Applications for MU Mixing Elements in Chemical Plants

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1. Introduction

The MU Mixing Element® developed and commercialized by MU Company to help protect the environment and lower production costs has been the subject of numerous papers to date.1) In this paper, we focus on the MU Scrubber®, which consists of a circular column containing a MU-SSPW (MU Static Spiral Perforated Wings) MU Mixing Element.

2. Background to the MU Scrubber

We begin by explaining the process by which the MU Scrubber was developed, outlined in **Figure 1**.

Figure 1-1 shows the first commercially produced MU Mixing Element, which had the world's smallest diameter (2.8 mm). This element consists of a single blade and tube. Multiple clockwise- and counterclockwise twisted elements are alternately arranged orthogonally to form a static in-tube fluid mixer called the MU Mixer. This MU Mixer achieves complete mixing even in the high viscosity range (e.g., over 100,000 cPs) and the fully developed laminar flow (up to a Reynolds number of 100). This eliminates dead space in the mixer and allows fluids to be homogenously mixed without the need for maintenance. Minimum mixing throughput is 0.01 ml/sec.

The element in Figure 1-2 consists of two blades. At the center of the element is a space that extends the entire axial length of the blades.

The clockwise and counterclockwise rotating elements shown in Figures 1-1 and 1-2 are arranged alternately to form a MU Mixer. This MU Mixer achieves homogenous mixing of fluids by eliminating striated (seaside rock-like) mixtures even in the fully developed laminar flow.

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Figure 1-3 shows a MU Mixing Element consisting of multiple clockwise and counterclockwise rotating perforated spiral blades (MU-SSPW) joined to a tube wall.

Figure 1-4 shows a MU Mixing Element (MU-SSPW)[2)] developed to treat large volumes (18,000-180,000 m^3/h) of exhaust gas. This MU Mixing Element consists of at least two types of blade (MU-SSPW) of differing dimensions (width, height, hole size, aperture ratio, etc.), which are arranged concentrically in a tube.

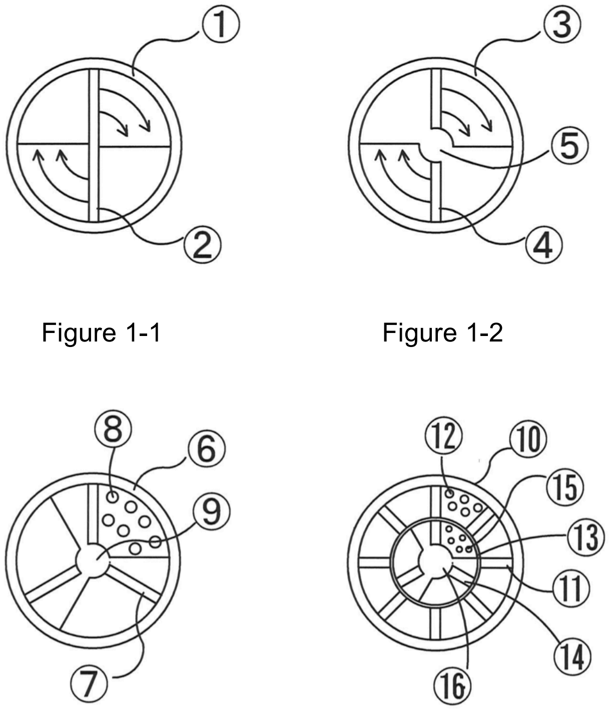


Figure 1-1 Figure 1-2

Figure 1-3 Figure 1-4

Parts	Number
Tube	①, ③, ⑥, ⑩, ⑬
Blade	②, ④, ⑦, ⑪, ⑭
Hollow space	⑤, ⑨, ⑯
Hole	⑧, ⑫, ⑮
Support ring	⑯

Figure 1 MU Scrubber development process

3. Explanation of MU Scrubber

3-1. Structure

The MU Scrubber is a static mixer that mixes fluids without the use of power, and it consists of a cylindrical tower housing a MU Mixing Element made up of multiple mixing blades (MU-SSPW) offering high-performance gas-liquid contact efficiency. The MU Mixing Element consists of clockwise and counterclockwise twisting spiral blades. The blades are perforated with numerous holes. Exhaust gas containing very fine particles and chemical substances is supplied from the top of the MU Scrubber.

Cleaning fluid pumped up from a tank in the bottom of the system is injected into the tower via spray nozzles positioned in a spray pipe arranged along the side of the tower. This cleaning fluid absorbs chemicals and dust in the exhaust gas as it descends from the top of the tower to the bottom, where it collects in a tank positioned downstream and is re-circulated back into the tower.

Thus while the exhaust gas fed through the tower and the circulating cleaning fluid are flowing in parallel through the MU Mixing Element, the gas and liquid are thoroughly mixed and brought into contact with one another through a process of repeated multiple division, gyration, merging, clockwise and counterclockwise spiral rotation, and radial and axial shearing.

Firstly, the effect of this method is to capture substances in the exhaust gas. As noted above, the system's increased gas-liquid contact efficiency raises capture efficiency. Chemical substances in the exhaust gas are absorbed chemically, and inert matter is captured by the cleaning fluid through physical contact. Microscopic particles of dust in the exhaust gas grow into coarser particles through cohesion and swelling while circulating through the system. They are also captured by microscopic bubbles formed in the tower by the powerful mixing of gas and liquid (the waterfall principle). Very fine particles are easily captured by the cleaning fluid and become suspended in it. Thus the exhaust gas is cleaned.

Secondly, matter is captured from the exhaust gas without causing any blockages to the system. This is due to the cooperative action of the MU Mixing Element with the air-liquid multiphase flow of the exhaust gas and cleaning fluid. This prevents clogging of the front and back surfaces of the blades and holes, and adhesion and accretion to the sides of the system caused by the adhesion and accretion of products of reaction, dust, and other matter.

Thirdly, this method reduces pressure loss while exhaust gas is being treated. This is due to the reduction of pressure loss resulting from the construction of the MU Mixing Element. Additionally, the injection of circulating cleaning fluid from spray nozzles in a spray pipe positioned on the side of the tower itself creates an ejector effect that helps further reduce pressure loss.

Exhaust gas that has been cleaned after passing through the MU Scrubber is next fed to a mist separator. Normally, the amount of waste liquid entrained with the treated exhaust gas in mist form grows as superficial velocity increases. This mist is collected by a separation system and circulating fluid tank. Fine spray contained in the gas flow is separated from the gas and returned to the circulating fluid tank. Meanwhile, the exhaust gas is released into the atmosphere or fed to the next process. To function as the mist separation system, we have developed a commercial product called the MU Separator, which uses a MU Mixing Element.

During treatment of exhaust gas, fresh fluid is fed into the MU Scrubber as appropriate. The purpose of this is to control the gas-liquid temperature, and cooling is normally effected utilizing the sensible heat and heat of evaporation of the fresh fluid. Another method that can be used is to install a heat exchanger on the circulating fluid line to cool or heat from the outside, and this is designed to suit this process.

A further objective of introducing fresh fluid is to control the concentration of matter captured in the waste circulating fluid in the tank, and waste fluid containing captured matter is discharged while maintaining the level of fluid in the tank.

3-2. Mixing principle

As **Figure 2** shows, clockwise twisting (clockwise turning) and counterclockwise twisting (counterclockwise turning) blades are arranged spirally along the inner periphery of the tube, and multiple clockwise and counterclockwise twisting blades are arranged alternately through a hollow space. The blades are perforated.

A conventional static mixer has no such hollow space. The edges of neighboring mixing elements are joined to form a static mixer. This hollow space particularly promotes radial merging from multiple fluid channels in the turbulent flow region and serves to raise the gas-liquid contact efficiency of the circulating fluid.

Functionally, the perforation of the blades increases mixing efficiency and creates a vortex that results in a self-cleaning action, thus making the system maintenance free. Fabrication-wise, this prevents the adhesion and accretion of dust to the blades and allows precision spiral blades to be cheaply forged using dies.

Flowing in parallel, the exhaust gas and cleaning fluid are mixed and brought into contact through division, merging, and shearing in the horizontal and vertical directions as they pass through the spirally clockwise twisting blades. In the hollow space, they merge and are then mixed and brought into contact by re-divided and sheared by the spiral of counterclockwise twisting blades. The gas and liquid are thus thoroughly mixed and brought into contact with each through continuously repeated multiple division, gyration, merging, inversion, and shearing in the radial and axial directions.

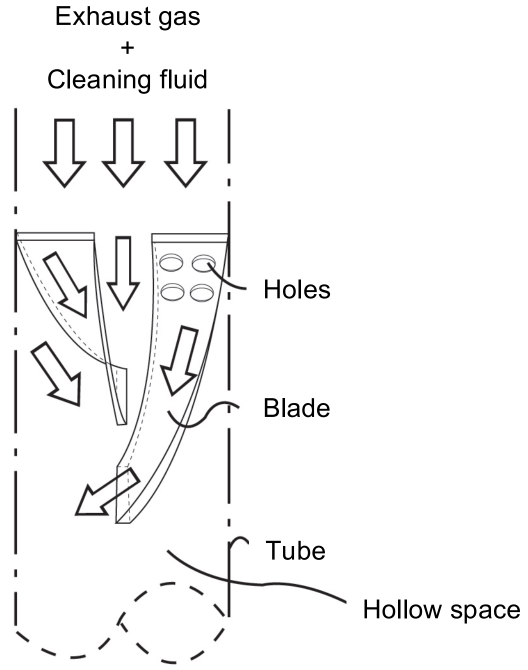


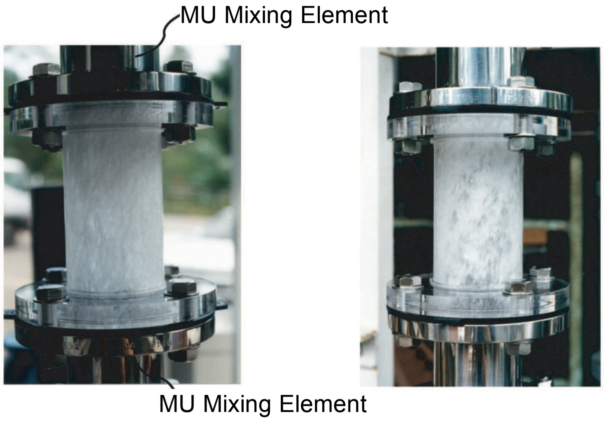
Figure 2 Schematic of gas-liquid contact by built-in MU Mixing Element

3-3. Mixing test

From the photos of mixing of gas and liquid shown in **Figure 3**, it may be observed that achieving a good mix and contact between gas and liquid using a MU Scrubber depends on two key points:

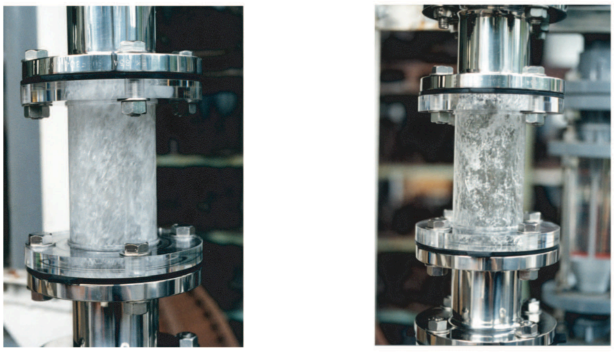
1) Increasing the liquid-to-gas ratio (gas velocity does not exceed a certain level)

2) Increasing the gas velocity (liquid-to-gas ratio does not exceed a certain level)



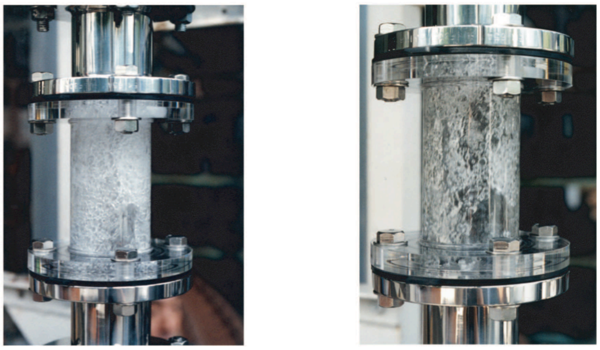
(a) Air flow rate per unit area: 35,000m^3/m^2・h
Gas velocity: 10 m/sec
L/G ratio*: 70 l/m^3

(b) Air flow rate per unit area: 35,000m^3/m^2・h
Gas velocity: 10 m/sec
L/G ratio: 45 l/m^3



(c) Air flow rate per unit area: 35,000m^3/m^2・h
Gas velocity: 10 m/sec
L/G ratio: 15 l/m^3

(d) Air flow rate per unit area: 35,000m^3/m^2・h
Gas velocity: 10 m/sec
L/G ratio: 8 l/m^3



(e) Air flow rate per unit area: 18,000m^3/m^2・h
Gas velocity: 5 m/sec
L/G ratio: 35 l/m^3

(f) Air flow rate per unit area: 18,000m^3/m^2・h
Gas velocity: 5 m/sec
L/G ratio: 15 l/m^3

Figure 3 State of mixing of gas and liquid

* L/G ratio = volume of liquid (l/h) / gas volume (m^3/h)

3-4. Benefits

1) Compactly installable on exhaust lines

The system has a gas superficial velocity of 2-30 m/sec and can be installed along exhaust pipes. As gas and liquid flow concurrently, there occurs no flooding or channeling, operation is possible at a maximum in-tower flow velocity of 30 m/sec, and the compact design helps bring down installation costs.

2) Low pressure loss

When started up, gas flows through the interior of the tower and liquid is circulated. The liquid-to-gas ratio at this time is in the range of 0.2-500 l/m^3. In order to achieve good contact between gas and liquid, however, the liquid-to-gas ratio is set on the high side at 50-500 l/m^3 near the maximum gas velocity of 2 m/sec. When the maximum velocity is 30 m/sec, the liquid-to-gas ratio is on the low side in the range of 0.1-20 l/Nm^3.

If low pressure loss is sought, the system can be operated at zero pressure loss by lowering the in-tower gas velocity or reducing the liquid-to-gas ratio. Under high gas velocity and high liquid-to-gas ratio conditions, on the other hand, which raise gas-liquid contact efficiency to the maximum, pressure loss may deviate from that during normal operation at up to 3 kPaG and increase.

3) Non-clogging and maintenance-free

Even under extremely demanding gas-liquid mixing conditions, as when highly adhesive dust is treated or solids such as metal oxides are extracted in the gas-liquid contact part, clogging by products is completely prevented and the system can be operated continuously for long periods (normally for at least 8,000 hours/year, and one system has been in continuous operation for 17 years). The system is also easy to dismantle and clean following extended use.

4) High-performance capture of dust, mist, and chemicals

Efficiency of removal by absorption of chemical substances per tower is between 90% and 99.99% or higher. Although efficiency of at least 99.999% is achievable depending on how processes are combined, this depends on the properties of the chemicals concerned. In addition, although micron-sized or smaller dust and mist can normally be captured with a removal efficiency of at least 90%, this varies according to compatibility with the cleaning fluid used.

If a further increase in removal efficiency is required, it is normally easily possible to achieve this by increasing the number of elements used.

5) Suitable for treating both highly and weakly concentrated gases

MU Scrubber can easily handle exhaust gas containing concentrations of chemicals ranging from 10% to 100%. There is no need to dilute with air or nitrogen. Due to the high gas-liquid contact efficiency, they are also suited to processing chemicals present in low concentrations of the order of tens of ppm.

6) Simple to design assuming attainment of vapor-liquid equilibrium due to high gas-liquid contact efficiency

Factors such as chemical absorption, evaporation/condensation phase changes, and physical absorption based on Henry’s law are designed by obtaining the gas/liquid composition, temperature, and required calorific value based on vapor-liquid equilibrium data. Regarding the absorption and desorption of chemicals in the gas and liquid, several cases of vapor-liquid equilibrium being achieved in a MU Scrubber have been confirmed. If the cleaning fluid is water, evaporation and condensation of water will reach vapor-liquid equilibrium.

7) Capable of simultaneous capture and cooling

The system captures dust and chemicals in the exhaust gas while simultaneously cooling the gas and liquid. This capacity to do both is an advantage of the MU Scrubber.

8) Upflow method can also be used

In this case, a distillation tower approach or similar is applied to multilayered MU Mixing Elements and theoretical plates are required.

In the case of substances with a low absorption rate, a higher number of plates is employed. Regarding absorption, the concentration of chemicals in drainage is increased and the concentration of chemicals in exhaust gas is infinitesimally reduced.

When used for diffusion, on the other hand, highly concentrated chemicals are absorbed from the absorbent and recovered as gas, and the concentration of chemicals in the absorbent after diffusion is dramatically reduced. There are also cases where the optimum design consists of a combination of parallel flow and upflow configurations.

4. System flow

Next, we explain the workings of a wet exhaust gas treatment system that uses a MU Mixing Element.

Table 1 shows the benefits of each system flow and **Figure 4** shows flow diagrams for each.

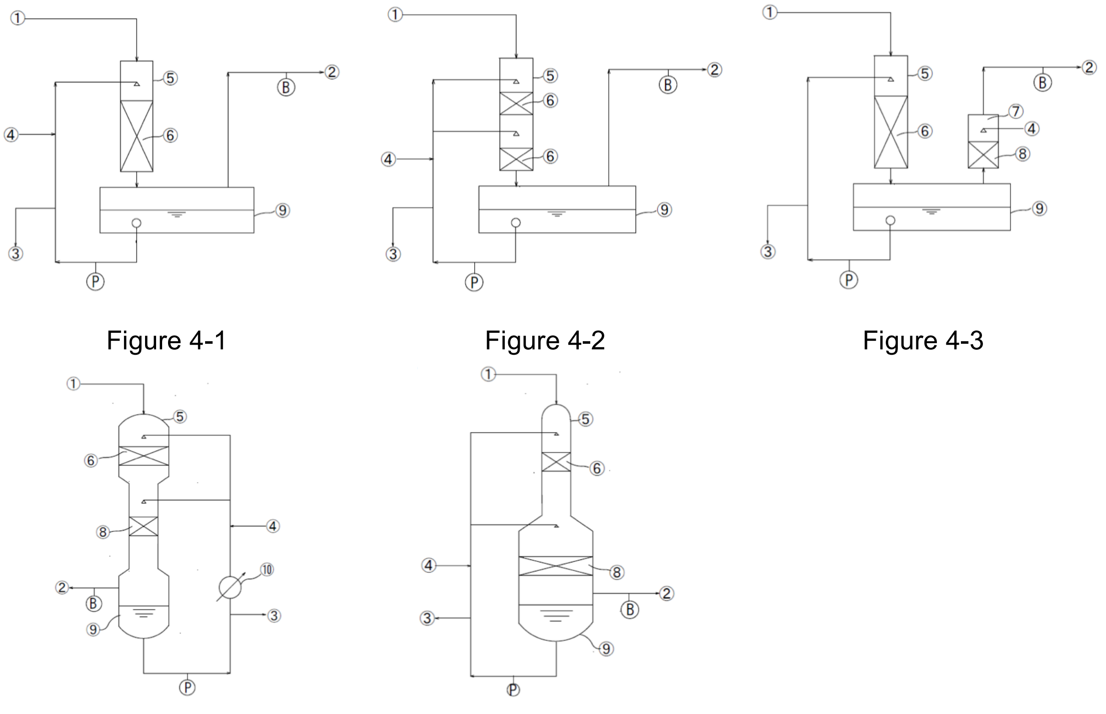


Figure 4-1

Figure 4-2

Figure 4-3

Figure 4-4

Figure 4-5

Number	Explanation
①	Source gas inlet
②	To atmosphere or next process
③	Drainage
④	Fresh solution or water
⑤	MU Scrubber
⑥	MU-SSPW MU Mixing Element
⑦	No. 2 MU Scrubber
⑧	MU-SSPW MU Mixing Element
⑨	Circulating fluid tank
⑩	Heat exchanger
Ⓟ	Circulating fluid pump
Ⓑ	Exhaust fan

Figure 4　System flows

Table 1 Benefits of each system flow

Number	Benefits
(1) Figure 4-1	Typical use of a MU Scrubber as a gas absorption and dust removal system. Variation due to pressure loss in the tower is ±3 mm wg.
(2) Figure 4-2	Composed of multiple MU Mixing Elements arranged in a MU Scrubber. Ideal for treating highly adhesive dust and highly concentrated gas. Used for exhaust desulfurization, dust removal, etc. Pressure loss can be reduced by spray effect. Can be designed without installation of an exhaust fan.
(3) Figure 4-3	Double-tower system used to treat highly concentrated HCl and NH_3+silane and titanium-based gases. After treatment, HCl concentration does not exceed 5 ppm and SiO_2 concentration does not exceed 10 mg/Nm^3.
(4) Figure 4-4	Used in single-tower configuration for gas absorbance, dust removal, and cooling to treat high-temperature exhaust gas. Used to treat incinerator exhaust gas. Especially effective as a means of removing dioxins and Hg. Also used in the form of a direct cooling tower for treating exhaust gas.
(5) Figure 4-5	A gas/liquid contact zone with differing gas velocities (10-30 m/sec at the top and 2-10 m/sec at the bottom) is provided in the tower for use as a means of removing microscopic particles and absorbing gas.

5. Examples of applications of the MU Scrubber

5-1. Absorption and recovery of HCl from exhaust gas

Figure 5 shows a photo of a 30% HCl recovery system consisting of a triple-tower MU Scrubber tower arrangement. This is currently in operation and in use as a dust removal tower and absorption tower for HCl absorption and recovery processes. For details of this process, see Mitani and Nishino.3)

The article that is the focus of this paper states, “it was confirmed that absorption occurs in accordance with almost vapor-liquid equilibrium” indicated in “Figure 7. Assessment of attainment of vapor-liquid equilibrium of HCl absorption.” **Figure 6** shows a dust removal tower that has been operating continuously, maintenance-free, for 8,000 hours per year. The dust removal rate is at least 95%. For high concentrations of HCl (25%-30%) and SiO2, 0.1-1.0 wt% absorbent is circulated.

Table 2 shows a comparison of the packed tower method and the MU Scrubber method. Compared with the packed tower method, the MU Scrubber tower is approximately half the diameter and 1.5 times as tall, and has half the packing height and 3% to 4% greater HCl recovery efficiency. Maintenance is performed almost zero times over the course of a year. Assuming the concentration of HCl in source gas to be 1,600 kg/h, recovery efficiency to be 96%, and the price of 30% HCl recovered to be 24,000 yen/ton, then the contribution to reducing production costs made by recovering HCl may be calculated as follows:

1,600 kg/h×0.96×8,000 h/yr=12,288,000 kg/yr

12,288 t ×24,000 yen/t=295 million yen

This works out as an approximately 300 million yen contribution to reducing production costs per year. Maintenance costs are also practically zero, further contributing to the reduction of production costs.

Empirical trials have also demonstrated that increasing the number of towers from three to four contributes to improved process stability and greater absorption efficiency.

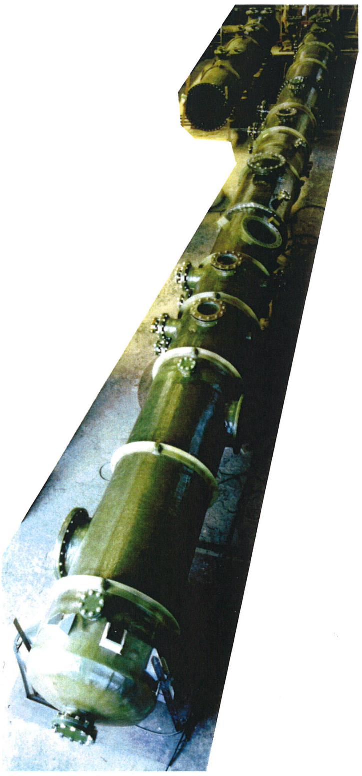


Figure 5　HCl absorption tower

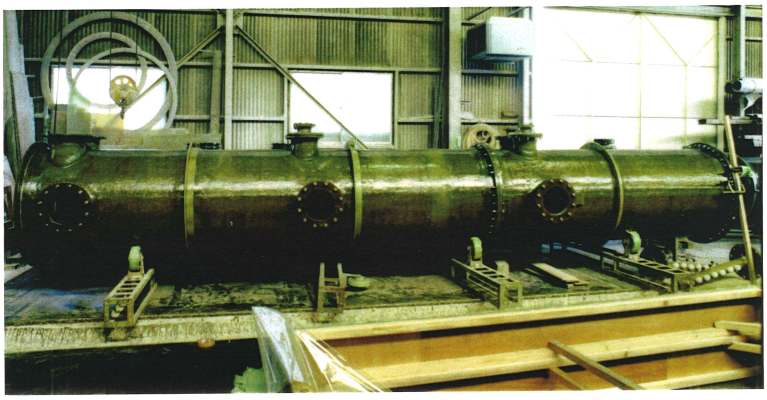


Figure 6 HCl gas dust removal tower

Table 2 Comparison of packed and MU HCl absorption towers

Item	Packed tower method	MU Scrubber method
Tower diameter	⌀ 1,700	⌀ 900
Tower height	14,000	21,000
Packing	Irregular packing	MU Mixing Element
Height	6 m	3 m
HCl recovery efficiency (%)	90-92	93-96
Maintenance (times/year)	2-3	0

5-2. Recovery of H_2 from exhaust gas

Figure 7 shows the system flow for the process of recovering and refining H_2 from exhaust gas. The MU Scrubbers consist of three towers arranged in series. The no. 1 and no. 2 MU Scrubbers operate in parallel flow and the no. 3 tower in counterflow.

The source gas contains H_2 (280-320 kg/h), HCl (440-500 kg/h), and TCS (30-50 kg/h).

After treatment, the concentrations of the exhaust gas are not more than 5 ppm of HCl and 0.1 mg/Nm^3 of SiO_2.

The contribution of the H_2 gas recovery and refinement process to production costs work out as follows, assuming use of H_2 to be 280-320 kg/h, price of H_2 to be 1,000 yen/kg, and operating hours to be 8,000h per year:

230-320 kg/h×1,000 yen/kg×8,000 h/yr=2.24-2.56 billion yen

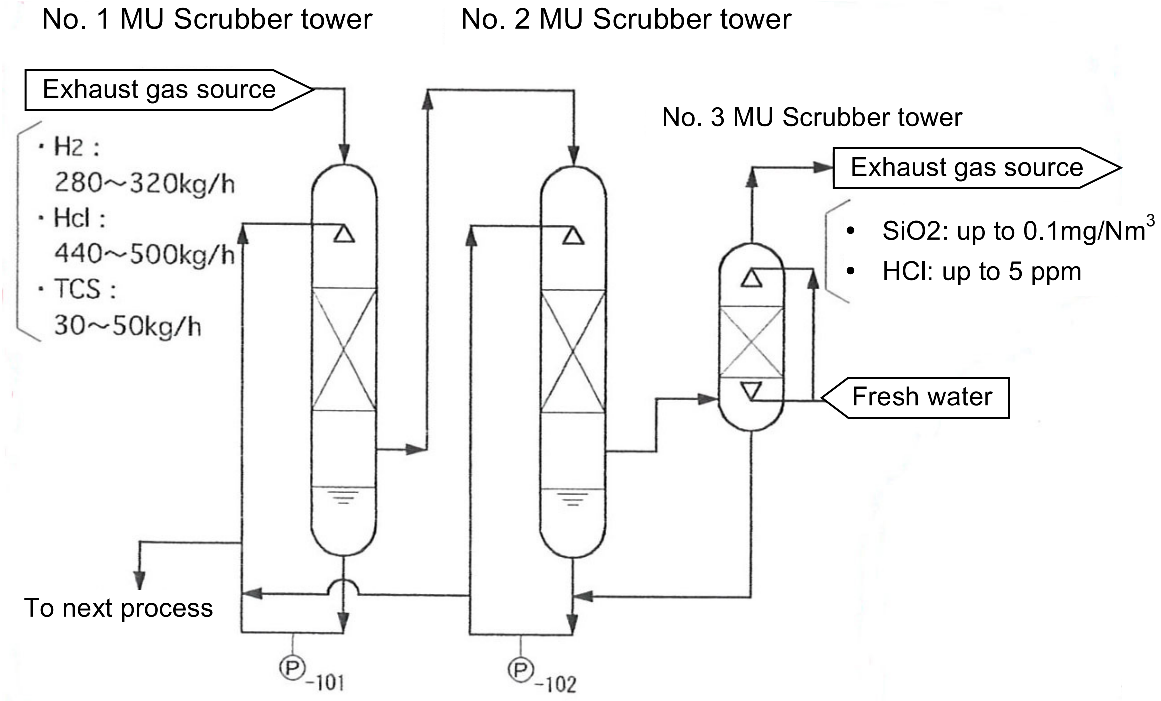


Figure 7 H_2 gas recovery and refinement system flow sheet

5-3. Absorption of silane-based gas and removal of dust from exhaust gas

When highly concentrated silane-based gases (e.g., $SiCl_4$) are removed by hydrolysis reaction, the hydrolysis reaction equation is

$SiCl_4+H_2O \rightarrow 2SiO_2+4HCl$

The SiO_2 generated takes the form of ultrafine (submicron-sized) particles, and highly efficient capture of SiO_2 particles by spray towers and packed towers has been hard. Conventionally, Venturi-based systems have been used. However, the drawback of such systems is that their high electricity consumption due to high pressure loss (500-1,000 mm wg) makes them expensive to run. It is also difficult to keep the concentration of HCl emitted into the atmosphere at 5 ppm or lower. The flow sheet for exhaust gas treatment at a synthetic silica plant is shown in **Figure 8**, and operating states are shown in **Photos 1 through 4**. The source gas passes through a MU Scrubber tower, circulating fluid tank, exhaust fan, and MU Separator tower before being released into the atmosphere. The source gas contains 3,000-5,000 ppm of HCl and 1-3 g/Nm^3 of SiO_2. The treated gas is released into the atmosphere containing not more than 5 ppm of HCl and 10 mg/Nm^3 of SiO_2. Shown in the photos are the middle section of a MU Scrubber tower (Photo 1), circulating fluid tank (Photo 2), and void tower (Photo 3), and the bottom (Photo 4-1), middle (Photo 4-2), and top (Photo 4-3) of a MU Separator tower.

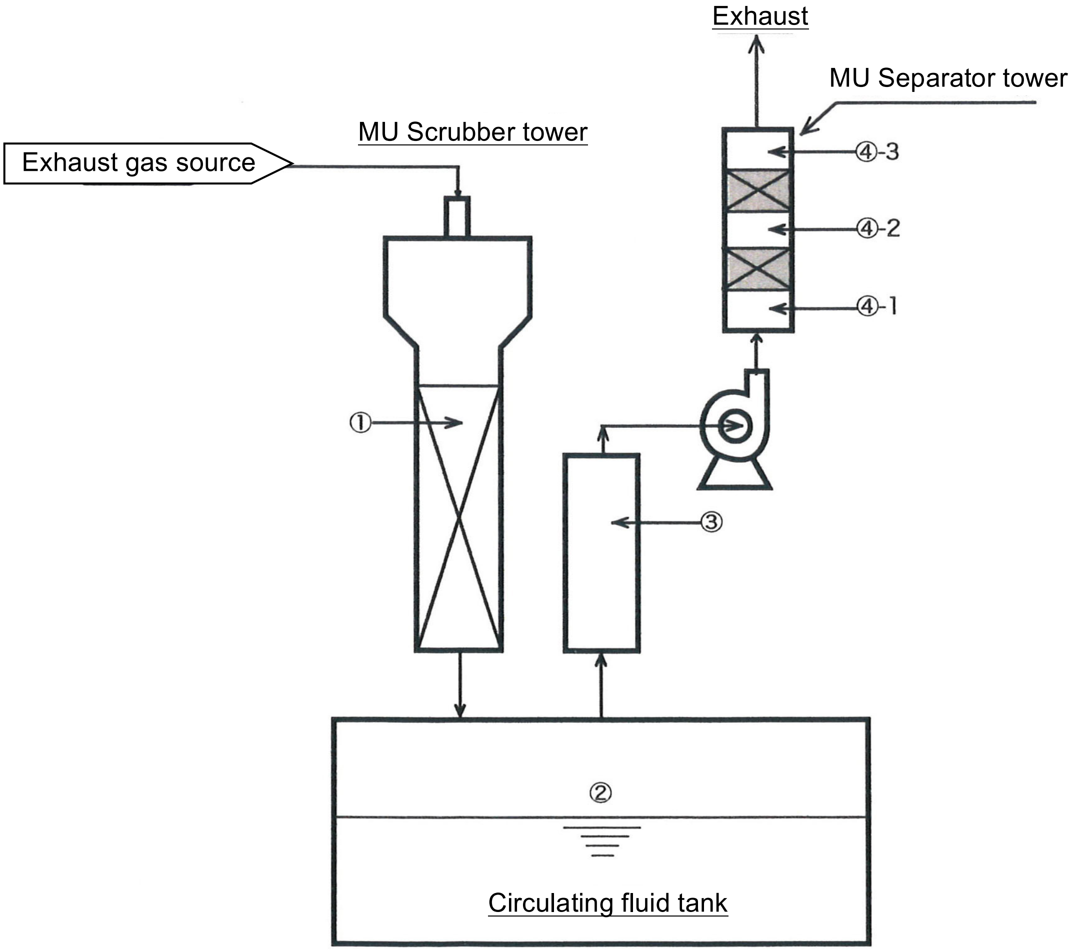


Figure 8 Flow sheet

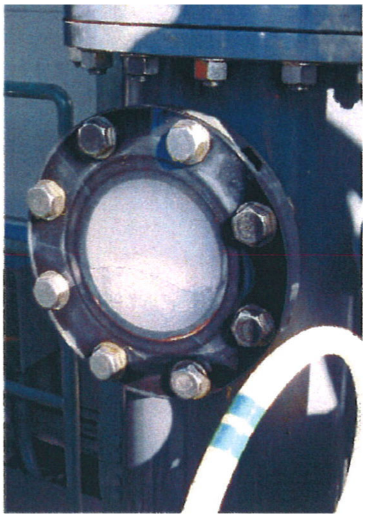


Photo 1 State of operation with silane-based gas

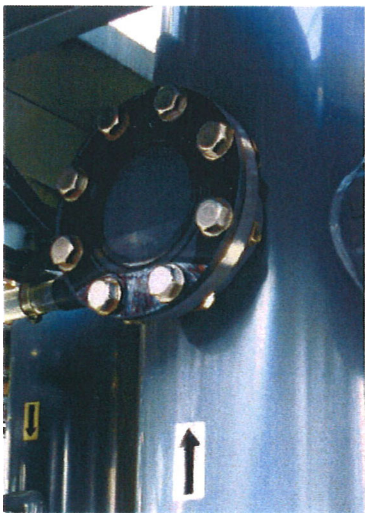


Photo 2

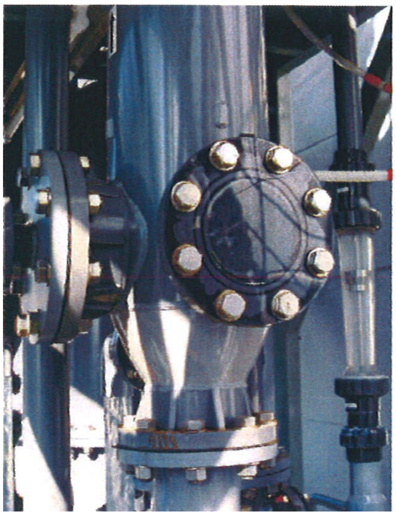


Photo 3

Photo 4-1

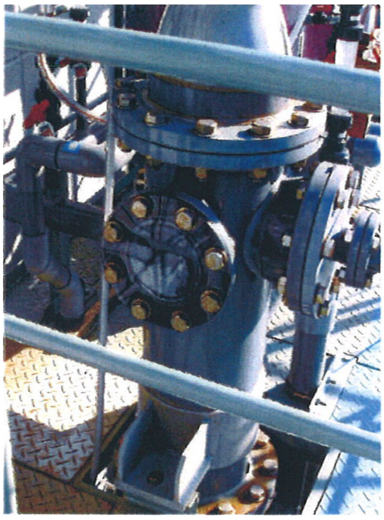


Photo 4-2

Photo 4-3

Photos 1 to 4 Operating states

5-4. Vacuum degassing of saline water to remove O_2 and CO_2

MU Mixing Elements are used in vacuum degassing diffusion treatment systems (MU Reactor tower) for degassing saline water to remove O_2 and CO_2.

The design specifications for the MU Reactor tower are as follows.

Saline water: $250m^3/h$

O_2 concentration: 5-20 ppm

CO_2 concentration: 100-300 ppm

NaCl concentration: 20 wt%

Ca-based compounds present in small concentrations

Degree of vacuum: -9,996 mm wg

Figure 9 shows flow sheets for a conventional vacuum degassing system and a MU degassing tower, and Figure 10 shows a conventional degassing tower (1) and MU degassing tower (2).

The MU Reactor tower is operating smoothly with no scaling caused by Ca-based compounds or other substances.

The tower itself is made of FRP and the MU Mixing Element is made of polypropylene (PP).

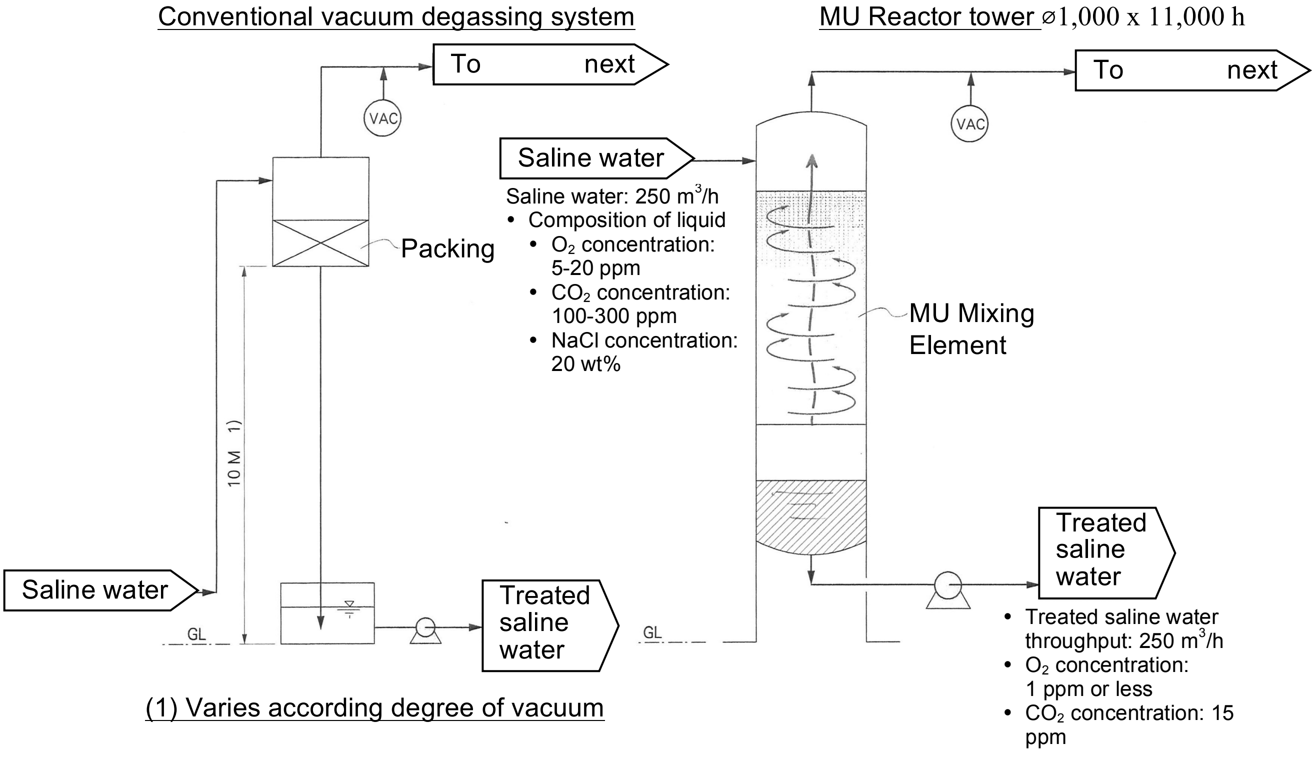


Figure 9 Comparison of conventional system and MU system

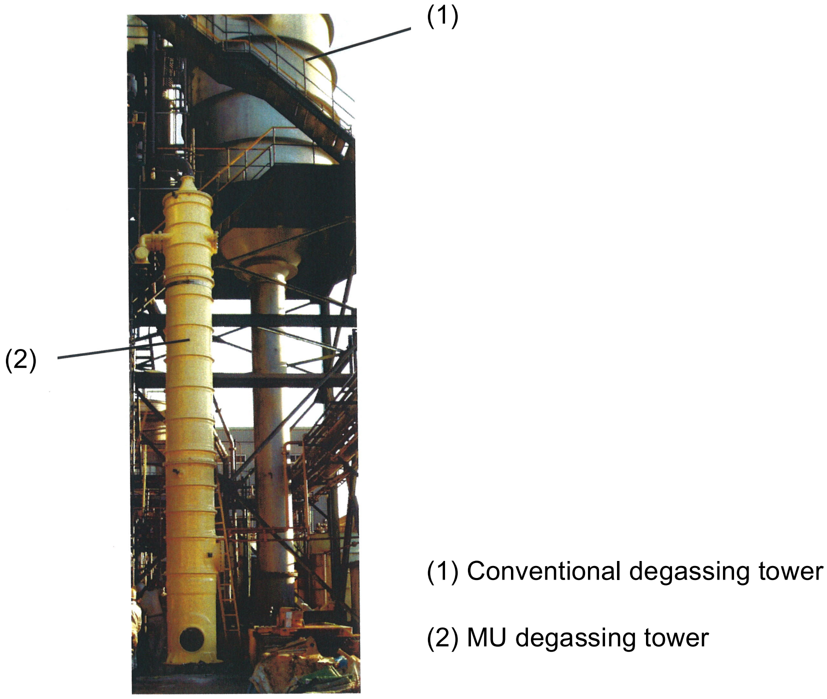


Figure 10 Comparison of conventional system and MU system

5-5. Large reaction vessel

A MU Eductor® is being used for this purpose. This contains a built-in MU Mixing Element, which mixes and stirs C_5-C_{10} hydrocarbons in a large reaction vessel with a diameter of 20 m and a volume of 4,000 m^3. The system flow is shown in **Figure 11**.

The MU Eductor measures 200A×500A×750H and is used to circulate 250 m^3/h×2 units=500 m^3/h. **Figure 12** compares the performances of a conventional ejector system and the MU Eductor system. **Figure 13** shows a comparison of the fluid mixing functions of the ejector method and the MU eductor method. This system is presently operating smoothly without causing any vibration that might affect processes, and it is hoped that it will be used in the future to help homogenize temperatures and concentrations in storage tanks containing liquids such as shale gas, LNG, and crude oil.

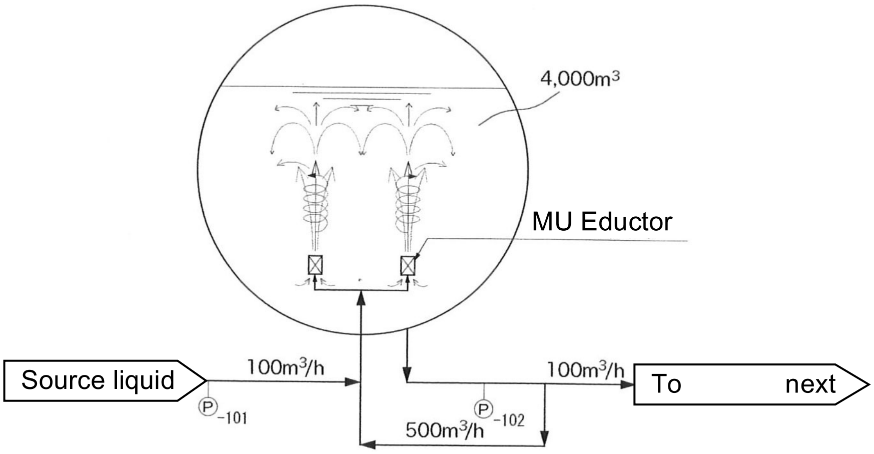


Figure 11 MU Eductor system flow diagram

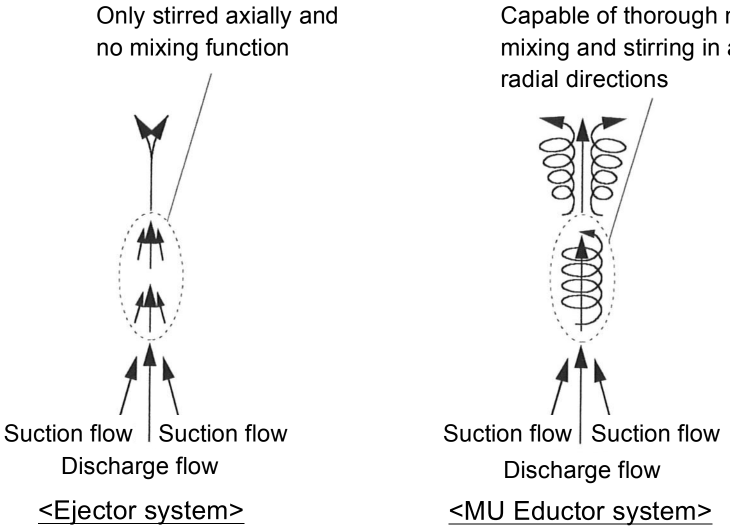
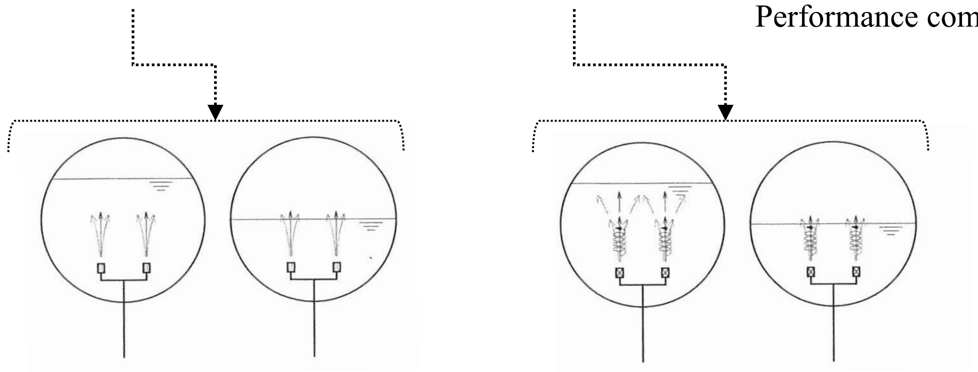


Figure 12 (left) Comparison of conventional ejector system and MU Eductor system flows

Figure 13 (bottom) Performance comparison



<Ejector system>

- Affected by stock height
- Generates considerable static electricity
- Inconsistent mixing
- 2-hour mixing time

<MU Educator system>

- Unaffected by stock height
- Generates little static electricity
- Thorough mixing
- 20-minure mixing time

5-6. Future technological development

(1) Absorption and diffusion of CO_2 in exhaust gas

Technological innovations need to be made to CO_2 gas absorption and diffusion processes in order to minimize the impact on global warming of CO_2 gas emitted by coal power stations. The problems with conventional technologies include:

1) Contamination by fine particles of amine-based absorbent

2) Clogging of absorption towers caused by adhesion and accretion of fine particles

3) Issues with diffusion efficiency relative to energy used by CO_2 stripping towers

These problems can be solved by using the MU Mixing Element. **Table 3** shows the advantages of using MU Mixing Elements.

Figure 14 shows the CO_2 capture system flow of a system consisting of a MU Mixing Element installed in an exhaust gas flushing tower, CO_2 absorption tower, and CO_2 stripping tower. Given how MU Mixing Elements have performed to date, this system should make a major contribution.

Table 3 Reduction of CO_2 gas absorption maintenance costs

MU has a self-cleaning action that dramatically reduces fouling. → Systems using conventional packing need cleaning once per year. However, MU can be operated continuously for five years.

Energy saving

High efficiency → Superior performance due to dynamic gas-liquid contact

Low differential pressure →

Low differential pressure	Conventional packing	MU	
Differential pressure (kPa/m)	0.2	0.04	1/5

Reduced installation cost

High efficiency (enhanced performance) → Smaller tower diameter

	Conventional packing	MU	
Tower diameter	4m	1.8m	1/2
Vapor velocity	1m/sec	5m/sec	

→ Tower height can be reduced

No fouling → No need for spares

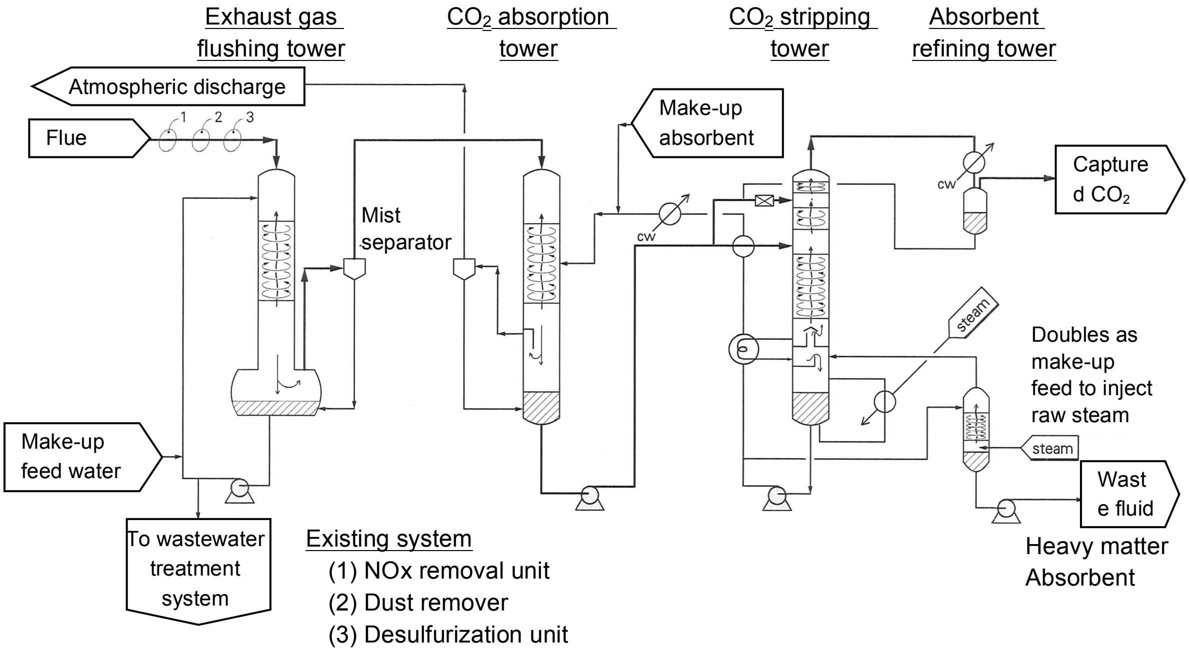


Figure 14 System flow for capture of CO_2 from exhaust gas by MU

(2) Treatment of vent gas released during an incident at a nuclear power plant

If nuclear fuel consisting of a mixture of UO_2 and UO_2+PuO_2 gets out of control for any reason when a plant is in operation and the internal pressure of the pressure vessel exceeds a set pressure, the pressure of gas in the pressure vessel has to be lowered in order to prevent the vessel from rupturing.

So that this vent gas, which contains multi-nuclide products of fission, can be brought within regulatory limits and released into the atmosphere, radioactive material consisting of microscopic products of fission and volatile gas must be removed. As we have seen, the advantages of MU Scrubbers include:

1) their high-performance ability to capture ultrafine particles;

2) their self-cleaning function and freedom from clogging caused by adhesion and accretion of products, which means they require no maintenance;

3) a single-tower system's combination of three functions, namely gas cooling, gas absorption, and dust removal;

4) their ability to be designed so that pressure loss does not exceed 5 kPa;

5) their ability to be designed so that in-tower gas velocity is in the range of 3-30

m/sec; and

6) their ability to be designed to occupy a smaller footprint.

In light of the above and their real-world performance to date, MU Scrubbers appear eminently suitable for treating vent gas.

5-7. Scaling up the MU Scrubber

Below we briefly describe how the MU Scrubber can be scaled up. Scaling up chemical systems is normally considered to be extremely difficult. It is especially hard to simulate the state of mixing of fluids in the turbulent flow zone. A process of simulating the state of flow of a fluid, beaker testing, and development of a pilot plant and then demonstration plant is therefore followed before an actual plant can be designed. In contrast, the MU Scrubber can be scaled up comparatively easily, as described below.

(1) Main mixing factors of the MU Mixing Element (for gas-liquid mixing and contact)

    1) Superficial velocity of liquid and gas
    2) Coefficient of viscosity, temperature, surface tension, etc. of liquid and gas
    3) L/G ratio (L/G=l/m^3)
    4) Gas-liquid contact time (element length ÷ gas velocity)
    5) Spray profile of spray nozzle and size of holes through which liquid passes
    6) Solubility, reaction speed, steam pressure
    7) Angle of rotation of blades
    8) Distance between neighboring elements (length of hollow space)
    9) Hole size and aperture ratio of blades
    10) Packing density of blades (m^2/m^3) (total surface area of blades ÷ element volume)

(2) Test factors

    1) Gas superficial velocity [m/s]
    2) L/G ratio [l/m^3]
    3) Dust concentration [mg/Nm^3]

4) Gas concentration [ppm]

(3) Design of actual plant (scaling up)

1) Based on the results of operating tests with actual gas, the actual plant is designed taking into account factors including gas velocity, L/G, gas-liquid contact time, permissible pressure loss, and the need for equipment to prevent blockages caused by dust in the exhaust gas intake under set optimum conditions. The tower diameter, tower height, location of introduction of exhaust gas, sprinkler position on the sprinkler pipe and method of sprinkling, and type of spray nozzle and spraying pattern are selected and determined.

2) Next, the structure of the MU Mixing Element is designed.

   (a) The packing density of the blades (total surface area of blades / tower volume [m^2/m^3]) is calculated to determine the number of blades.

   (b) The angle of rotation of clockwise and counterclockwise rotating blades is determined.

   (c) The hole size and aperture ratio of the perforated blades are determined.

   (d) Performance to date and test results are examined, and the final design is determined taking into account factors including structure and causes of problems with the chemical reaction process so as to maintain high performance and ensure no maintenance is required.

   (e) Operational control conditions (dust density, salt concentration, and pH of the circulating fluid) are provided by the client.

   (f) Possible problems that might arise with extended use are considered.

(4) Summary

Taking the above into careful consideration, a comprehensive judgment is made based on our own past performance figures, the results of tests at the client's end, and other data, and the actual system is designed with greater originality and imagination.

6. Conclusion

We have been through some stormy times in the 32 years since our foundation, but with our small crew we have successfully navigated all the difficulties that have come our way. That we have managed to do so is thanks to the tremendous guidance and cooperation of all our stakeholders, and we would like to take the opportunity here to thank them all.

Following Matsuo Basho's principle of *fueki ryuko* (constancy and change), we are committed to probing reality and exploring, step by step, the uncharted mysteries of the spiral which embody the continuity of the *mu* of nothingness as we seek greater knowledge of the laws of nature in our quest to produce technological innovations that will help protect the global environment and reduce production costs.

Gathering seawards
The summer rains, how swift it is!
Mogami River*

Matsuo Basho, *Oku no Hosomichi* ("Mogami River")
Translated by Donald Keene

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* In the 1680s when this *haiku* was written, the Mogami River Basin was studded with gold and silver mines. Not a clear river, its waters tinged in patches with complex hues because of waste water from the mines would have flowed. Small boats carried rice on the swift current down to the port of Sakata, from where it was transported by the larger *kitamaebune* cargo ships to the capital, Kyoto. It appears to us that these images were employed metaphorically by Basho.

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