature, shows a graph at 20°C, and Principal Figure 9 shows the temperature correction factor for exhaust gas temperatures in the range of 0 to 450°C with 20°C as temperature correction factor 1.0.

7.6.2 Method of Calculating Particle Size Requiring Cunningham's Correction Factor:

When the particle size is less than 1μm, it is necessary to use Cunningham's correction factor (C). C is expressed by the following equation by approximation based on equation (2).

$$C = 1 + \frac{1.257 \times 2n}{Dp} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

Where, Dp : Particle size (μm)
n : Mean free path of gas molecules (μm)

If C in equation (6) is substituted with equation (9), equation (10) for particle size (Dp_{50}) is obtained.

$$Dp_{50}{}^{2} + 1.257 \times 2n \times Dp_{50} - \frac{18 \times 60 \times \pi \times N \times Y_{50} \times \mu \times Dcn^{3} \times 10}{4 \times Qs} = 0 \ \ldots \ (10)$$

n is determined from equation (11).

$$n = 2.10 \times 10^{-5} \times (172 + 0.4 \times \theta) \times \sqrt{(273 + \theta s)} \ \ldots\ldots\ldots \ (11)$$

Accordingly, if equation (7) was substituted for equation (10), and only the positive solution of the quadratic equation of Dp_{50} was taken to be the particle size Dp_{50}, equation (12) is obtained.

$$Dp_{50} = -1.26 \times n + \sqrt{1.58 \times n^{2} + \frac{1.08 \times \pi \times N \times Y_{50} \times Dcn^{3} \times (172 + 0.4 \times \theta s) \times 10^{-1}}{4 \times Qs}} \ \ldots (12)$$

Substitute equation (11) for equation (12) and obtain the particle size at each stage. Equations (12) and (11) are those respectively shown in 7.6.2 of the Principal Text. Equation (12) may also be used for particulates of 1μm and above. However, actually since, with particulates of 1μm and above, there is practically no difference from the particle size determined by equation (8), it is quite sufficient to carry out the calculation using equation (8).

(1) **Rounding Off Particle Size:** As the classified particulates themselves of an impacter, both theoretically and structurally, have a certain particle size distribution, there is a limit to the classification accuracy. Accordingly, with normal impacters, the third digit of the particle size obtained by calculation shall be rounded off and only the value up to the second digit shall be adopted

as the significant figure, as shown in Explanatory Table 3.

Explanatory Table 3 Examples of Rounding Off of Particle Size

Calculated Particle Size	Rounded Off Particle Size
15.432 µm	15 µm
0.4378 µm	0.44 µm

(2) **Physical Constants Required for Particle Size Calculation:** The physical constants required for particle size calculations are the viscosity coefficient of the gas (µ), the mean free path of gas molecules (n) and Cunningham's correction factor (C). Given here is a summarized commentary on these physical constants.

(a) **Viscosity Coefficient of Gas:** Exhaust gas is normally a combination of N_2, O_2, CO_2, SOx, NOx and other gases but as far as the viscosity of the gas is concerned, it can be treated more or less as the viscosity of air.

Although there are various experimental equations in the viscosity coefficient equations of gas such as the Sutherland equation and Hirshfelder equation, shown here is a relatively simple and widely used equation for air.

$$\mu = 170 \times 10^{-6} \times \left(\frac{T}{273} \right)^{0.768} \quad \ldots\ldots\ldots\ldots\ldots\ldots (13)$$

Where, µ : Viscosity coefficient of gas (g/cm·s)
T : Absolute temperature of gas (K)

Equation (13) inscribes a gentle curve for temperature, but if this was approximated to a straight line, it would still have practically no effect on the calculation of particle size. Accordingly, equation (7) is obtained by approximating to a straight line the temperature range of 0 to 450°C of equation (13).

$$\mu = 10^{-6} \times (172 + 0.4 \times \theta s) \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Where, θs : Exhaust gas temperature (°C)

If equation (7) is used to calculate the particle size, the calculation becomes relatively simple.

(b) **Mean Free Path of Gas Molecules:** The mean free path (n) of gas molecules is expressed by the following equation.

$$n = \frac{82.057 \times \mu \times T}{0.499 \times P \times M \times \sqrt{\dfrac{8 \times R \times T}{\pi \times M}}} \times 10^4 \quad \ldots\ldots\ (14)$$

Here, the internal pressure of a normal impacter is about 1 atmosphere, and the molecular weight of gas (M) may also be considered as the molecular weight of air.

Here, P : Pressure of gas (1 atm)
M : Molecular weight of air (28.9) (g/mol)
R : Gas constant [8.31×10^7 (erg/K·mol)]
T : Absolute temperature of gas [273 + θs (°C)](K)

and if these are substituted, together with the equation (7) for viscosity coefficient of the gas (μ), in equation (14), equation (11) is obtained. Equation (11) is the function of only the temperature. Therefore, the mean free path of the gas, when the internal pressure of the impacter is normal, is influenced by practically the temperature only.

Also, when the internal pressure of the impacter is small, since n becomes large in accordance with equation (14), the measurement of fine particulates becomes possible with a low pressure type impacter.

(c) **Cunningham's Correction Factor:** When the particulates dispersed in the air flow are small, a phenomenon of the particulates slipping into the voids in the gas molecules in motion occurs, and a correction for inertial theory of particulates becomes necessary. The correction factor in such a case is Cunningham's correction factor. Cunningham's correction factor (C) is usually expressed by equation (2).

In equation (2), since, in the particle size range that is obtained by an impacter, the index item may be ignored, equation (9) is obtained by adopting up to the third item of equation (2). As is clear from equations (9) and (11), Cunningham's correction factor varies depending on temperature, particle size and pressure. In a normal impacter, since the internal pressure is about 1 atmosphere, Cunningham's correction factor depends on particle size and temperature, but with particle size of 1μm or more the factor becomes $C \doteqdot 1$, and, conversely, the smaller the particle size is, the bigger the effect on temperature. Cunningham's correction factor becomes as per Explanatory Table 4 depending on exhaust gas temperature and particle size.

In exhaust gas temperatures of 500°C or higher, pay heed to the fact that Cunningham's correction factor increases even with particle sizes of 1μm or more.

Explanatory Table 4 Cunningham's Correction Factor Depending on Exhaust Gas Temperature and Particle Size

Exhaust Gas Temperature (°C)	Cunningham's Correction Factor	
	Dp = 1 μm	Dp = 0.1 μm
20	1.163	2.63
200	1.289	3.89
500	5.547	6.47
800	1.850	9.50

(3) **Example of Particle Size Calculation:** The following shows an example of an actual calculation.

(a) **When Cunningham's Correction Factor is Not Required:** The 50% separation size at the 4th stage is calculated when the exhaust gas temperature $\theta s = 143°C$, and the suction flow rate at the suction nozzle $Qs = 17$ l/min., as follows:

From Principal Table 2, N, Dcn and Y_{50} at the 4th stage are $N = 264$, $Dcn = 0.72mm$, and $Y_{50} = 0.14$.

Accordingly, from the equation in 7.6.1 of the Principal Text:

$$Dp_{50\ 4} = \sqrt{\frac{2.70 x 3.14 x 264 x 0.14 x (0.72)^3 x (172+0.4 x 143) x 10^{-2}}{17}} = 4.0\ (\mu m)$$

(b) **To Obtain Physical Size from Graph:** Obtain the physical size when the conditions are the same as (a) above, from Principal Figures 8 and 9, Since the suction flow rate at the suction nozzle $Qs = 17$ l/min., from Principal Figure 8, the physical size obtained at 20°C is 3.5μm. In addition, since the exhaust gas temperature is 143°C, from Principal Figure 9, the temperature correction factor is 1.15.

From this $Dp_{50\ 4} = 3.5\mu m \ X\ 1.15 = 4.0\mu m$ is obtained.

(c) **When Cunningham's Correction Factor is Required:** The 50% separation size at the 8th stage is calculated when the exhaust gas temperature $\theta s = 310°C$, and the suction flow rate at the suction nozzle $Qs = 21$ l/min., as follows:

From Principal Table 2, $N = 156$, $Dcn = 0.25mm$ and $Y_{50} = 0.14$. Accordingly, from the equation in 7.6.2 of the Principal Text, first the mean free path of the gas molecules (n) is calculated, as follows:

$$n = 2.10 x 10^{-5} x (172 + 0.4 x 310) x \sqrt{(273 + 310)}$$
$$= 0.15\ (\mu m)$$

In addition, using n, the particle size ($Dp_{50\ 4}$) is calculated as follows:

$$Dp_{50\ 8} = -1.257 \times 0.150 + \sqrt{1.58x(0.150)^2 + \frac{1.08x3.14x156x0.14x(0.25)^3x(172+0.4x310)x10^{-1}}{4 \times 21}}$$

$$= 0.48\ (\mu m)$$

(4) **Low Pressure Type Impacter:** With normal cascade impacters, the particle size that can be measured is about 0.3µm and above, but by lowering the internal pressure of the classifier-collector, it is possible to measure even smaller particle sizes. Theoretically, if the internal pressure of the classifier-collector is lowered, from equation (14), the mean free path of the gas molecules (n) increases, accompanying which Cunningham's correction factor also increases in accordance with equations (2) or (9). As a result, from equation (6), the particle size (Dp_{50}) diminishes and under pressure reduction the collection of even finer particles is possible. In such a case, the approximation equation shown in 7.6.2 of the Principal Text cannot be used and it is necessary to obtain the particle size (Dp_{50}) by repeatedly substituting an appropriate Dp_{50} in equation (2).

8. Summarizing of Measured Results

8.1 Integrated Distribution: It is customary for the amount of dust collected at each stage of the cascade impacter, after being summarized as shown in Principal Table 3, to be expressed by the integrated distribution curve using the undersize (D) [or the oversize (R), R + D = 100%] as the axis of ordinates and the undersize (or the oversize) which is the particle size (Dp) as the axis of abscissas (refer to Principal Figure 10).

However, it is known that the distribution of many kinds of dust, when drawn on logarithmic normal probability paper, come out at as a line; these kinds of dust are known as having a logarithmic normal distribution.

Logarithmic normal distribution [$f(\mathrm{Dp})$], where Y is the mass percentage (integrated undersize percentage) of all the particulates smaller than the particle size (Dp), is expressed by the following equation:

$$Y = 100\int_{0}^{\mathrm{Dp}} f(\mathrm{Dp}) \times d(\log \mathrm{Dp}) \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (15)$$

If this equation is used, the integrated distribution can be expressed by the two values of average particle size (Dpn) and standard deviation (σg) and Dpg and σg can be obtained by logarithmic normal probability paper (Principal Figure 11).

$$\sigma g = \frac{\text{Integrated undersize 84.13\% size}}{\mathrm{Dpg}} = \frac{\mathrm{Dpg}}{\text{Integrated undersize 15.87\% size}} \quad \dots\dots \quad (16)$$

These 84.13% and 15.87% lines are entered in logarithmic normal probability paper same as the 50% line.

For example, σg of Principal Figure 11 is:

$$\sigma g = \frac{4.6}{2.05} = \frac{2.05}{0.91} \fallingdotseq 2.25$$

On the other hand, it is known that much of the dust that is generated in industrial processes comply with the Rosin-Rammler distribution. The Rosin-Rammler equation is expressed as follows:

$$R = 100 \exp(-\beta \mathrm{Dp}^{n}) = 100 \times 10^{-\beta \mathrm{Dp}^{n}} \quad \dots\dots\dots\dots\dots\dots \quad (17)$$

Here, factor (β) (or β') and index (n) of the particle size (Dp), are constants determined by the kind of dust, β (or β') being called the grading characteristic factor and n, the distribution index. The following equation is obtained by taking the common logarithm of the two sides of equation

(17) two times:

$$\log (2-\log R) = \log\beta' + n\log Dp \quad \text{.......................} \quad (18)$$

That is to say, by taking log Dp as the axis of abscissas and log (2-log R) as the axis of ordinates, equation (18) is expressed as a relationship to a straight line. A diagram with such special gradations is called a Rosin-Rammler diagram. By expressing factors β and n with this diagram, it is possible to characterize the size of the particulates and the state of distribution.

In the remarks, it was mentioned that the integrated distribution curve could be expressed by the interpolation method. There are the following ways of obtaining the integrated distribution curve by the interpolation method and each has its characteristics.

The calculation process of Mizohata, etc.'s method of inducing the function for expressing the integrated distribution, employing Tokusaka's curved composite theory, is simple and has many features such as being able to cope even when there is a deviation from the logarithmic normal distribution.

Also, there is a way to draw a very smooth curve within the given conditions by adding the natural conditions at spline function to the foregoing method and not fixing the minimum and maximum particle sizes.

In a method using the fourth to ninth degree equations of Lagrange's interpolation method, which is the usual interpolation method, it is reported that, as relative standard error, the variation at the position and height of the peak of the curved distribution due to the second degree, is within 3.5%.

Besides these, from the fact that part of the particle size distribution is applicable to the logarithmic normal distribution, there is a method whereby the integrated distribution curve can be expressed by laying two logarithmic normal distribution curves on top of each other, and, as an interpolation method, there is way of drawing a smooth, distortionless curve easily and accurately with a personal computer, employing the tertiary spline function.

8.2 **Frequency Distribution:** Frequency distribution should be called a way of finely expressing particle size distribution, and is expressed by the number or by the ratio of mass of particulates contained in appropriate particle size intervals.

If the ratio of dust in a certain range of physical size classification δDp (in case of semi-logarithmic scale, δlogDp) is δR, frequency (f) is:

$$f = \left| \frac{\delta R}{\delta Dp} \right| \text{ or } f = \left| \frac{\delta R}{\delta \log Dp} \right| \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (19)$$

The frequency distribution curve can be obtained by plotting the frequency (f) against the particle size (Dp).

Frequency distribution is expressed either by this sort of frequency distribution curve or by histogram.

A histogram, generally, makes the physical size classification width the same and expresses the number of appearances (that is, the rate of collection δW/W) by the height of columns, or, even if the classification width was not the same, by lining up columns with areas in proportion to the number of appearances. In this Standard, the latter method of expression was employed in 8.2 of the Principal Text. The reason for that was that, of the data obtained by employing a cascade impacter, the 50% separation size (Dp_{50}) which denotes the classification width, is not only determined by the jet nozzle bore (Dc), but by the suction flow rate (Qs) and several other parameters, so it would be difficult to make the intervals equidistant.

Note that, from the integrated distribution curve, although it would be possible to obtain δR for the equal classification widths (δDp) (or δlogDp), and to draw a histogram of equal widths, it was not adopted in this Standard. This was because, for the beginner, the obtaining of classification widths would cause confusion and other inconveniences.

Note that a convenient method of taking the classification width of each stage of a cascade impacter as 50% separation size and making the height of the columns the collection rate (δW/W) has been included as a reference at the end of the Principal Text. This was because current circumstances were taken into consideration as although this differs from the original definition of frequency distribution, it is nevertheless convenient and so is in general use.

Next, the work of accurately preparing a frequency distribution curve from a histogram is not necessarily easy. In drawing a smooth curve, it should not always pass through the mid point of the top side of each column, instead it should be smoothed out so that the area covered by the curve and the area cut off by the curve are equal. In order to obtain a smooth distribution curve, it is possible to approximate the cumulative distribution data to the 50% classification size and from that differential, obtain the frequency distribution. The interpolation method for that purpose was described in a preceding paragraph.

As mentioned in the foregoing, since the work of preparing a frequency distribution curve is not entirely easy, it is many times expressed by integrated distribution.

Method of Calibrating Cascade Impacters: This Standard specifies the method of measuring the particle size distribution of dust by cascade impacter and does not specify the calibration method, but in order to check performance, it is desirable that the calibration method be specified by a separate Standard.

In the calibration of cascade impacters and other particle size distribution measuring devices, there are still some technical problems with respect to the evaluation of the particles for calibration and of the classification performance test results employing those particles, and, although up to now, there is no calibration method that has been established with the agreement of the various fields, in practice, various methods of calibration are being used.

The performance of a cascade impacter is currently guaranteed by the maker's in-house calibration, but since independent calibration by the user is also conceivable, an example of a calibration method is introduced herewith for reference.

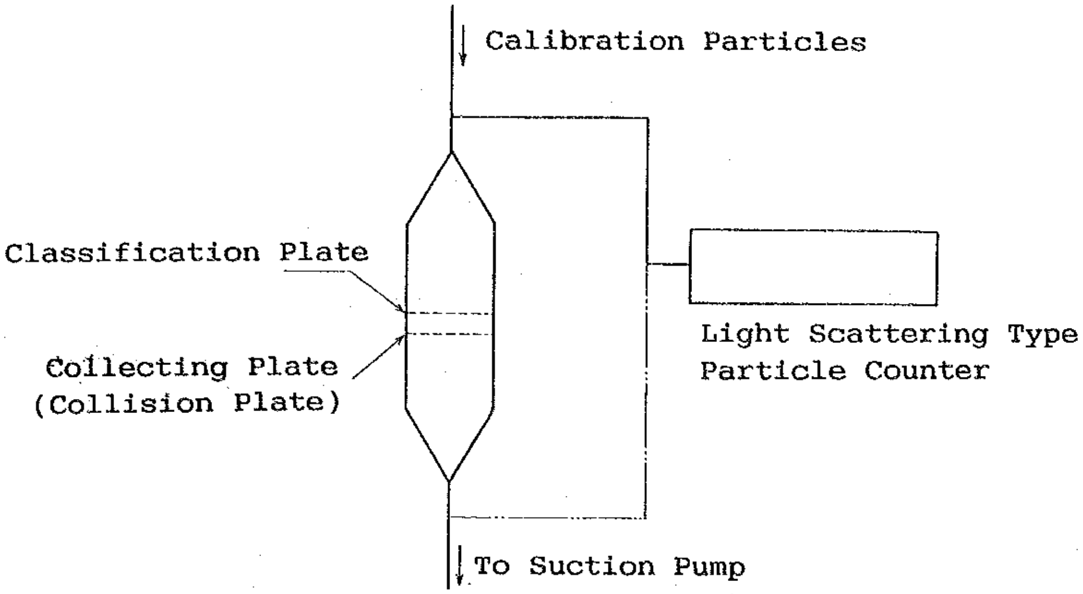
(1) **Scope of Calibration:** Calibration mentioned here shall apply to calibration of each individual classification plate.

(2) **Particles Used for Calibration:** Particles of a pre-known size such as polystyrene latex particles or dioctyl phthalate (DOP) particles with a density close to 1 shall be used for calibration.

(3) **Method of Generating Particles for Calibration:** Particles for calibration shall be diffused with an atomizer or other device and shall be reduced to the required density with clean air.

(4) **Calibration Method:** Set the classifying plate and the collision plate as shown in Explanatory Figure 13, suck in the generated particles for calibration, and, using a light scattering type particle counter specified in JIS B 9921 (Particle Counter by Light Scattering Method), measure the particle quantity concentration by particle size before and after suction, and obtain the characteristics of the classifying plate and the 50% separated particle size.

Note that the flow rate of the air containing the calibration particles to be set when calibrating, shall be one point within a certain flow rate range.



Explanatory Figure 13 **BLOCK DIAGRAM OF CALIBRATION METHOD**

APPENDIX 4 Calculation of Simulation for 9 Stacks of Central Puerto and Central Costanera Power Station (for 3 month long term sumulation from June to August)

Appendix 4 Calculation of Simulation for 9 Stacks of Central Puerto and Central Costanera Power Station (for 3 month long term simulation from June to August)

b:PUCOS **Number of Stack: 9** **Emission Source Data**

	X(m)	Y(m)	Ho(m)	D(m)	Q(Nm'3/h)	T('C)	C(ppm)
1	10000.0	10000.0	70.0	7.6	1220400.0	136.0	202.0
2	9040.0	9020.0	64.0	4.2	896400.0	136.0	201.0
3	9520.0	10380.0	47.0	5.0	270000.0	136.0	200.0
4	9560.0	10360.0	45.0	5.6	439200.0	136.0	201.0
5	9600.0	10320.0	47.0	3.0	896400.0	136.0	201.0
6	13060.0	5780.0	86.7	6.5	471600.0	136.0	604.0
7	12980.0	5840.0	86.7	6.5	471600.0	136.0	407.0
8	13100.0	5740.0	97.5	4.8	1238400.0	136.0	201.0
9	12800.0	5700.0	155.0	5.6	1105200.0	136.0	200.0

Wind Direction N

Wind Speed (m/s)	Day Insolation (cal/cm^2/h)						Day & Night		Night Cloud Amount			
	>50	hr	49-25	hr	<24	hr	8-10	hr	5-7(10)	hr	0-4	hr
0.0	A	0	A-B	0	B	0	D	0	F	0	G	0
1.5	A	2	A-B	0	B	0	D	0	F	0	G	10
2.5	A-B	2	B	0	C	0	D	0	E	0	F	13
3.5	B	1	B-C	0	C	0	D	0	D	0	E	5
5.0	C	0	C-D	0	D	0	D	0	D	0	D	0
7.0	C	0	D	0	D	0	D	1	D	0	D	0

Wind Direction NNE

Wind Speed (m/s)	Day Insolation (cal/cm^2/h)						Day & Night		Night Cloud Amount			
	>50	hr	49-25	hr	<24	hr	8-10	hr	5-7(10)	hr	0-4	hr
0.0	A	0	A-B	0	B	0	D	0	F	0	G	0
1.5	A	1	A-B	0	B	0	D	0	F	0	G	13
2.5	A-B	1	B	0	C	0	D	1	E	0	F	17
3.5	B	0	B-C	0	C	0	D	1	D	0	E	12
5.0	C	4	C-D	0	D	0	D	3	D	0	D	4
7.0	C	1	D	0	D	0	D	0	D	0	D	1

Wind Direction NE

Wind Speed (m/s)	Day Insolation (cal/cm^2/h)						Day & Night		Night Cloud Amount			
	>50	hr	49-25	hr	<24	hr	8-10	hr	5-7(10)	hr	0-4	hr
0.0	A	0	A-B	0	B	0	D	0	F	0	G	0
1.5	A	0	A-B	0	B	0	D	3	F	0	G	15
2.5	A-B	1	B	1	C	0	D	0	E	0	F	16
3.5	B	0	B-C	2	C	0	D	1	D	0	E	5
5.0	C	0	C-D	0	D	0	D	6	D	0	D	7
7.0	C	0	D	0	D	0	D	1	D	0	D	0

Wind Direction ENE

Wind Speed (m/s)	Day Insolation (cal/cm^2/h)						Day & Night		Night Cloud Amount			
	>50	hr	49-25	hr	<24	hr	8-10	hr	5-7(10)	hr	0-4	hr
0.0	A	0	A-B	0	B	0	D	0	F	0	G	0
1.5	A	1	A-B	0	B	0	D	0	F	0	G	5
2.5	A-B	0	B	0	C	0	D	1	E	0	F	8
3.5	B	0	B-C	0	C	0	D	2	D	1	E	2
5.0	C	0	C-D	0	D	0	D	7	D	1	D	5
7.0	C	0	D	0	D	0	D	2	D	0	D	6

Wind Direction E

Wind Speed (m/s)	Day Insolation (cal/cm^2/h) >50	hr	49-25	hr	<24	hr	Day & Night 8-10	hr	5-7(10)	hr	Night Cloud Amount 0-4	hr
0.0	A	0	A-B	0	B	0	D	0	F	0	G	0
1.5	A	0	A-B	0	B	0	D	0	F	0	G	5
2.5	A-B	0	B	0	C	0	D	0	E	0	F	7
3.5	B	0	B-C	0	C	0	D	2	D	0	E	11
5.0	C	2	C-D	1	D	0	D	1	D	3	D	11
7.0	C	0	D	0	D	0	D	2	D	1	D	3

Wind Direction ESE

Wind Speed (m/s)	Day Insolation (cal/cm^2/h) >50	hr	49-25	hr	<24	hr	Day & Night 8-10	hr	5-7(10)	hr	Night Cloud Amount 0-4	hr
0.0	A	0	A-B	0	B	0	D	0	F	0	G	0
1.5	A	0	A-B	0	B	0	D	0	F	0	G	4
2.5	A-B	0	B	0	C	0	D	2	E	1	F	6
3.5	B	0	B-C	0	C	0	D	9	D	1	E	10
5.0	C	2	C-D	2	D	0	D	19	D	2	D	19
7.0	C	0	D	2	D	1	D	11	D	6	D	5

Wind Direction SE

Wind Speed (m/s)	Day Insolation (cal/cm^2/h) >50	hr	49-25	hr	<24	hr	Day & Night 8-10	hr	5-7(10)	hr	Night Cloud Amount 0-4	hr
0.0	A	0	A-B	0	B	0	D	0	F	0	G	0
1.5	A	0	A-B	0	B	0	D	2	F	1	G	0
2.5	A-B	0	B	0	C	0	D	1	E	1	F	1
3.5	B	0	B-C	0	C	0	D	4	D	0	E	2
5.0	C	0	C-D	0	D	1	D	11	D	2	D	6
7.0	C	0	D	0	D	0	D	6	D	0	D	0

Wind Direction SSE

Wind Speed (m/s)	Day Insolation (cal/cm^2/h) >50	hr	49-25	hr	<24	hr	Day & Night 8-10	hr	5-7(10)	hr	Night Cloud Amount 0-4	hr
0.0	A	0	A-B	0	B	0	D	0	F	0	G	0
1.5	A	2	A-B	0	B	0	D	3	F	0	G	1
2.5	A-B	2	B	0	C	0	D	0	E	1	F	3
3.5	B	0	B-C	0	C	0	D	0	D	0	E	5
5.0	C	0	C-D	0	D	0	D	8	D	1	D	6
7.0	C	0	D	0	D	0	D	3	D	0	D	1

Wind Direction S

Wind Speed		Day Insolation		(cal/cm^2/h)			Day & Night				Night Cloud Amount	
(m/s)	>50	hr	49-25	hr	<24	hr	8-10	hr	5-7(10)	hr	0-4	hr
0.0	A	0	A-B	0	B	0	D	0	F	0	G	0
1.5	A	0	A-B	0	B	1	D	3	F	0	G	4
2.5	A-B	0	B	0	C	1	D	5	E	1	F	6
3.5	B	0	B-C	0	C	0	D	6	D	2	E	11
5.0	C	2	C-D	1	D	2	D	27	D	5	D	9
7.0	C	0	D	0	D	0	D	4	D	2	D	2

Wind Direction SSW

Wind Speed		Day Insolation		(cal/cm^2/h)			Day & Night				Night Cloud Amount	
(m/s)	>50	hr	49-25	hr	<24	hr	8-10	hr	5-7(10)	hr	0-4	hr
0.0	A	0	A-B	0	B	0	D	0	F	0	G	0
1.5	A	7	A-B	1	B	0	D	6	F	3	G	18
2.5	A-B	2	B	3	C	0	D	8	E	3	F	10
3.5	B	0	B-C	0	C	0	D	11	D	2	E	20
5.0	C	0	C-D	0	D	0	D	17	D	10	D	18
7.0	C	0	D	0	D	0	D	5	D	0	D	8

Wind Direction SW

Wind Speed		Day Insolation		(cal/cm^2/h)			Day & Night				Night Cloud Amount	
(m/s)	>50	hr	49-25	hr	<24	hr	8-10	hr	5-7(10)	hr	0-4	hr
0.0	A	0	A-B	0	B	0	D	0	F	0	G	0
1.5	A	4	A-B	0	B	1	D	4	F	1	G	11
2.5	A-B	5	B	2	C	0	D	5	E	2	F	14
3.5	B	0	B-C	0	C	1	D	5	D	0	E	17
5.0	C	1	C-D	0	D	0	D	1	D	1	D	12
7.0	C	0	D	0	D	0	D	0	D	0	D	0

Wind Direction WSW

Wind Speed		Day Insolation		(cal/cm^2/h)			Day & Night				Night Cloud Amount	
(m/s)	>50	hr	49-25	hr	<24	hr	8-10	hr	5-7(10)	hr	0-4	hr
0.0	A	0	A-B	0	B	0	D	0	F	0	G	0
1.5	A	0	A-B	0	B	0	D	1	F	0	G	5
2.5	A-B	1	B	1	C	0	D	3	E	2	F	18
3.5	B	2	B-C	0	C	0	D	0	D	0	E	9
5.0	C	0	C-D	0	D	0	D	0	D	0	D	4
7.0	C	0	D	0	D	0	D	0	D	0	D	0

Wind Direction W

Wind Speed (m/s)	Day Insolation (cal/cm^2/h)						Day & Night				Night Cloud Amount	
	>50	hr	49-25	hr	<24	hr	8-10	hr	5-7(10)	hr	0-4	hr
0.0	A	0	A-B	0	B	0	D	0	F	0	G	0
1.5	A	6	A-B	1	B	0	D	5	F	0	G	14
2.5	A-B	1	B	1	C	0	D	7	E	0	F	13
3.5	B	1	B-C	0	C	0	D	2	D	1	E	7
5.0	C	2	C-D	1	D	0	D	0	D	0	D	8
7.0	C	0	D	0	D	0	D	0	D	0	D	4

Wind Direction WNW

Wind Speed (m/s)	Day Insolation (cal/cm^2/h)						Day & Night				Night Cloud Amount	
	>50	hr	49-25	hr	<24	hr	8-10	hr	5-7(10)	hr	0-4	hr
0.0	A	0	A-B	0	B	0	D	0	F	0	G	0
1.5	A	5	A-B	0	B	0	D	2	F	1	G	22
2.5	A-B	3	B	0	C	0	D	2	E	0	F	14
3.5	B	2	B-C	0	C	0	D	1	D	0	E	14
5.0	C	3	C-D	1	D	0	D	2	D	2	D	15
7.0	C	0	D	0	D	0	D	2	D	1	D	8

Wind Direction NW

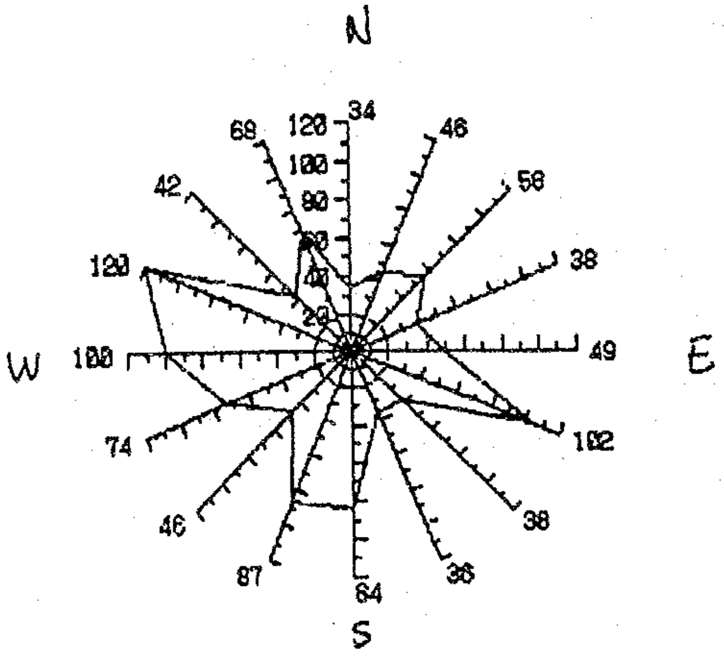
Wind Speed (m/s)	Day Insolation (cal/cm^2/h)						Day & Night				Night Cloud Amount	
	>50	hr	49-25	hr	<24	hr	8-10	hr	5-7(10)	hr	0-4	hr
0.0	A	0	A-B	0	B	0	D	0	F	0	G	0
1.5	A	1	A-B	0	B	0	D	0	F	1	G	13
2.5	A-B	4	B	1	C	0	D	1	E	2	F	23
3.5	B	4	B-C	0	C	0	D	1	D	0	E	11
5.0	C	2	C-D	0	D	0	D	6	D	0	D	23
7.0	C	2	D	1	D	2	D	8	D	0	D	14

Wind Direction NNW

Wind Speed (m/s)	Day Insolation (cal/cm^2/h)						Day & Night				Night Cloud Amount	
	>50	hr	49-25	hr	<24	hr	8-10	hr	5-7(10)	hr	0-4	hr
0.0	A	0	A-B	0	B	0	D	0	F	0	G	0
1.5	A	1	A-B	0	B	0	D	0	F	0	G	8
2.5	A-B	1	B	0	C	0	D	2	E	0	F	9
3.5	B	0	B-C	0	C	0	D	1	D	0	E	5
5.0	C	0	C-D	0	D	0	D	0	D	0	D	7
7.0	C	0	D	0	D	1	D	2	D	0	D	5

Wind Direction CALM

	Day						Day & Night			Night		
	Insolation		(cal/cm^2/h)							Cloud Amount		
Wind Speed (m/s)	>50	hr	49-25	hr	<24	hr	8-10	hr	5-7(10)hr		0-4	hr
0.0	A	5	A-B	0	B	0	D	7	F	1	G	55
1.5	A	0	A-B	0	B	0	D	0	F	0	G	0
2.5	A-B	0	B	0	C	0	D	0	E	0	F	0
3.5	B	0	B-C	0	C	0	D	0	D	0	E	0
5.0	C	0	C-D	0	D	0	D	0	D	0	D	0
7.0	C	0	D	0	D	0	D	0	D	0	D	0



Calm: 68 hrs

Data
Range: X=20000.0, Y=20000.0
Numbers of stack: 9   Road: 1   Measurement Point: 1
Total hours: 1199
Calm Continueing hours: 180.00 min
Plume Rise Formula: Concawe

Cmax=4.7761E-003 Concentration of Superposition (ppm)

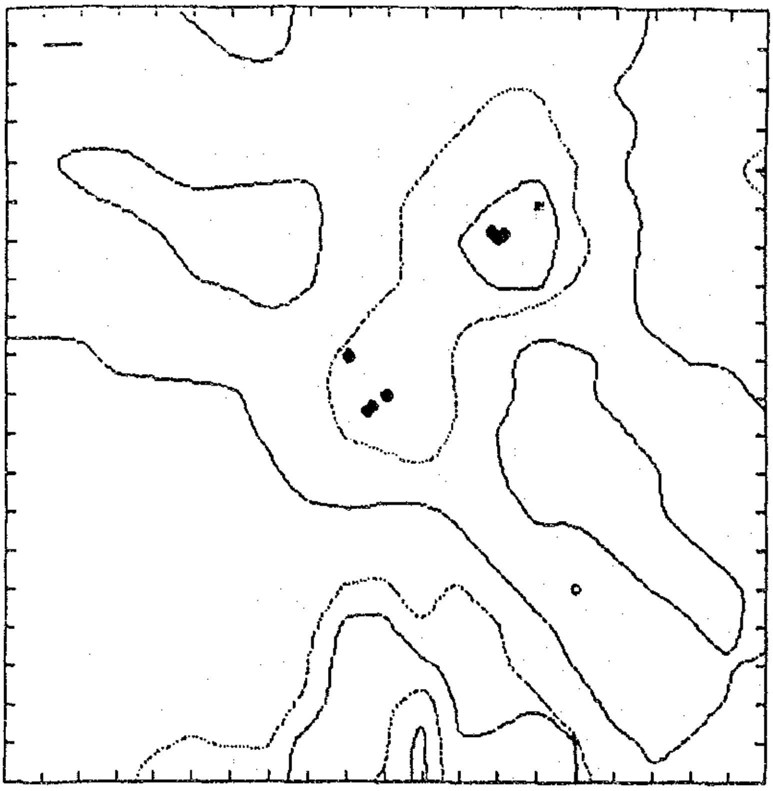
Y(m)							X(m)
	0	1000	2000	3000	4000	5000	6000
0	1.54E-003	1.59E-003	1.62E-003	1.57E-003	1.52E-003	8.27E-004	8.23E-004
1000	1.57E-003	1.61E-003	1.65E-003	1.68E-003	1.55E-003	1.62E-003	9.52E-004
2000	1.59E-003	1.63E-003	1.67E-003	1.70E-003	1.73E-003	1.64E-003	1.62E-003
3000	1.78E-003	1.65E-003	1.69E-003	1.73E-003	1.82E-003	1.70E-003	1.60E-003
4000	1.56E-003	1.26E-003	9.33E-004	9.56E-004	1.25E-003	1.60E-003	1.59E-003
5000	1.71E-003	1.75E-003	1.31E-003	1.14E-003	9.85E-004	9.73E-004	8.78E-004
6000	1.73E-003	1.83E-003	1.86E-003	1.74E-003	1.30E-003	9.66E-004	9.58E-004
7000	1.74E-003	1.84E-003	1.88E-003	1.89E-003	1.90E-003	1.22E-003	1.07E-003
8000	1.59E-003	1.66E-003	1.67E-003	1.68E-003	1.83E-003	1.77E-003	1.51E-003
9000	8.31E-004	8.59E-004	8.75E-004	1.54E-003	1.58E-003	1.68E-003	1.68E-003
10000	8.30E-004	8.59E-004	8.75E-004	8.87E-004	9.21E-004	9.46E-004	1.07E-003
11000	8.17E-004	8.46E-004	8.60E-004	8.70E-004	8.81E-004	9.15E-004	9.42E-004
12000	8.01E-004	8.28E-004	8.05E-004	8.11E-004	7.32E-004	7.52E-004	8.46E-004
13000	7.57E-004	7.84E-004	7.94E-004	7.27E-004	7.20E-004	7.34E-004	7.65E-004
14000	7.34E-004	7.00E-004	6.92E-004	7.05E-004	7.14E-004	6.60E-004	6.93E-004
15000	6.53E-004	6.55E-004	6.83E-004	6.15E-004	6.28E-004	6.41E-004	6.52E-004
16000	6.19E-004	6.36E-004	5.88E-004	6.05E-004	6.16E-004	6.16E-004	5.89E-004
17000	5.34E-004	5.48E-004	5.61E-004	5.89E-004	5.92E-004	6.02E-004	5.17E-004
18000	5.24E-004	5.36E-004	5.48E-004	5.60E-004	5.69E-004	4.93E-004	5.01E-004
19000	5.12E-004	5.24E-004	5.35E-004	5.33E-004	4.94E-004	4.73E-004	4.83E-004
20000	5.00E-004	5.11E-004	5.09E-004	5.19E-004	4.35E-004	4.42E-004	4.48E-004

Cmax=4.7761E-003 Concentration of Superposition (ppm)

Y(m)							X(m)
	7000	8000	9000	10000	11000	12000	13000
0	8.14E-004	1.45E-003	1.59E-003	1.45E-003	1.48E-003	2.32E-003	2.31E-003
1000	8.23E-004	1.50E-003	1.63E-003	1.53E-003	1.67E-003	1.82E-003	2.34E-003
2000	1.58E-003	1.50E-003	1.62E-003	1.62E-003	1.66E-003	1.91E-003	2.37E-003
3000	1.54E-003	1.60E-003	1.61E-003	1.65E-003	1.87E-003	2.32E-003	2.80E-003
4000	1.51E-003	1.42E-003	2.15E-003	2.13E-003	2.28E-003	3.04E-003	2.93E-003
5000	8.20E-004	8.54E-004	1.77E-003	2.17E-003	2.74E-003	3.16E-003	3.72E-003
6000	8.66E-004	9.52E-004	1.69E-003	2.11E-003	2.73E-003	3.87E-003	3.91E-003
7000	1.00E-003	1.09E-003	1.71E-003	2.13E-003	2.72E-003	3.01E-003	3.88E-003
8000	1.22E-003	1.46E-003	1.84E-003	2.98E-003	3.29E-003	2.55E-003	2.25E-003
9000	2.19E-003	1.82E-003	2.71E-003	3.57E-003	3.46E-003	2.00E-003	1.33E-003
10000	1.48E-003	2.14E-003	2.68E-003	3.49E-003	3.25E-003	2.31E-003	1.34E-003
11000	1.32E-003	1.76E-003	2.48E-003	3.00E-003	3.30E-003	2.23E-003	1.18E-003
12000	1.04E-003	1.56E-003	1.88E-003	1.77E-003	2.31E-003	2.13E-003	1.23E-003
13000	9.11E-004	1.12E-003	1.18E-003	1.06E-003	9.31E-004	1.43E-003	1.50E-003
14000	7.51E-004	8.05E-004	6.51E-004	6.13E-004	7.23E-004	8.85E-004	1.42E-003
15000	6.04E-004	5.91E-004	4.56E-004	4.28E-004	6.14E-004	4.07E-004	1.01E-003
16000	5.55E-004	5.23E-004	3.20E-004	3.23E-004	4.76E-004	3.82E-004	3.78E-004
17000	5.27E-004	4.88E-004	2.85E-004	2.88E-004	3.38E-004	3.75E-004	3.72E-004
18000	5.08E-004	4.67E-004	2.69E-004	2.71E-004	1.44E-004	3.69E-004	3.66E-004
19000	4.88E-004	3.02E-004	2.60E-004	2.60E-004	8.23E-005	3.57E-004	3.54E-004
20000	4.24E-004	2.91E-004	2.51E-004	2.33E-004	7.95E-005	3.43E-004	3.31E-004

Cmax=4.7761E-003 **Concentration of Superposition (ppm)**

Y(m) \ X(m)	14000	15000	16000	17000	18000	19000	20000
0	2.29E-003	2.38E-003	2.23E-003	9.73E-004	9.62E-004	9.55E-004	9.51E-004
1000	2.33E-003	2.17E-003	1.69E-003	1.00E-003	9.76E-004	9.62E-004	9.28E-004
2000	2.33E-003	2.26E-003	1.16E-003	1.05E-003	1.00E-003	6.40E-004	5.61E-004
3000	2.96E-003	1.69E-003	1.39E-003	1.12E-003	7.02E-004	5.91E-004	5.69E-004
4000	3.37E-003	2.39E-003	1.24E-003	8.70E-004	6.76E-004	5.46E-004	3.12E-004
5000	4.78E-003	2.20E-003	1.37E-003	1.13E-003	6.91E-004	5.98E-004	5.76E-004
6000	4.42E-003	2.98E-003	1.75E-003	9.15E-004	7.03E-004	6.04E-004	5.77E-004
7000	3.98E-003	2.27E-003	1.38E-003	1.03E-003	8.92E-004	7.56E-004	6.29E-004
8000	1.40E-003	2.28E-003	1.57E-003	1.01E-003	9.28E-004	8.93E-004	8.65E-004
9000	9.56E-004	7.31E-004	1.47E-003	1.57E-003	1.15E-003	1.12E-003	1.08E-003
10000	1.02E-003	8.56E-004	1.59E-003	1.55E-003	1.53E-003	1.51E-003	1.08E-003
11000	8.75E-004	9.07E-004	8.22E-004	1.60E-003	1.59E-003	1.51E-003	1.46E-003
12000	9.84E-004	1.09E-003	1.06E-003	1.04E-003	1.71E-003	1.61E-003	1.55E-003
13000	1.09E-003	1.08E-003	1.08E-003	1.04E-003	1.77E-003	1.73E-003	1.59E-003
14000	1.37E-003	1.48E-003	1.15E-003	1.03E-003	1.00E-003	1.61E-003	1.56E-003
15000	1.33E-003	1.53E-003	1.49E-003	1.19E-003	9.68E-004	9.09E-004	1.53E-003
16000	1.11E-003	1.27E-003	1.44E-003	1.39E-003	1.26E-003	9.72E-004	1.49E-003
17000	6.70E-004	1.21E-003	1.39E-003	1.35E-003	1.27E-003	1.22E-003	1.01E-003
18000	3.59E-004	8.21E-004	1.32E-003	1.27E-003	1.23E-003	1.19E-003	1.15E-003
19000	3.50E-004	3.31E-004	1.09E-003	1.22E-003	1.19E-003	1.15E-003	1.11E-003
20000	3.27E-004	3.22E-004	6.16E-004	1.18E-003	1.14E-003	1.11E-003	1.07E-003



Xm 20000
b:PUCOS Region

Cmax ppm 4.77608e-00
Imax: 14 Jmax: 5

Numbers of Stack : 9
Number of Road : 1
Number of Measuring Points: 1
Total Hours : 1199
Calm Continueing hours : 3

Point of -> Maximum Ground Level Concentration

—— 0.75 ······ 0.5
—— 0.25 ······ 0.1
—— 7.5e-002 ······ 5.e-002
—— 2.5e-002 ······ 1.e-002

Y m 20000

APPENDIX 5 Text Book of Air Pollution Control Technology

Appendix 5 Text Book of Air Pollution Control Technology

(1) Sulfur oxides

1) Technology trend

With economic activity expanded worldwide, the amount of sulfur oxides discharged to the global environment is on the rapid rise, creating a serious problem of large-scale environmental destruction, such as acid rains. Efforts to reduce sulfur oxides (SO_2, SO_3) contained in flue gas produced by burning fossil fuel are actively pursued only in industrialized countries.

Sulfur oxides are produced when sulfur contents in fuel react with oxygen in the air. At present, countries attempt to reduce sulfur oxides in the following three ways:

a) Reduction of ground level concentration
b) Use of low sulfur content fuel
c) Installation of flue gas desulfurization equipment

a) is accomplished by increasing the height of stacks and bundling them, which improve the diffusion effect and lead to reduction of ground level concentration.

b) is designed to reduce sulfur oxides contained in flue gas by using desulfurized fuel oil, crude oil, or LNG and other gases which do not contain sulfur.

c) represents affirmative measures to remove sulfur oxides directly from flue gas.

2) Exhaust gas desulfurization methods

The worldwide installed capacity of flue gas desulfurization equipment is around 200 million KW (gas volume of 700 million Nm^3/h), and 90% are located in

Japan, the U.S., and former West Germany.

Desulfurization equipment is roughly divided into the wet and dry types, and most of desulfurizers in operation are of wet type. The wet type flue gas desulfurization process is classified into many types, which are generally indicated by absorbent, alkali material and by-product.

Table A5-1 classifies major desulfurization processes according to the type of absorbent, alkali material, and by-product. Among them, industrial boilers and boilers for large non-utility power plants mostly use processes producing gypsum for further use, in particular the lime-gypsum method. On the other hand, the non-recovery process is mostly used for smaller boilers because of large cost involved in the recovery process. The recovery process is installed only when by-products are consumed internally or can be sold on a long-term commercial basis. Smaller industrial boilers are mostly equipped with the discharge process using $Mg(OH)_2$ or NaOH as a raw material (discharged as magnesium sulfate or salt cake solution).

Table A5-1 Major Exhaust Gas Desulfurization Processes

Method	Process Type	Absorbent	State of Absorbing Solution	Raw Material		By-product
Wet Method	Lime-gypsum Method	Calcium sulfite $CaSO_3$	Slurry	Calcium carbonate Slaked lime Unslaked lime	$CaCO_3$ $Ca(OH)_2$ CaO	Gypsum
	Mg-gypsum Method	Magnesium sulfite $MgSO_3$ Calcium sulfite $CaSO_3$	Slurry	Slake lime Calcium carbonate	$Ca(OH)_2$ $CaCO_3$	Gypsum

(continued)

Wet Method	Soda Sulfite-Salt Cake Method	Sodium sulfite Na_2SO_3	Solution	Caustic soda	NaOH	Salt cake Discharge
	Soda Sulfite Recovery Method			Caustic soda	NaOH	Soda sulfite
	Soda Sulfite-Gypsum Method			Calcium carbonate Slaked lime Unslaked lime	$CaCO_3$ $Ca(OH)_2$ CaO	Gypsum
	Soda Sulfite-Sulfuric Acid Method			-		Sulfuric acid
	Dilute Sulfuric Acid-Gypsum Method	Dilute sulfuric acid	Solution	Calcium carbonate	$CaCO_3$	Gypsum
	NH_3-Ammonium Sulfate Method	Ammonium sulfite $(NH_4)_2SO_3$	Solution	Ammonia	NH_4OH	Ammonium sulfate
	NH_3-Gypsum Method			Slaked lime	$Ca(OH)_2$	Gypsum
	Al-gypsum Method	Basic aluminum sulfate $Al_2(SO_4)_3$ Al_2O_3	Slurry	Calcium cargonate	$CaCO_3$	Gypsum
	Mg Method	Magnesium sulfite	Solution	Magnesium hydroxide	$Mg(OH)_2$	Magnecium sulfate Discharge
Dry Method	Activated Carbon Absorption Method	Activated carbon		Activated carbon		Sulfur
	Spray Dryer Method	$Ca(OH)_2$ Na_2CO_3	Slurry	Slaked lime Sod ash	$Ca(OH)_2$ Na_2CO_3	Gypsum Others

All types of desulfurization equipment currently in use, excepting simple types, are capable of removing more than 90% of sulfur contained in flue gas.

3) Wet desulfurization methods

As shown in Table A5-1, the desulfurization process is classified into more than 10 types. Most of commercialized processes are of wet type. In particular, the wet type lime-gypsum method is widely used in Japan. With operation of more than 20 years, the process is highly reliable and is at a near completion level of technology. It is most widely used at thermal power plants because of the following reasons:

a) Lime stone used as a raw material for absorbing agent is available locally in large quantities. Lime stone is easy to use and most economical to process and handle.

b) The by-product, gypsum, has a high commercial value for cement and gypsum board, and can be stored safely in large quantities.

Since lime stone is the cheapest and most abundant SO_2 absorbing agent, the lime stone (lime) method will continue to be the most popular desulfurization method worldwide.

At the same time, given the increase in construction and operation costs due to the increasing use of larger systems, technology development is progressed for cost reduction through system integration, simplification, and energy saving.

(a) Wet type lime-gypsum method: basic process

The process described below was one of first commercialized, wet type, lime-gypsum, flue gas desulfurization processes. Since then, it has been modified in various stages and a large number of processes have been developed. This section defines the process as the basic process of the wet-type lime-gypsum method, which is described as follows.

In the basic process of flue gas desulfurization using the wet type lime-gypsum method, sulfite gas (SO_2) in flue gas is subject to liquid-vapor contact with an absorbing slurry containing lime stone in the absorber to produce calcium sulfite. Calcium sulfite in the absorbing solution is oxidized with air to produce gypsum, which is dehydrated to obtain the useful by-product. The system diagram of the lime-gypsum desulfurization equipment is shown in Figure A5-1.

The process consists of the cooling, absorption and reheating section, the oxidization and recovery section, and the material preparation section.

a) Cooling/absorption/reheating section

Exhaust gas produced from the boiler in combustion is pressurized by a desulfurization booster, and after heat exchange with gas at the outlet of the desulfurizer through a gas gas heater, enters a prescrubber. In the prescrubber, flue gas is cooled down by spraying a fluid recirculated in the tower, while removing dust, HCl, HF, and other impurities contained in the gas. The impurities so absorbed in the prescrubber become Cl- and F- ions, which accumulate in the circulated liquid. To control their concentration levels in the liquid, some of the liquid is regularly discharged and sent to a waste water treatment plant.

Exhaust gas cleaned in the prescrubber passes through a mist eliminator at the outlet of the prescrubber for removal of accompanied mist and enters an absorber.

In the absorber, SO_2 gas contained in the flue gas is absorbed and removed through a liquid-vapor contact with slurry containing lime stone, which is circulated in the absorber. The major chemical reaction in the absorption process is as follows:

$$CaCO_3 + SO_2 + 1/2H_2O \dashrightarrow CaSO_3 \cdot 1/2H_2O + CO_2\uparrow$$

Part of calcium sulfite produced in the absorber is oxidized by oxygen in the flue gas to become gypsum ($CaSO_4 \cdot 2H_2O$). The flue gas after desulfurization goes through the absorber's mist eliminator to remove accompanied mist, and is heated through the heat exchange process with gas to the inlet of the desulfurizer using a gas gas heater, before being released to the air through a stack.

b) Oxidization and gypsum recovery section

The calcium sulfite slurry produced in the absorber is extracted and sent to an oxidizer where it is oxidized by the air to become gypsum:

$$CaSO_3 \cdot 1/2H_2O + 1/2O_2 + 3/2H_2O \dashrightarrow CaSO_4 \cdot 2H_2O$$

In the process, to prevent unreacted calcium carbonate contained in the absorbing solution from being mixed in gypsum to cause poor quality, sulfuric acid is injected into the oxidizer to neutralize unreacted calcium carbonate.

The gypsum slurry produced in the oxidizer is condensed to a specific concentration in a thickener, and after dehydration through a gypsum separator, it is sent outside the system as the by-product.

The top clear part of the gypsum thickener is sent to the materials preparation section and is used for preparation of a raw material. Some are also sent to the prescrubber and is used as make-up water.

c) Materials preparation section

Lime stone used as a raw material, stored in a lime stone silo, is supplied to a materials pit through a dosing feeder and is mixed with the top clear part of the gypsum thickener to produce lime stone slurry. After being adjusted to a specific concentration, the slurry is supplied to the absorber and is used as the absorbing agent.

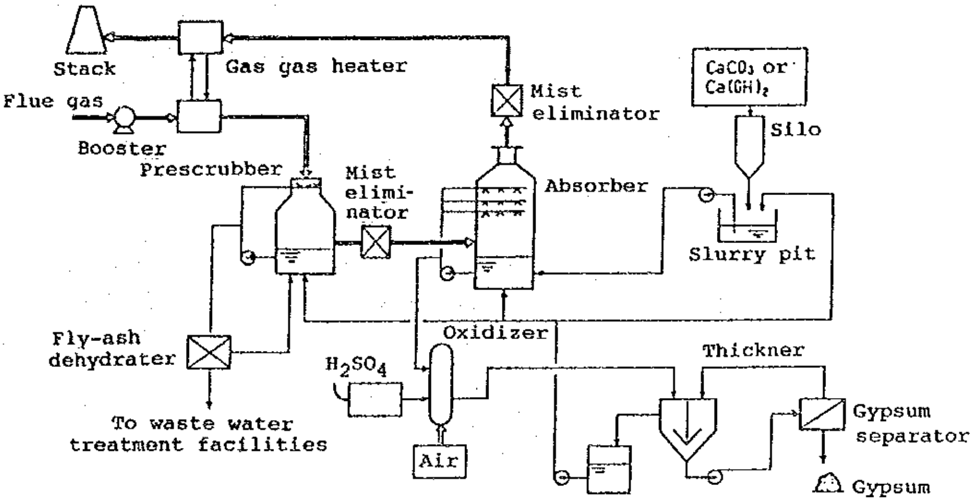


Figure A5-1 System Diagram of Basic Process of Lime-Gypsum Desulfurization Equipment

The wet type lime stone (lime) process has a major disadvantage in that gypsum produced in the process causes scaling. Part of calcium sulfite produced through the absorption process ($CaSO_3 \cdot 1/2H_2O$) is oxidized by oxygen in the gas to become gypsum ($CaSO_4 \cdot 2H_2O$) which deposits inside the absorber, piping, and demister.

To prevent scaling, the process is equipped with various features, including design and operation of the absorber.

In addition to prevention of scaling, the prescrubber is designed to remove ash in the flue gas to improve the quality of gypsum, and to remove HCl and HF in the gas so as to prevent corrosion and deterioration of reactivity of lime stone in the absorber.

Major disadvantages of the lime-gypsum process are relatively high cost due to the complexity of the process consisting of a prescrubber, an absorber, an oxidizer, and many other auxiliary equipment, and large water consumption to prevent scaling.

(b) JBR process

The process is a superior process having advantages in less scaling problem, simple configuration with relatively a small number of equipment for space saving, and low construction and operation costs.

Process Description

The process is one type of the lime-gypsum method, and using lime stone as a neutralizing agent, it absorbs, oxidizes and neutralize SOx in flue gas to fix it as gypsum. The process is made up of the following three sections.

a) Absorption, oxidization, neutralization, and crystallization section

All processes of SOx absorption, oxidization, neutralization, and crystallization are completed in a jet bubbling reactor (JBR).

JBR forms a core of the process and serves as a key element of process simplification, considerable reduction of required space, and significant saving in construction cost.

Exhaust gas introduced to the process is cooled down in a prescrubber by spraying cooling water. Then, it is injected into an absorbing solution in JBR to form bubbles, through which desulfurization occurs. JBR is a large reactor which is filled with lime stone and gypsum slurry, and has spargers (made of plastic pipes) through which flue gas is injected to form bubbles for desulfurization and dust removal. The desulfurization rate is more than 90%.

Desulfurized flue gas goes through the eliminator for mist removal, and is released through the stack to the air. Absorbed SO_2 is oxidized by the air blown into the reaction layer and oxygen in the flue gas, then reacts with calcium in the absorbing solution to become gypsum and crystallize. The gypsum slurry so obtained is partially extracted to maintain the concentration of gypsum in the absorbing solution at a specific range, and is sent to the gypsum dehydration section.

b) Lime stone supply section

Lime stone powders received and stored in a tank are supplied through a feeder to a slurry tank. The desirable slurry is prepared by adding JBR's overflow fluid and is supplied to JBR.

c) Gypsum dehydration section

The gypsum slurry extracted from JBR is sent to the gypsum dehydration section, where it is dehydrated by a solid-fluid separator (centrifuge or vacuum filter) and is separated into gypsum and mother liquor.

Gypsum is stored in a warehouse before shipment, and mother liquor is sent back to JBR.

The process is capable of producing quality gypsum with almost 100% of utilization rate of lime stone, without adding sulfuric acid. Gypsum produced from the process is sold for materials of cement and gypsum board. The process is also characterized by a very small COD in waste water.

Figure A5-2 illustrates the system diagram of the JBR process.

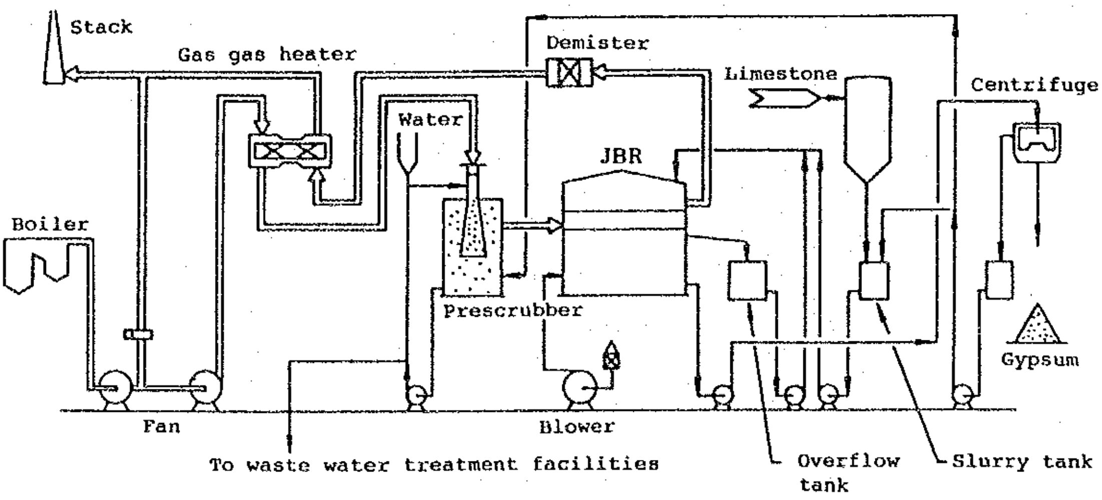


Figure A5-2 System Diagram of JBR Process

(c) Magnesium-gypsum process

Adding magnesium to the absorbing solution used for the lime-gypsum method improves the desulfurization effect considerably. The magnesium-gypsum process has been developed to make use of this phenomenon. To obtain the same rate of desulfurization, therefore, the magnesium-gypsum method allows the absorber to be smaller than that for the lime-gypsum method, together with a smaller liquid/gas (L/G) ratio. Originally, the method to add magnesium to lime was developed. However, because lime is more costly than lime stone, the present method to add magnesium to lime stone has been commercialized.

(d) Other wet processes

a) Gypsum by-production methods

In addition to the above lime (lime stone) method, there are various gypsum by-production methods shown in Table A5-2. These processes were produced to improve stability and desulfurization efficiency when the lime stone-gypsum method was not reliable enough. Most of the processes, therefore, were built in the 1970s.

Among them, the aluminum sulfate-lime stone method in [1] has relatively many advantages. 20 plants have been constructed up until recently, compared to other processes which have not been installed since 1985. The method in [2] has disadvantages in large plant cost and power consumption. The methods in [3], [4] and [5] absorb SOx by suing soda or ammonia and use lime or lime stone as the precipitating medium. Because of problems related to soda loss and waste water treatment, new facilities have not been constructed recently. The method in [6] resolves lime in a calcium chloride solution, and the method in [7] adds maleic acid to lime stone. Neither methods are not widely used because [6] requires corrosion resistant materials and [7] requires waste water treatment. The method in [8] discharges less waste water but requires relatively high operating cost as it uses formic acid.

Table A5-2 Comparison of Gypsum By-Production Methods

No.	Process	Ease of Operation	Desulfurization Rate	Construction Cost	Power Consumption	Waste Water	Absorbing Agent Cost
[1]	Aluminum sulfate-lime stone method	o	•	o	o	•	•
[2]	Diluted sulfuric acid-lime stone method	o	•	x	x	•	o
[3]	Soda-lime stone method	•	o	x	x	•	•
[4]	Soda-lime method	•	o	x	o	•	x
[5]	Ammonia-lime method	•	o	x	o	x	x
[6]	Calcium chloride-lime method	•	•	•	•	o	x
[7]	Organic acid soda-lime stone method	o	o	o	o	x	x
[8]	Formic acid-lime stone method	o	o	o	o	x	x

Notes: o; Excellent •; Fair x; Poor

b) Ammonia absorption method

The technology to absorb SO_2 by an ammonia solution and oxidize it to produce ammonium sulfate for fertilizer is relatively simple, but is not widely used in industrialized countries, partly because ammonium sulfate is already in oversupply as the by-product in the nylon production process, and partly because the gas after desulfurization produces thick white smoke, which, seemingly particles of ammonium sulfate, is difficult to be washed away by water. Although the wet type of electrostatic precipitator has been used in some facilities, the need for advanced equipment prohibits wide use and few facilities are operated in Japan.

(e) Ash (dust) treatment methods

The wet type desulfurizer also serves as a wet dust collector. In the desulfurization equipment using spray towers, concentration of dust at the outlet of the absorber reaches less than $100mg/Nm^3$. In the flue gas desulfurizer for coal-fired boilers, dust is treated by either the ash separation or ash mixing method. Under the ash separation method, a prescrubber is installed before an absorber for prior washing and dust removal. The method is effective in preventing the deterioration of the desulfurization effect due to the inflow of HCl and HF in flue gas to the absorber, while reducing impurities in gypsum by removing dust in advance, thereby to improve the quality of gypsum. Under the ash mixing method, the absorber performs absorption of SO_2 gas and the removal of dust, HCl and HF simultaneously. Compared to the ash separation method, it offers cost advantage while purity of gypsum recovered is relatively low.

Selection of either method is governed by quality requirements for gypsum and economy of the flue gas desulfurizer. Generally, the ash separation method is suitable for the situation where the quality of gypsum is important, whereas the ash mixing method is preferred when economy is given of priority. Its by-product, gypsum, is used for cement and board, and gypsum produced in the ash mixing method can be used as gypsum board.

(f) Gas reheating system

The wet desulfurization method has a disadvantage in that flue gas after desulfurization needs to be reheated to 90°C - 100°C, before discharge, because flue gas leaving the absorber is fully saturated with water and it produces white smoke or corrodes the flue. Originally, reheating was carried out by the after-burner using low-sulfur fuel. Then, from the energy saving viewpoint, the gas gas heater to heat low-temperature gas at the outlet of the desulfurizer by high temperature gas at the inlet. The gas gas heater is divided into a) rotary/ reproduction type, b) medium circulation type, and c) heat pipe type.

a) Rotation/reproduction type

The rotor having radial barriers is filled with laminated, corrugated plates as a heat storage medium. The rotor rotates between high temperature gas and low temperature gas to effectuate heat exchange, thus heat is transferred from the former to the latter through the laminated/corrugated plates.

The method allows the system to be made compact in size. On the other hand, its construction allows dust and gas to leak from the untreated high temperature gas side to the low temperature gas side, resulting in relatively poor desulfurization and dust-removal performance.

b) Medium circulation gas gas heater

Heat is transferred by circulating a heat medium between two separate shell-and-tube exchangers. It has advantages in absence of dust or gas leakage, and the ability to adjust flue gas temperature by varying the amount of medium circulation or using a heat medium heater. Also, the heater can be made into a large size, with the highest flexibility in equipment layout.

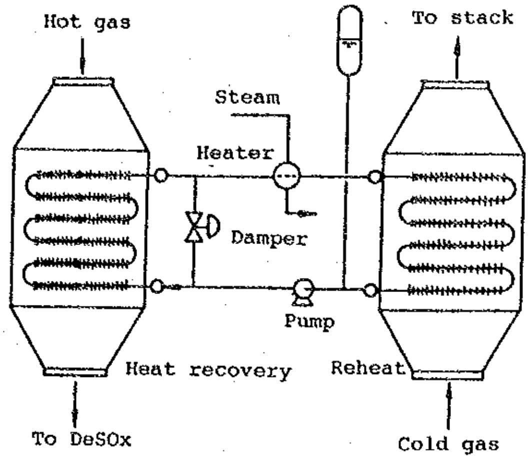


Figure A5-3 Medium Circulation Gas Gas Heater

c) Heat pipe type gas gas heater

A heat medium is sealed in a closed system, where the medium is heated and evaporates in a high temperature section, and releases heat and condenses in a low temperature section. The condensed medium returns to the high temperature section to repeat the process. Since heat exchange is performed in the form of natural circulation of the heat medium, no driving part is required to consume much less operating power. (Figure A5-4)

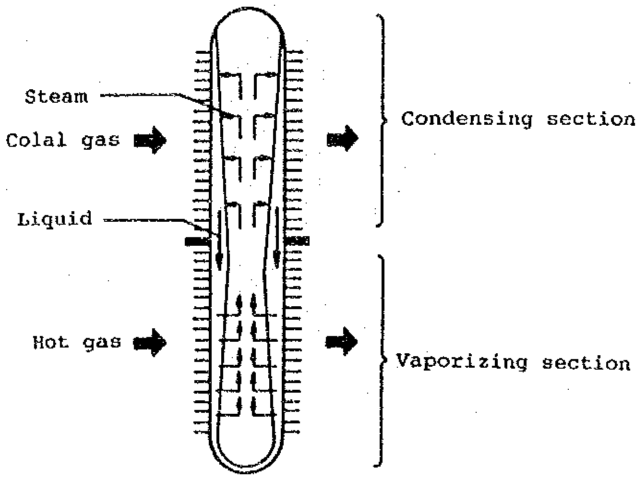


Figure A5-4 Heat Pipe Type Gas Gas Heater

The conventional gas gas heater has been mostly of rotation/reproduction type. Because of dust and gas leakage, however, the non-leak type medium circulation heater or the heat pipe type gas gas heater is increasingly used recently when high desulfurization or dust removing performance is required. Whichever type is selected, the facility cost increases due to the use of a gas reheating system.

4) Dry and semi-dry desulfurization methods

(a) Dry desulfurization method

The simplest method is to blow lime stone powders into a furnace kept at 800°C or higher and to absorb SO_2 by CaO produced during the decomposition of $CaCO_3$ and collect it by using the electrostatic precipitator (EP). This method can only achieve the desulfurization rate of 30% even if the amount of $CaCO_3$ used doubles the theoretical amount against SO_2, thus only 15% of lime is utilized.

On the other hand, slaked lime $Ca(OH)_2$ is generally small particles of μm, which easily reacts with SO_2. By blowing slaked lime into a furnace kept at about 900°C or a duct or reactor at 200°C to 400°C, 40% - 50% desulfurization is accomplished under mole ratio of 2.

These methods are not used at large gas sources because of relatively low desulfurization rates. In Japan, a few hundred units are used to remove SO_2 and HCl for purification of flue gas from solid waste incinerators in urban areas. To improve the desulfurization rate, some countries are experimenting the method to spray water to the downstream of the blow point of the lime stone in the furnace or the upstream of the blow point of slaked lime of the duct.

(b) Semi-dry desulfurization method

Slaked lime slurry is sprayed into the absorber kept at 150° - 250°C, and $CaSO_3$ produced is dried by heat of exhaust gas and that produced by reaction. Powder products are collected by the electrostatic precipitator or bag filters.

The desulfurization rate can be improved by increasing water content in the slurry to give more moisture to flue gas, and lowering temperature to a level where steam saturation occurs.

The bag filter method can desulfurize flue gas when gas passes through lime layers depositing on bag's surface, with desulfurization rate of around 90% under mole ratio of 1.5. Nevertheless, the bug filter causes greater pressure loss than the EP and increases power cost.

The method needs to use slaked lime as an absorbing agent, because lime stone is not suitable for the purpose. In addition, the amount of slaked lime blown into the absorber is 1.5 times the theoretical amount, so that the cost of absorbing agent increases when flue gas with high SO_2 concentration is to be treated.

5) Simplified desulfurization methods

(a) Semi-dry type simplified desulfurization method

The process consists of "primary desulfurization" in which lime stone powders are blown into the furnace, and "secondary desulfurization" to spray water into flue gas.

A water-spray cooling tower is provided between the air heater and the dust collector. Lime stone powders are sprayed into the boiler at around 1,200°C with the mole ratio of 2 - 5 and pass through the spray tower for improved reactivity.

The desulfurization rate increases with decrease in gas temperature toward the dew point of steam and reaches 80% at 60°C with the mole ratio of 3.

Most of the SO_2 desulfurization process are done in the spray tower.

The method requires relatively small facility cost and space because of the simplified process. Also, no slurry is used to assure ease of operation and maintenance and to eliminate the need for drainage. One disadvantage is large consumption of lime stone powders.

(b) Magnesium hydroxide absorption effluent method

The slurry containing magnesium hydroxide ($Mg(OH)_2$) is used as an absorbing agent. Magnesium sulfite produced from SO_2 absorption is oxidized by the air and a magnesium sulfate solution is discharged.

Because of its simplicity and low facility cost, including the cost of the absorbing agent which is much cheaper than caustic soda, the method has been increasingly used since 1980. In Japan, about 100 plants have been constructed to treat flue gas from industrial operation.

As magnesium sulfate is an ingredient of seawater, it can be safely discharged into the ocean. The method is suitable for small- to medium-scale desulfurization facilities and can be widely used in countries where power plants and factories are located near the sea.

6) Desulfurization cost

Table A5-3 shows cost estimates of the lime stone-gypsum method for a higher case (plant cost of US$190/KW with power consumption of 2%) and a lower case (plant cost of US$95/KW with power consumption of 1%). For each case, calculation is made for two depreciation periods, 7 years and 15 years which are adopted in Europe and the U.S.

In the lower cost case, the desulfurization cost per 1KWh is estimated at 7 to 8 cent. The cost is around one half that found a few years ago and has been realized for fuel oil-fired boilers. It is also expected to achieve for coal-fired boilers.

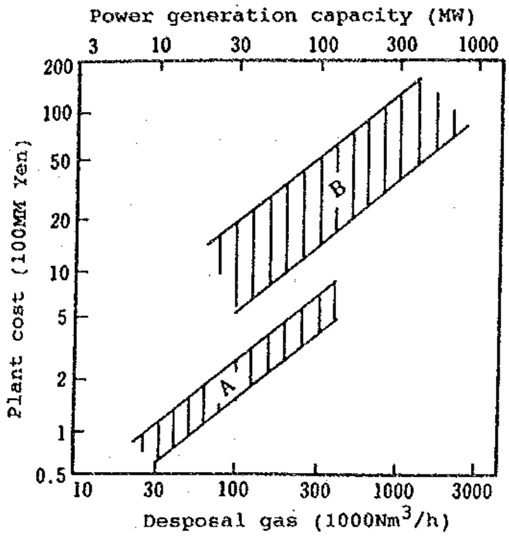
Table A5-3 Cost Estimates for Lime Stone-Gypsum Method

(500MW coal-fired boiler, capacity utilization rate of 70%, SO_2 - 1000ppm; desulfurization rate of 92%)

		High		Low	
Capital investment (million US$)		95		47	
Annual Cost (million US$)	Fixed cost	21.90(a)	14.30(b)	10.80(a)	7.00(b)
	Power cost (11 cent/kWH)	7.05(c)	7.05(c)	3.50(d)	3.50(d)
	Lime stone/chemical	3.33	3.33	3.33	3.33
	Other	7.62	7.62	6.67	6.67
	Sub-total	39.90	32.30	24.30	20.50
	Gypsum (85,000 tons/year)	-2.43(e)	-2.43(e)	-1.62(f)	-1.62(f)
	Total	37.47	29.87	22.68	18.88
Annual cost per KWh (cent)		1.22	1.00	0.70	0.60
Annual cost per SO_2-m3 (US$)		4.15	3.32	2.53	2.11
Annual cost per SO_2-kg (US$)		1.45	1.16	0.89	0.74

Notes: a) 23% of plant cost
b) 15% of plant cost
c) Power consumption - 2%
d) Power consumption - 1%
e) Gypsum - US$ 28.60/ton
f) Gypsum - US$ 19.00/ton

General relationship between the size of the desulfurization facility and plant cost is shown in Figure A5-5. The cost of the desulfurizer using soda or magnesium as an absorbing agent (A in the figure) is around one half that of the lime stone-gypsum method (occupying the lower part of the zone in B).



(US$ = 105 Yn)

Figure A5-5 **Relationship between Size of Desulfurization Facility and Plant Cost**

(A for the soda or magnesium absorption/disposal method and B for the lime stone-gypsum method and others)

Figure A5-6 compares the plant cost and running cost for various processes. Note that the cost is indexed on the basis of the lime stone-gypsum method (capital cost of US$143/KW, and power consumption of 1.5%) which cost is 100.

The soda or magnesium absorption/disposal method requires low plant cost but higher running cost (mainly the cost of absorbing agent). Thus it is not economical for large plants and is widely used for smaller plants.

The magnesium absorption method producing sulfuric acid requires relatively high plant and running costs.

The method to recover soda sulfite and ammonia sulfate requires relatively low plant and running costs, but demand for the by-products is limited.

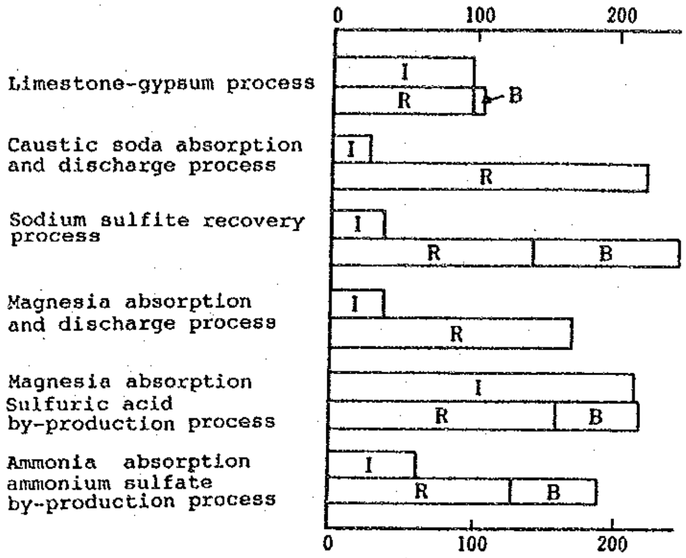


Figure A5-6 Comparison of Capital Cost (I) and Running Cost (R) of Selected Desulfurization Processes

(B - Revenue from sales of by-product; R+B - Total cost; R - Net cost)

(2) Dust removal technology

1) Dust production and control measures

When any fuel except for gas fuel such as LNG is burned in a boiler, ash content in the fuel turns into dust. Thus, for most of boilers which burn fossil fuels including fuel oil, crude oil, and coal, proper measures are called for to reduce or control the amount of dust produced from such combustion. The amount of dust varies with the type of fuel. Comparing fuel oil and coal, the latter has high ash content, hundred times that of the former, to produce a much larger amount of dust.

At present, the widely practiced measures to control dust production are as follows:

(a) The use of high-grade fuel

(b) Proper combustion control

(c) Installation of the dust collector

A primary example of (a) is to use gas fuel such as LNG.

Control measures in (b) involve the careful control of combustion in a boiler to minimize dust production. Recently, more and more thermal power plants in Japan use automated combustion control systems to reduce the amount of dust produced when load is changed.

Control measures in (c) are characterized by the removal of dust in flue gas discharged from boilers at non-gas-fired power plants by means of dust collectors. Usually, coal-fired boilers are required to use dust collectors, so are oil-fired boilers if more strict control is imposed. In Japan, power plants are equipped with high performance collectors at all of coal- and oil-fired thermal power plants, capable of effectively removing dust. As for the type of dust collector, a cyclone dust separator and an electrostatic precipitator are used in combination for coal-fired power plants. For oil-fired power plants, electrostatic precipitators form an integral part of pollution control systems.

2) Cyclone dust separator

The cyclone dust separator serves as a pretreatment stage for the electrostatic precipitator and is often used at coal-fired power plants and other plants which burn fuel producing a large amount of dust. As its name implies, the cyclone creates a circular flow of flue gas, accompanied by centrifugal force, to separate and collect suspended particles in the gas. If a large amount of flue gas is to be handled, two or more cyclones are needed to collect particles. Cyclones arranged in parallel are called the multicyclone, which is mostly used for power plant boilers.

3) Bag filter

The bag filter (BF) is a device to catch dust in flue gas by using a bag-like cloth filter. In Japan, it is widely used for industrial purposes, including steel plants, but not at coal-fired thermal power plants. On the other hand, in the U.S., the bag filter for coal-fired power plants has been commercialized and is widely used at those in the U.S. and Australia since 1973.

As shown in Table A5-4, the largest advantage of the BF lies in its ability to achieve a high rate of dust collection regardless of the type of coal. On the other hand, it is subject to large draft loss, requires relatively a large space for installation, and the filter has relatively short life. Nevertheless, its ability to collect dust at a steady rate makes it popular for the use at coal-fired thermal power plants in the U.S. and Australia, where more than 100 units are operated or planned.

In Japan, although the BF has been commercialized for industrial coal-fired boilers, it has not been used at thermal power plants, partly because technical requirements for the dust collection devices as the high performance flue gas treatment systems for thermal power plants are different from those in other countries, and partly because the BF is inferior to the EP in terms of economy and maintainability.

Table A5-4 Comparison of Bag Filter (BF) and Electrostatic Precipitator (EP) for Coal-Fired Thermal Power Plants

No.	Item	BF	EP
1	Collection Performance	Less affected by the change in the type of coal, offering constant collection performance.	Collection performance is afffected by certain types of coal.
2	Maintenance	Periodical replacement of filters is required. (once every 2 or 3 years)	Annual maintenance suffices.
3	Pressure Loss	High (100-150mmH_2O)	Low (20mmH_2O)
4	Running Cost	Large	Small
5	Operation Record	The U.S. and Australia, not Japan.	Widely used in many countries.

Compared to the EP, the BF has a low rate of capturing particles smaller than 1 microns and produces pressure loss a few times larger. To compensate for these disadvantages, the electrostatic bag filter has been developed and is commercially used by the steel industry in Japan.

The electrostatic bag filter has a static charger in front of a bag filter, where corona discharge is produced to electrically charge dust in flue gas, which is then captured by the filter at the later stage.

4) Electrostatic precipitator

(a) Collection performance requirements

Recently, in Japan, there is increasing demand for high dust collection performance to an extent that flue gas is not visible.

Generally, a smoke is recognized by human eyes by scatter light reflected by particles. Its thickness is governed by concentration of dust, as well as a sum of surface areas of particles, i.e., the smaller the particle size is, the thicker the smoke is. Thus, to prevent a visible smoke from occurring, reduction of dust concentration as well as the removal of sub-micron particles are essential, requiring the high performance electrostatic precipitator.

Together with other requirements, various types of electrostatic precipitators have been developed according to characteristics of dust contained in various types of flue gas, and are in commercial use.

(b) General outline of electrostatic precipitator

The EP electrically charges dust in flue gas by using corona discharge, and separates and collects them by action of electric field (coulomb force). More precisely, producing corona charge by applying high voltage to the discharge electrode causes particles in flue gas to be attracted and deposit on the collecting electrode on the opposite side. Particles so collected are then led to a hopper by using a rapping device. The EP is classified into two types according to the range of installation temperature, namely high temperature type and low temperature type.

The low temperature EP is installed in a low temperature range (140°C - 160°C) at the outlet of the boiler's air preheater. On the other hand, the high temperature EP is installed in a high temperature range (350°C - 400°C) at the outlet of the boiler's economizer. The high temperature EP is used because, while the EP's collection efficiency largely depends upon electrical resistance of dust, dust's electrical resistance decreases with the rise in temperature with a smaller difference due to the type of coal used. At present, the high temperature EP is used at coal-fired thermal power plants which burns different types of coal.

Recent coal-fired thermal power plants are successfully removing 99.9% or more of dust produced from boilers by using the wet desulfurizer in combination with the EP, either the low temperature or high temperature type.

Figure A5-7 shows typical construction of a dry type electrostatic precipitator.

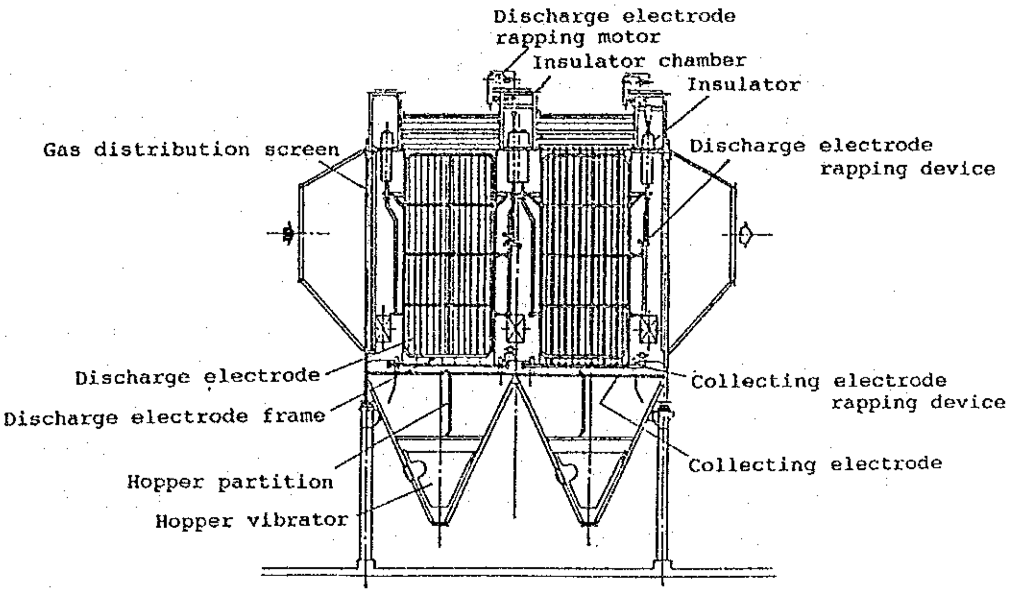


Figure A5-7 Typical Construction of Electrostatiic Precipitator

(c) Comparison of dust properties in flue gas from oil-fired and coal-fired boilers

Properties of boiler flue gas vary greatly with the type and characteristics of fuel, and the type of combustion system.

Table A5-5 shows typical properties of flue gas and dust produced from oil-fired and coal-fired boilers.

Comparing fuel oil and coal, coal has ash content 100 to 200 times greater than fuel oil does, resulting in the amount of dust in flue gas more than 100 times greater and higher resistivity of dust.

The dry electrostatic precipitator is said to show stable performance when dust's resistivity is between $10^4\Omega$cm and $10^{11}\Omega$cm. Dust having resistivity exceeding $10^{12}\Omega$cm is called high resistance dust. When dust's resistivity is high, an abnormal phenomenon peculiar to the electrostatic precipitator, called inverse ionization, occurs to reduce the collection efficiency considerably. Dust produced from coal-fired boilers has sometimes high electrical resistance, depending on the type of coal burnt, and special design considerations are made for the EP.

Dust produced from oil-fired boilers is smaller than that from coal-fired boilers. In particular, dust from oil-fired boilers is often less than 1 micron. More important, both types of boilers produce large amounts of small particles to make it difficult for the ordinary EP to maintain dust concentration at the boiler's outlet below 100mg/Nm^3. To maintain dust concentration at the outlet below 40mg - 50mg/Nm^3, the high performance EP capable of capturing submicron particles is essential.

Table A5-5 Comparison of Properties of Dust in Exhaust Gas from Oil-Fired and Coal-Fired Boilers

Item		Oil-fired	Coal-fired
Gas quantity	%	100	approx. 120
Gas temperature	°C	130 - 150	130 - 150
Gas pressure	mmAq	0 - +100 (forced draft)	-200 - -500 (balance draft)
Dust quantity at inlet	g/m3N	0.05 - 0.15	10 - 20
Particle diameter	μm	3>	30>
Dust contents			
SiO2	wt%	ash content: 15 - 20	60 - 75
Al2O3	"	-	15 - 20
SO3	"	25 - 35	0.3 - 0.7
C	"	50 - 60	0.4 - 0.8
Resistivity	Ω-cm	104 - 108	1010 - 1013
Nominal specific gravity	g/cc	0.1 - 0.2	0.6 - 0.8
Re-scatterability		High	Low
Adhesiveness		Large	Small
Abrasiveness		Large	Small

(d) EP for oil-fired boilers

Suspended dust in flue gas from oil-fired boilers consists of oil ash, unburnt carbon, and a trace of SO_3 mist, which are mostly in micron size and ten times smaller than dust from coal-fired boilers.

Also, dust from oil-fired boilers is mainly made of carbon, which has low resistivity and small nominal specific gravity, opposite to dust from coal-fired boilers. As a result, dust may be re-scattered and pass through the EP without being captured.

One solution to this problem is to inject NH_3 gas into flue gas prior to the EP and to allow ammonia sulfate thus produced to mix with dust to increase resistivity, thereby to improve the collection rate. In this case, the amount and method of NH_3 gas injection should be carefully controlled to ensure sufficient reaction. Otherwise, acidic ammonium sulfate is produced to cause ash clogging and corrosion and to adversely affect electrical charging.

(e) EP for coal-fired boilers

a) High temperature EP

The high temperature EP has been increasingly used at coal-fired thermal power plants in the U.S. since the 1970s. It takes advantage of characteristics that dust's resistivity declines in a high temperature range at the outlet of the boiler economizer. As a result, it is capable of capturing fly ash that cannot be collected by the conventional low temperature EP.

At the same time, however, the high temperature EP operates in a high temperature range between 320°C and 360°C to treat a larger amount of flue gas, requiring larger equipment than the low temperature EP does. Also, care shall be taken to select appropriate materials capable of structurally withstanding high temperature, and to deal with thermal distortion and expansion/contraction.

b) Low temperature EP

The low temperature EP in the low temperature range at the outlet of the boiler's air preheater has been operated at many plants, since the first use at coal-fired thermal power plants in the 1950s, and has been proven to be highly reliable. However, collection performance tends to decline due to dust with high resistivity, and the following provisions are required in relation to equipment design features:

a. The use of the collecting electrode with construction to allow smooth transfer of rapping impacts to compensate for strong adhesion of highly resistive dust to the collecting electrode

b. The use of the discharge electrode with shape to provide discharge characteristics enough to prevent deterioration of performance due to the adhesion of dust to the electrode, which reduces discharge current

c. The use of the intermittent charge control system to reduce the charge accumulated on the collecting electrode, thereby to prevent damage by dust with high resistivity

d. The increase in EP capacity for improved collection performance

(3) Technologies to Remove Nitrogen Oxides

1) Production of nitrogen oxides (NOx) and control measures

NOx in the air is produced from both natural and man-made sources. Natural sources include thunderbolts, volcanic eruption, and bacterial activity. Man-made sources are divided, according to the type of discharge, to fixed sources (such as thermal power plants and factories), mobile sources (automobiles, ships, aircraft, diesel locomotives), and small group sources (kitchens and heating facilities). Thus, compared to sulfur oxides, NOx sources are diverse and are widely distributed.

The amount of NOx (NO and NO_2) produced worldwide is approximately 100 million tons/year from man-made sources, which are much smaller than 500 million tons produced from natural sources. However, NOx produced from man-made sources concentrates on densely populated urban areas and industrial zones to present a serious environmental problem.

The most adverse effect of NOx is that it reacts with hydrocarbons under the influence of ultraviolet rays to produce photochemical oxidants (photochemical smog), which present a problem in large cities with heavy automobile traffic, including developing countries. Various researches have revealed that photochemical oxidants contribute to forest damage, prompting regulatory control of exhaust gas from automobiles in Japan and the U.S., followed by Western Europe. Other countries also have concern.

Nitrogen oxides, known as NOx, include nitrogen oxide (NO), nitrogen peroxide (NO_2), and nitrogen suboxide (N_2O). More than 90% of NOx produced from combustion are NO, with a small amount of NO_2.

NOx produced from combustion of a fuel in a boiler are mostly nitrogen monoxide (NO) and nitrogen dioxide (NO_2), and generally, NO accounts for around 95% of NOx. NOx produced from combustion are divided into thermal NOx which is produced when nitrogen molecules in the air mixed with the fuel reacts with oxygen under high temperature, and fuel NOx which is produced when nitrogen compounds contained in the fuel are oxidized during combustion. Although varying with the type and method of combustion, thermal NOx accounts for 100% of all NOx produced from combustion of gas, 30% - 40% in the case of fuel oil or crude oil, and 10% - 20% in the case of coal. Thermal NOx can be reduced by lowering combustion temperature and oxygen concentration, and reducing the period of combustion gas staying in the high temperature range. On the other hand, fuel NOx can be controlled by using a low-nitrogen-content fuel.

At present, there are three types of measures in place to reduce nitrogen oxides produced from power plant boilers:

a) The use of less polluting fuel
b) Improvement of combustion
c) Installation of flue gas NOx reduction equipment

a) means the use of light oil or LNG with small nitrogen content.

b) involves the improvement of combustion method to reduce production of NOx in the boiler combustion process.

c) is designed to remove nitrogen oxides directly from flue gas.

2) The use of less polluting fuel

Fuel NOx can be reduced by using a fuel with low nitrogen content or removing nitrogen content from the fuel before the use. As for fuel oil, nitrogen can be partially removed in the process of reducing sulfur through hydrogenated desulfurization. Another effective measures are the reduction of excess air in the combustion process.

As 15% - 50% of nitrogen in the fuel are converted to fuel NOx, its production increases with the increase in fuel's nitrogen content. Generally, nitrogen content in the fuel is the highest in coal, followed by fuel oil/crude oil, naphtha, and gas. Thus, light distillates contain less nitrogen and thus produce less fuel NOx. In particular, gas fuel such as LNG contains few nitrogen compounds and produces few fuel NOx. Also, it does not produce much thermal NOx, because it can be thoroughly mixed with the air to complete combustion within a much shorter period than coal, fuel oil or crude oil does. On the other hand, coal, fuel oil, and crude oil have higher nitrogen content, and coupled with combustion period and flame temperature, they produce a larger amount of fuel NOx.

3) Improvement of combustion

Major combustion management measures for NOx reduction are as follows:

(a) Low excess air combustion method
(b) Two-stage combustion method
(c) Exhaust gas mixing method
(d) Low NOx burner

(a) Low excess air combustion method

As discussed above, production of thermal NOx increases with the rise in combustion temperature, the increase in O_2, and the increase in time staying in the high temperature range. In particular, NOx can be reduced by 10% to 30% by reducing O_2 in the combustion gas by half (2% to 3%). This can be accomplished by reducing excess air for combustion. Careful control is required to prevent incomplete combustion accompanied by soot due to insufficient air supply. Table A-5-6 shows reduction of NOx production through low excess air combustion.

In developing countries, O_2 in combustion gas is not measured and highly excess air is used to avoid incomplete combustion. As a result, NOx production amounts to [2] in Table A5-6. By controlling excess air to the minimum required level on the basis of accurate measurement of O_2 in the combustion gas, NOx can be reduced by 20% - 30%, with saving in fuel consumption by 5% - 10%.

Reduction of excess air also leads to the reduction of SO_3. SO_3 adversely affects the environment and corrodes equipment after a combustion furnace or boiler, such as air heaters and EPs. Since SO_3 cannot be fully removed through the wet type flue gas desulfurization process, control of excess air is considered as an important means to reduce it.

Table A5-6 Reduction of NOx by Low Excess Air Combustion

(Unit: NOx ppm)

Fuel	Coal	Fuel Oil	Gas
N(%)	0.7-3	0.1-0.5	0
O_2 Equivalent (%)	6	4	5
[1] Standard Combustion	550-800	400-500	300-400
[2] Air Excess Combustion	600-900	500-600	350-450
[3] Low Oxygen Combustion	450-650	300-400	200-300

(b) Two-stage combustion method

This is relatively a simple method to reduce NOx. By reducing air for first combustion (first stage), a reducing atmosphere is created to reduce NOx, and over-fire air is injected from the upper part of the furnace to induce complete combustion. As a result, combustion temperature is decreased. This method is particular effective in combusting coal since it can reduce fuel NOx in the reducing atmosphere. On the other hand, the method tends to increase unburnt carbon in the ash. It also tends to cause incomplete or unstable combustion to produce unburnt matters such soot and CO. Finally, the two-stage combustion method produces a reducing atmosphere in the high temperature range (around 1,500°C), calling for appropriate corrosion control measures.

To implement the two-stage combustion method in existing boilers, an over-air port should be provided in the upper part of the burner.

(c) Exhaust gas circulation method

Part of flue gas at 350°C - 400°C is returned to around the burner to mix with combustion air, thereby to reduce combustion temperature and O_2 concentration during combustion and to decrease NOx production. A fan and duct should be provided to circulate flue gas.

If an excess amount of flue gas is recirculated, the method causes poor combustion, although effective in reducing NOx. An appropriate amount of recirculation is said to be 20% to 30% of the amount of combustion air.

(d) Low NOx burner

The low NOx burner is designed to achieve optimum combustion by forming a fuel-rich combustion zone and a fuel-lean combustion zone for the purpose of initiating premix combustion and diffusing combustion at each burner. As a result, combustion temperature and oxygen concentration at the burner are reduced and the duration of combustion gas staying around the burner is shortened to reduce production of NOx.

Many types of low NOx burner have been developed.

(e) Overall effect of combustion management

By combining various methods described above, the significant effect of NOx reduction can be expected.

In Japan, more than 100,000 fixed sources (accounting for 95% of total flue gas discharged) have successfully reduced NOx through improvement of combustion.

Relative small boiler facilities have reduced NOx by 20% - 40% by converting their fuel from fuel oil to kerosene and using the low NOx burner. Large boilers have achieved the reduction rate of 60% to 70% by combining the low NOx burner, two-stage combustion, and/or flue gas circulation. (See Table A5-7) NOx at the boiler outlet has been reduced to 150ppm - 300ppm for coal-fired boilers, and 80ppm - 200ppm for fuel oil, 60ppm - 100ppm for kerosene, and 40ppm - 80ppm for gas.

While national NOx emission standards can be cleared through combustion management, additional NOx reduction methods are needed to treat flue gas to comply with local ordinances and agreements with local governments.

Table A5-7 Reduction of NOx by Combustion Improvement

(Unit: NOx ppm)

Fuel		Coal	Fuel oil	Kerosene	Gas
N(%)		0.7-3	0.1-0.5	0-0.03	0
O_2 equivalent (%)		6	4	4	5
[1]	Standard combustion	550-800	400-500	350-450	300-400
[2]	Air excess combustion	600-900	500-600	400-500	350-450
[3]	Low oxygen combustion	450-650	300-400	250-350	200-300
[4]	[3] + two-stage combustion	300-500	200-300	150-250	150-200
[5]	[3] + flue gas circulation	350-550	200-300	150-250	150-200
[6]	[4] + flue gas circulation	200-400	100-250	100-150	80-120
[7]	[6] + low NOx burner	150-300	80-200	60-100	40- 80

4) Flue gas NOx reduction methods

Opposed to the desulfurization process, the removal of NOx through flue gas treatment is mainly done by the dry method, while the wet method is not generally used.

The wet type NOx reduction method is not widely accepted because of the following reasons:

a) NO has low reactivity with the absorbing solution.

b) Although the reactivity can be improved by oxidizing NO to NO_2, the cost of oxidizing agent is high.

c) The solution after absorption contains No_3^- and NO_2^-, which is difficult to be disposed.

Alternatively, flue gas with high NO content can be absorbed by adding $NaClO_2$ to the solution for oxidization, but the disposal of the effluent presents a problem.

The most widely used dry method is the reduction of NOx to N_2. Possible reducing agents include various gases such as H_2, CH_4, and CO. But they are consumed in large amounts by reacting with O_2 in the flue gas, so that ammonia which selectively reacts with NOx is mostly used.

(a) Selective catalytic reduction method

At present, the selective catalytic reduction method is most widely used as a mainstream of flue gas NOx reduction equipment. In particular, it is used for most of large boilers. Recently, it is increasingly used as NOx reduction equipment for gas turbines, diesel engines, and solid waste incinerators.

The method causes NOx to selectively reacts with ammonia on a catalyst for reduction to N_2 and H_2O. It offers the following advantages:

a) The simple process allows the ease of operation and provides high reliability with a small risk of equipment failure.

b) There is no need for effluent treatment and reheating of flue gas.

c) A high NOx reduction effect can be obtained.

d) No by-product is produced.

e) Simplified operation allows the ease of coordination with gas sources.

Process Description

The process mainly consists of a NOx reduction unit to produce de-NOx reaction, a NH_3 injector to inject NH_3 - a reducing agent - into flue gas, and a NH_3

supply source.

Flue gas from the boiler is mixed with NH_3 injected through a NH_3 injection nozzle, and is induced to a de-NOx reactor through a gas flow regulating plate and others. Here, NOx in the flue gas selectively reacts with NH_3 on the surface of the catalyst, in accordance with the following chemical formulas (1) and (2), and is reduced to N_2 and H_2O, which are then sent to subsequent equipment.

$$4NO + 4NH_3 + O_2 \xrightarrow{CATA} 4N_2 + 6H_2O \quad ....(1)$$
$$NO + NO_2 + 2NH_3 \xrightarrow{CATA} 2N_2 + 3H_2O \quad ....(2)$$

If the NOx reduction reactor is subject to clogging because of high dust content in flue gas, a soot blower may be installed on the upstream of the reactor.

NH_3 for reduction is transported by a tank lorry and stored in a liquid ammonium tank. When used, it is vaporized in a NH_3 vaporizer, passes through an accumulator, and is diluted by part of air from a forced draft fan (FDF) for the boiler. Then, it is injected evenly into flue gas through the NH_3 injection nozzle. The amount of NH_3 injection is determined by multiplying the amount of NOx flowing into the reactor, which is determined on the basis of NOx concentration at the inlet of the NOx reduction equipment as well as signals representing the amount of flue gas, such as boiler load signals, by a specific NH_3/NOx mole ratio.

The catalyst which governs performance of the NOx reduction equipment is of porous type. Flue gas flows over the surface of the catalyst and enters pores as a result of diffusion phenomenon to decompose NOx. The catalyst is in either a granular, plate or grid form. Thermal power plants burning fuel oil, crude oil, or coal use the plate or grid type catalyst to prevent clogging by dust. Some of gas-fired thermal power plants use the granular catalyst. Most of the catalyst is made of titan oxides. The NOx reduction efficiency reaches more than 80% even for flue gas from coal-fired plants.

Figure A5-8 shows general configuration of the flue gas NOx reduction equipment using the selective catalytic reduction method.

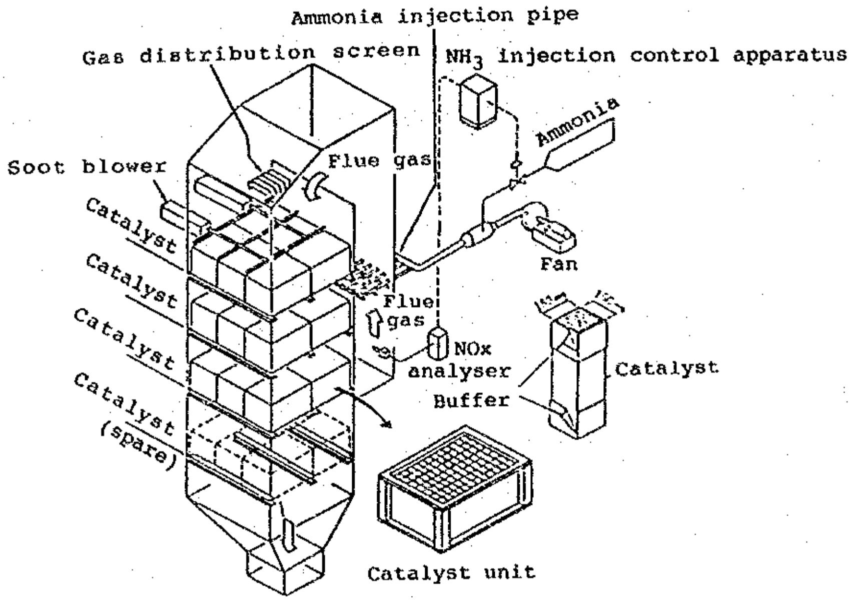


Figure A5-8 Configuration of Flue Gas De-NOx Equipment (Selective Catalytic Reduction Method)

(b) Selective Non-catalytic reduction method

The selective non-catalytic reduction method reduces and decomposes NOx in flue gas in the high temperature gas range and under presence of NH_3 and

O_2, without using a catalyst. The de-NOx reaction progresses in the gas temperature range between 800°C and 1,050°C, with the highest rate of NOx reduction being obtained between 950°C and 1,000°C. To complete the reaction, detention time of 0.1 seconds or longer, preferably 0.4 seconds or more, is required.

The chemical formulas are as follows:

$$4NO + 4NH_3 + O_2 \longrightarrow 4N_2 + 6H_2O$$
$$4NH_3 + 5O_2 \longrightarrow 4NO + 6H_2O$$
$$4NH_3 + 3O_2 \longrightarrow 2N_2 + 6H_2O$$

Selective non-catalytic reduction method, while requiring very high reaction temperature, is applicable to flue gas containing large amounts of dust and is less costly to construct. To secure the high NOx reduction rate, however, the detention time in the range between 900°C and 1,000°C must be 0.4 seconds or longer, with mole ratio in the range between 2 and 3. The large mole ratio results in a large amount of unreacted NH_3. In particular, treating flue gas containing SOx produces $(NH_3)_2SO_4$ and NH_4HSO_4, which may affect a heat exchanger and other downstream equipment.

The selective non-catalytic reduction method has been adopted at many plants. The rate of NOx reduction is said to be generally 40% - 50% since a mole ratio is established in consideration to leak NH_3.

(c) In-furnace NOx reduction method

Under this method, a fuel is injected to the upper part of flame (1,200°C - 1,300°C) in a furnace to produce reducing environment, where NOx is reduced through reaction with hydrocarbons. While some NOx is produced when air is supplied for complete combustion, the overall rate of NOx reduction reaches around 50%.

The in-furnace NOx reduction process consists of two stages. The first stage is the reduction of NO through reaction with hydrocarbon, which requires the following three conditions:

a) Atmosphere temperature is more than decomposition temperature for hydrocarbon (around 900°C).

b) Presence of oxygen

c) The amount of hydrocarbon to be mixed for reduction (fuel) exceeds chemical equivalent of oxygen in presence.

Under these conditions, NO in flue gas reacts with oxygen and hydrocarbon to decompose into N_2, H_2O, CO, and hydrocarbon radical in the initial reaction phase, while some remains in flue gas as nitride.

The second stage involves completion combustion of the unburnt fuel carried over from the first stage, under the following two conditions:

a) Atmosphere temperature is above reaction temperature for the unburnt fuel.

b) The sufficient amount of oxygen to completely burn unburnt matters is supplied gradually with low concentration.

Under these conditions, the unburnt fuel and nitride produced in the first stage burn to become CO_2, N_2, and H_2O, together with some NO.

In actual operating condition, 90% of total fuel is introduced through a main burner and 80% of total combustion air is supplied from an air hole immediately above the burner. Then, the fuel equivalent to remaining 10% for reduction is injected through a fueling port above the air hole, and air for combustion of unburnt fuel, remaining 20% of total combustion air, is introduced through the upper part of the port.

Compared to non-catalytic NOx reduction using ammonia, in-furnace NOx reduction uses the fuel as the reducing agent, thus offering better economy with the similar rate of NOx reduction.

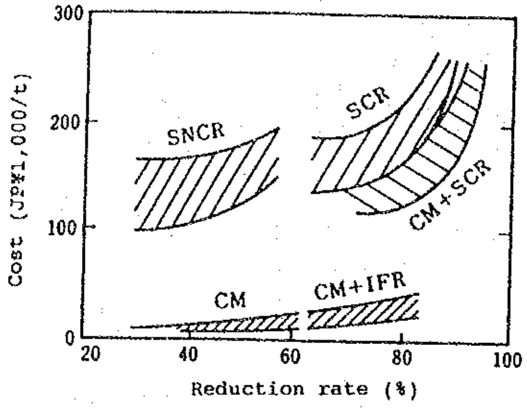
In conclusion, the method may not be applicable to existing boilers and furnaces because additional height is required, it provides low-cost NOx reduction for new boilers.

5) Comparison of NOx Reduction Costs

(a) Comparison of various methods

The rates of NOx reduction and the costs required for selected methods are compared on the basis of Japanese plants, as shown in Figure A5-9. Combustion management is the most economical approach and can achieve 60% reduction. The in-furnace NOx reduction method is also less costly, and in combination with combustion management, the reduction rate can reach at around 80%.

Catalytic NOx reduction is high performance and high cost, and can be used economically in combination with combustion management. Non-catalytic ammonia NOx reduction is less costly than the catalytic method, but the NOx reduction rate is relatively low with a large loss of ammonia.



(1US$ = 105 Yen)

Figure A5-9 Comparison of NOx Reduction Costs (NO_2 1 ton)

The oil-fired boiler produces 400ppm of Nox with no reduction measures.
SCR: Selective catalytic reduction method
SNCR: Selective non-catalytic reduction method
CM: Combustion management
IFR: In-furnace NOx reduction

(b) Selective catalytic reduction method cost

Selective catalytic reduction method costs at Japanese plants are estimated as follows.

Large NOx reduction facilities for power plants cost US$ 62 - 76/kW for coal-fired boilers, US$ 33 - 43/kW for oil-fired boilers. These costs increase by 10% to 20% when installed to the existing boiler.

NOx reduction costs are estimated in Table A5-8. The catalyst is all assumed to be of parallel flow type (honeycomb or plate).

Service life of catalyst is based on actual records in the case of coal- and oil-fired boilers, 5 years and 8 or 10 years respectively. For natural gas-fired boilers which have few record of replacement, 16 years are assumed. Electricity is mostly consumed by fans used to compensate for pressure loss of flue gas due to NOx reduction.

The NOx reduction cost is 0.35 - 0.43 cent for coal-fired boilers with inlet NOx concentration of 250ppm - 400ppm, 0.17 - 0.20 cent for oil-fired boilers of 120ppm - 200ppm, and 0.11 cent for natural gas-fired boilers of 60ppm.

The cost decreases with the decrease in inlet NOx concentration, it is desirable to reduce NOx through combustion management rather than directly processing flue gas with high NOx content. (See Figure A5-9) It should be noted, however, that the NOx reduction cost per unit decreases with the increase in NOx concentration.