Applications for the MU-SSPW Element in CCS and Related Areas

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1. Introduction

MU Company, Ltd. has marketed many environment-improving products that incorporate the MU-Static Spiral Perforated Wings (MU-SSPW) element as an internal mechanism.

Products in the diverse product line that incorporate this principle range from the MU-AERATOR, a compact water treatment unit, to the MU-SCRUBBER, a large-capacity waste gas treatment unit.

For many of these products, applications became possible as a result of testing in response to customer requests. This paper will present recent examples of application and examples of scaled-up application following testing, focusing in particular on the use of the MU-SSPW element in wet type CO_2 capture equipment in CCS systems as noted below. It is the authors' hope that this overview will provide a greater understanding of the MU-SSPW element and the features not available in conventional packing elements and trays.

1) About the MU-SSPW element
2) Applications in CCS
3) Recent examples of application
4) Examples of scaled-up application

2. About the MU-SSPW element

(1) Inside the MU-SSPW element, liquid spirals downward due to gravity, turning right and left and cleaning the entire element. This self-cleaning action ensures that there is no fouling or clogging. The liquids are absorbing liquids or reflux liquids used in such systems (**see Fig. 1**).

(2) The liquid spirals downward evenly throughout the entire element, so there are no dead spaces. Moreover, the liquid includes microbubbles, so there is no tendency to foaming, further improving internal gas-liquid contact efficiency. **Fig. 2** and **Table 1** show a comparison of the gas-liquid contact mechanism in the MU-SSPW and that of a conventional unit.

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(3) The denser the internal configuration that is used in an effort to achieve high performance, the more vulnerable it is to fouling. The compatibility of high performance and fouling resistance seems to be close to impossible to achieve. Only the MU-SSPW element has an internal configuration that achieves this balance. Its particular feature is that it allows parallel flow operation. This has paved the way toward many applications in the areas of reaction, dust removal and gas cooling.

MU Company has prepared test equipment that can accommodate many different operations. First the company embarked on a slow and steady process of conducting tests with actual gases to confirm performance, thereby gaining acceptance of the concept of the MU-SSPW element and having it adopted for use in actual plants. MU-SSPW elements have been installed in semiconductor plants and in the heart of chemical manufacturer facilities such as cement, pulp, synthetic rubber and so on, where operations that entail considerable fouling are conducted. Over a period of 40 years, the product has earned customer satisfaction and gained many repeat customers, as examples will show later.

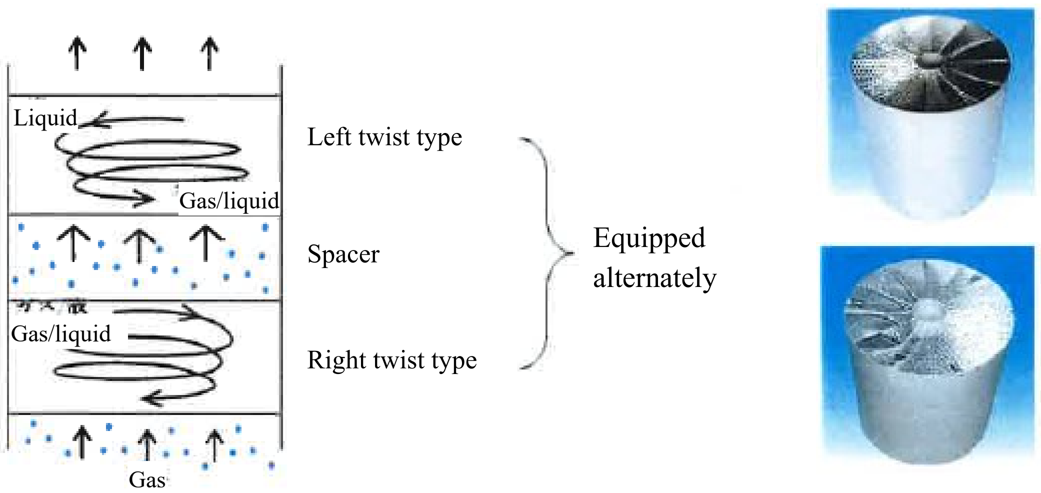

Fig. 1 MU-SSPW element

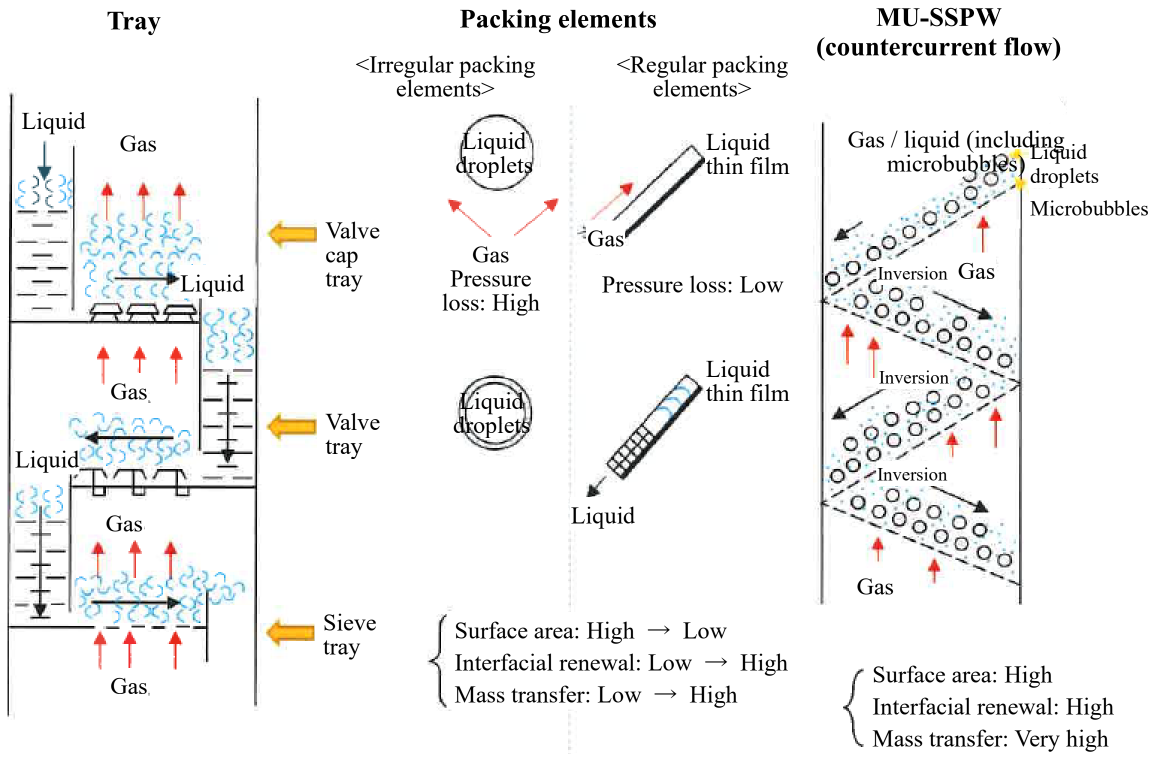

Fig. 2 Comparison of gas-liquid contact mechanisms

Table 1 Comparison with conventional type gas-liquid contactor

Gas-Liquid Contactor	Trays	Packings		MU
Internal Mechanism	Conventional trays	Irregular packing elements	Regular packing elements	MU-SSPW element
1. Categories of gas phase / liquid phase Continuous phase	Liquid	Gas		No distinction
Dispersion layer	Gas	Liquid		
2. Gas-liquid contact mechanism	Gas bubbles pass through liquid	Gas collides with liquid droplets	Gas contacts liquid via liquid thin film	Gas-liquid (including microbubbles) mixing with inversion
3. Assessment of mass transfer based on double film theory 1) Specific surface area	Large	Medium-sized	Small	Large
2) Frequency of interfacial renewal	Low	Low	High	High
3) Mass transfer rate	Low	Medium	High	High
4. Characteristics 1) Processing capacity	Small	Medium-sized	Large	Large

2) Pressure loss	High	Medium	Low	*1) Low
3) Resistance to fouling and clogging	High	Medium	Low	*2) High
4) Parallel flow operation	Not possible	Countercurrent operation is dominant		*3) Possible

Notes:

*1) Approximately 1/3 - 1/4 regular packing elements

*2) Maintenance-free properties

*3) Compact design is possible as there are no flooding restrictions

3. Applications in CCS

In October 2012, the authors visited the CCS BD-3 plant currently under construction at the Boundary Dam Power Station of the Saskatchewan Power Corporation ("SaskPower") in the province of Saskatchewan, Canada. This is the world's largest in terms of CCS by a single-line plant, capturing a million tons of CO_2 per year using amine solvents. When we arrived at the site and saw it with our own eyes, we were astonished at its size. The pretreatment towers and CO_2 absorption reaction towers in particular are not conventional cylindrical towers but square towers reminiscent of enormous buildings.

The plant began operating in October 2014. In October 2015, we met the president of SaskPower, Mike Marsh, again at the CCS Forum in Fukuoka. Mr. Marsh gave a presentation on the history of the CCS Project, in which 1.1 billion dollars had been invested. After the forum, we were able to talk to him privately and learn the actual situation in detail. The major issues were fouling and clogging. Because of these issues, long-term operation was not possible, and packing elements cleaning and replacement, as well as replacement of the amine solvent, were needed, and corrective measures were currently being studied.

We explained MU Company's views regarding such a situation.

According to a report issued in April 2021, a cumulative total of 4 million tons of CO_2 has been captured. This is the result in the seventh year of operation, so presumably the issue of clogging has not been resolved completely. We had the opportunity to visit other CCS facilities in addition to Boundary Dam, leading us to recognize anew that the major issues are tower size and fouling.

Previously at CCS plants, there was a feeling that, in the event of fouling, it was only necessary to halt plant operations and conduct cleaning, and during that period emissions could be released through the original smokestacks. Recently, however, maintenance and utility costs have skyrocketed, and there is also a recognition that captured CO_2 in itself is an outstanding product (CCUS), and as a result major engineering companies are entering the market of CCS plant construction and competition is intensifying. Furthermore, CCS plants are expanding to include not only thermal power stations but also ironworks, cement factories, and waste incineration facilities.

CCS plants are made up of a waste gas pretreatment tower, CO_2 reactive absorption towers, and a CO_2 stripping tower.

The waste gas includes low-concentration CO_2 of 10-20 vol%, so the load of the pretreatment towers and the CO_2 reactive absorption tower is greater than that of the CO_2 stripping towers. The greater the quantity of CO_2 to be captured, the larger these two towers will become. In addition, the performance of the pretreatment tower that removes the dust and H_2S contained in the waste gas is also crucial. If the waste gas pretreatment is inadequate, dust and H_2S will accumulate in the amine solvent in the next process, eventually polluting the entire system.

Fig. 3 shows a system with the MU-SSPW element installed, enabling the three functions of dust removal, H_2S reaction and removal, and gas direct cooling to be accomplished in a single compact tower. This unit is compact, but it has been designed especially for parallel flow operation, for which MU Company has a long record of accomplishments. In a similar fashion, large CCS systems can be made compact with parallel flow operation of the CO_2 reactive absorption tower, as shown in **Fig. 4** and **Table 2**.

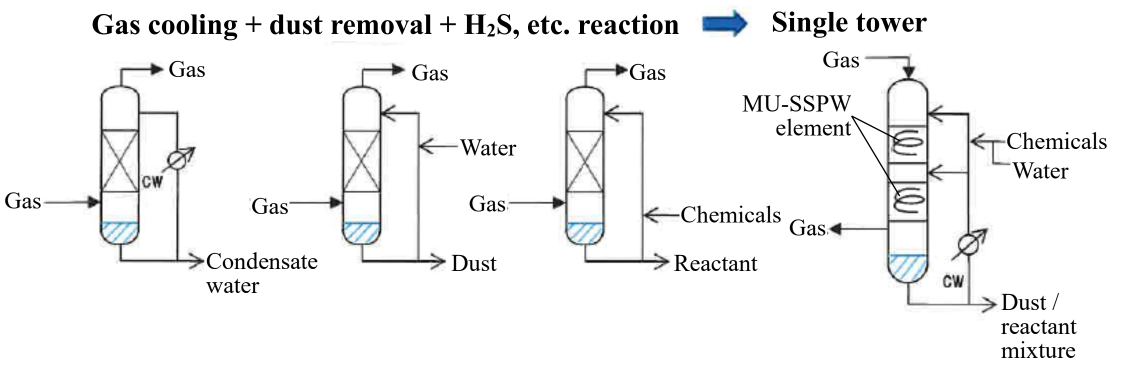

Fig. 3 Single tower parallel flow operation for pretreatment

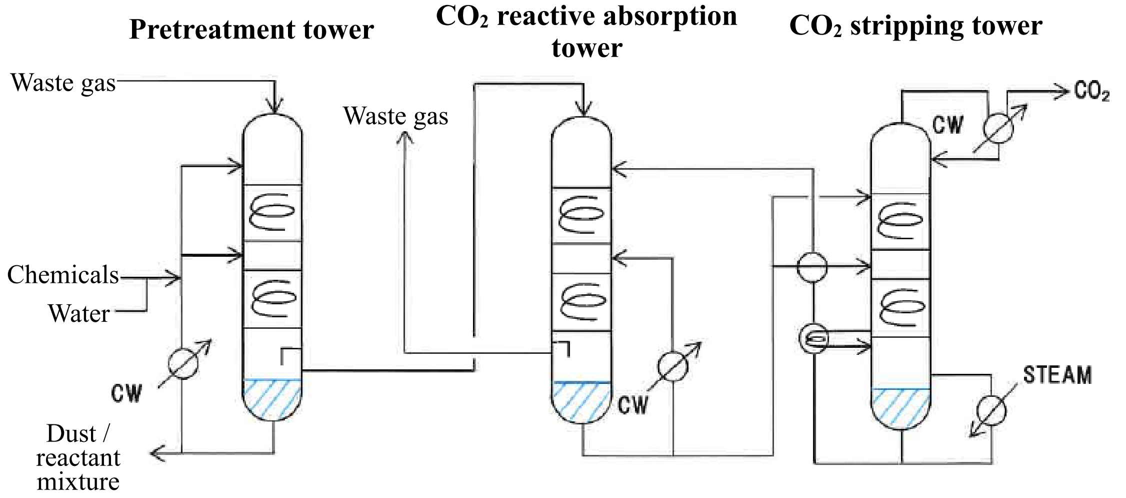

Fig. 4 MU-CCS process

Table 2 CCS capacity (CO_2 recovery quantity t/y) and tower diameter

Tower / CCS capacity	Pretreatment tower		CO_2 reactive absorption tower			CO_2 stripping tower	
	Existing countercurrent flow (m □)	MU parallel flow (m φ)	Existing countercurrent flow (m □)	MU countercurrent flow (m φ)	MU parallel flow (m φ)	Existing countercurrent flow (m φ)	MU countercurrent flow (m φ)
500,000 t/y	7.7	3.9	7.7	5.7	3.9	3.4	2.2
1 million t/y	11.0	5.5	11.0	8.0	5.5	4.8	3.1
1.5 million t/y	13.4	6.8	13.4	10.0	6.8	5.9	3.7
2 million t/y	15.4	7.8	15.4	11.0	7.8	6.8	4.3
3 million t/y	18.9	9.6	18.9	14.0	9.6	8.3	5.2

4. Capture system

Previously, the authors have introduced the achievements of the treatment of various types of wastewater and waste gases with a system made up of parallel flow and countercurrent flow with MU-Static Spiral Perforated Wings (MU-SSPW) elements as packing elements. In this paper, we would like to introduce two types of capture systems for which there has been increased demand in recent years.

First, we will look at an example of a system capturing ammonia gas that is emitted to a flare when the safety valve of the large liquid ammonia storage tank is activated.

This system captures the gas emitted from the safety valve, the last fortification that ensures that the abnormal rise in tank pressure does not occur. The key point for installing some kind of unit at the safety valve outlet is to design a system that takes into consideration the need for measures to ensure that the unit does not cause an increase in pressure of the upstream tanks. The system is also characterized by the fact that the temperature of the gas that is emitted varies widely between −30°C and 200°C depending on the emission conditions. For these reasons, a safe risk prediction design from the approaches of fail-safe, foolproof and simplification is crucial.

The following fishbone chart (**Fig. 5**) shows an example of risk assessment from the initial stages of design. It is helpful in convening representatives from the system administration departments, environmental safety departments, technology departments and so on for wide-ranging discussions in order to nip danger in the bud.

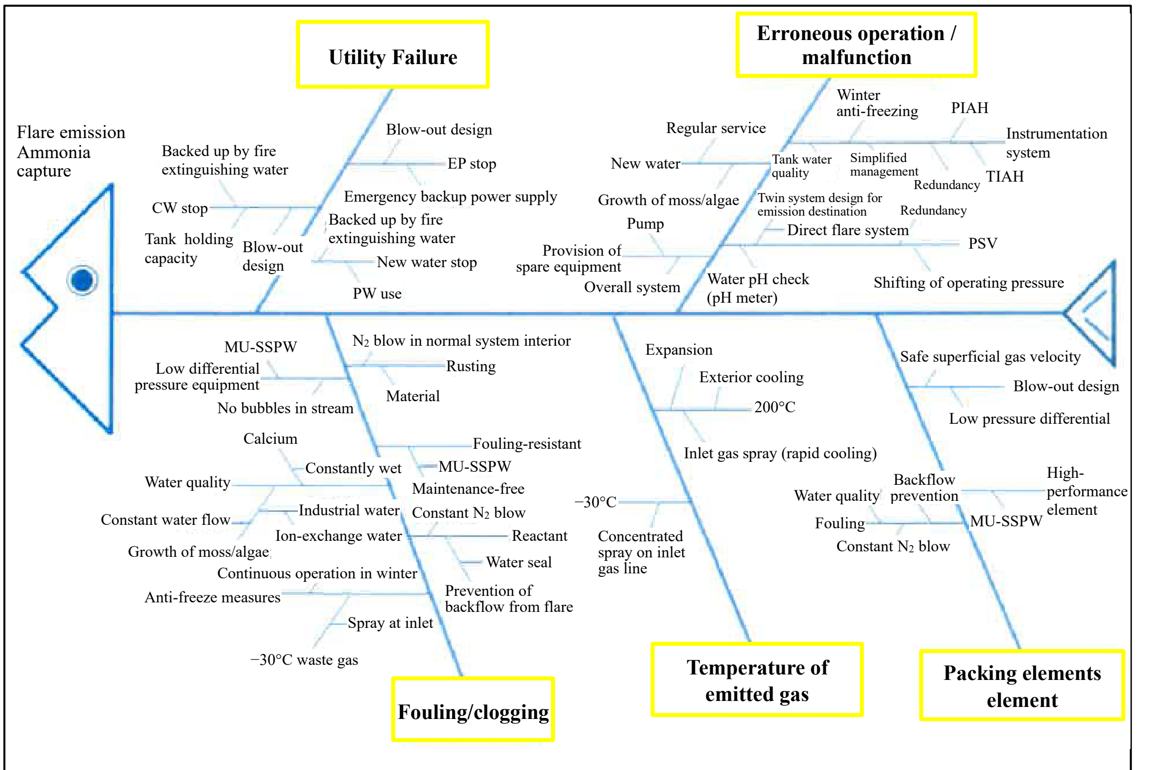

Fig. 5 Sample risk assessment

Fig. 6 is a simplified diagram of the flow.

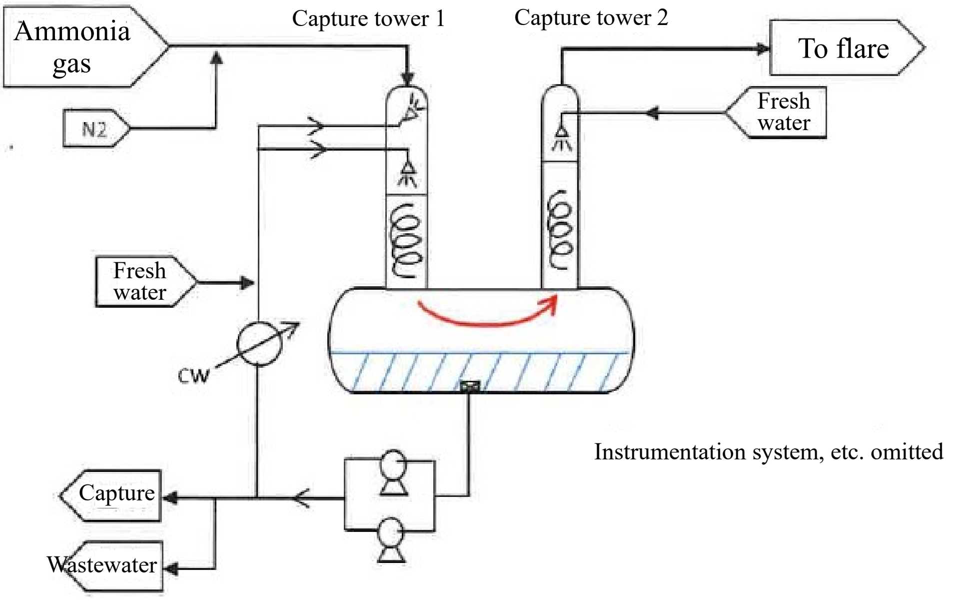

Fig. 6 Large-capacity ammonia gas emission

In the first tower (parallel flow operation), gaseous ammonia is mixed with a large quantity of water to absorb the ammonia. As a result of this process, 90% or more of the gaseous ammonia is absorbed and captured in the bottoms of the tower. At the same time, the system temperature rises due to the heat of absorption, but the increase is controlled by external cooling of the circulating water. The quantity of circulating water is determined by the amount of heat generated by absorption.

In the second tower (countercurrent flow operation), the ammonia in the gas which is at gas-liquid equilibrium at the system control temperature is completely absorbed and captured using fresh water. The tower configuration is parallel flow + countercurrent flow operation.

MU-SSPW elements offering low differential pressure and high gas-liquid contact efficiency are used in both of these towers. The first tower in particular can conduct parallel flow operation processing at a gas flowrate of 5m/sec or greater. The tower diameter can be reduced, so if a large amount of gaseous ammonia is emitted, the tower can be made compact (with the diameter reduced by half or more), and the use of MU-SSPW elements reduces equipment costs and is extremely advantageous. Conversely, if the quantity of gaseous ammonia emitted is small, it would be more economical to process it in a single countercurrent flow tower as shown in **Fig. 7**.

This method is suitable for small emission quantities using countercurrent flow operation in a single standard tower. Finally the branching points are determined based on design conditions.

5. System for capturing dissolved matter in the waste liquid

Next, let's look at an example of a system for capturing dissolved matter in waste fluid. The substances dissolved in the waste fluid in the first tower (countercurrent flow operation) are dispersed to the top of the tower by blowing air or nitrogen or other inert gases from the bottom of the tower. The gases dispersed to the top of the tower are made to react with chemicals in the second tower (parallel flow operation) to recover them as useful products. This tower configuration is countercurrent flow + parallel flow, the opposite of the system shown in **Fig. 6**.

The key point here is that the substances dissolved in the first tower, the dispersion tower, cannot be dispersed unless they are converted from an ionized state to a molecular state, so control of pH balance is required. For example, to disperse ammonia, the pH must be controlled to the alkaline side; for dispersion of the iodine in brine, it must be controlled to the acid side.

In the second tower, reaction and absorption are conducted using parallel flow operation, so the gas flowrate in the tower can be 5m/sec or greater. Accordingly, the tower diameter can be reduced and the system can be made compact. Another major feature of this system is that the gas used for dispersion can be circulated using a blower and reused, so the operation can be conducted in a completely closed loop.

5-1. Key points for design

(1) For the first tower, the dispersion tower, an element with high gas-liquid contact efficiency must be selected, reducing the flowrate of the circulating gas. This will make the tower even more compact, making it possible to reduce equipment costs and reduce blower energy consumption.

(2) At the same time, the reduction of the circulating gas is directly related to a more compact configuration for the second tower.

(3) Due to the processing of waste liquid and brine, the tower interior tends to become fouled easily. An element that can withstand fouling should be selected.

(4) For the second tower, the reactive absorption tower, an element that is suitable for parallel flow processing should be selected. This is true of the first tower as well, but even if initial investment is cheaper, if maintenance costs are high, it will create problems for system operation in the future.

(5) If a great deal of heat is generated by the absorption and reaction in the second tower, an external heat removal system in which a cooler is installed on the circulating line can be selected.

(6) Moreover, if a high temperature is ideal for the dispersion conditions in the first tower, system heating is also possible. Heating can be accomplished by an external heater or directly blowing raw steam. However, the degree to which this will affect product moisture in the second tower must be taken into consideration.

Fig. 8 shows an example of ammonia capture in a closed system using the MU-SSPW element based on the aforementioned conditions.

Over the past 40 years, the MU-SSPW element has established a proven track record and earned customer satisfaction under special conditions such as those described above. The outstanding capabilities of the MU-SSPW element have been recognized overseas as well and are widely known, and it has been introduced in technical publications in Japan[1–4] as well as technical manuals[5] for the certification of air pollution control technologies overseas.

In particular, the parallel use of the MU-SSPW element is unique in the world. We would like to develop further applications of parallel flow of MU-SSPW element with our customers.

Up to now, we have discussed the capture of highly concentrated gaseous NH_3 using the MU-SSPW element.

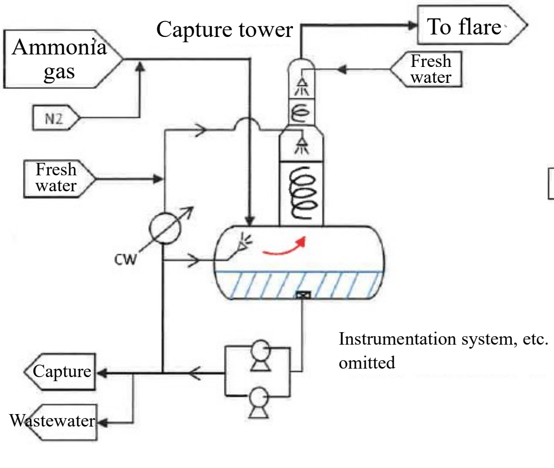

Fig. 7 For small-capacity ammonia gas release

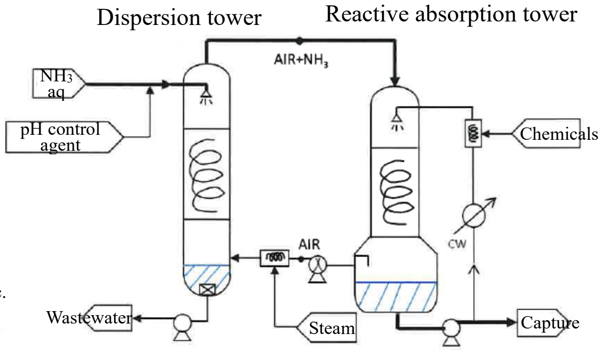

Fig. 8 Ammonia capture using closed system

6. Scaling up

Next, **Table 3** shows the ease of scaling up for the MU-SSPW element. This can be used as an example to facilitate an explanation of scaling up, a crucial perspective for plant design.

Table 3 Units for testing ease (reliability) of scaling up, compared with full-scale units

	Direction of gas-liquid flow	Diameter of MU-SSPW element (mm)		Functions				Notes			
		Test unit	Actual unit	Dust removal		Gas absorption		Dispersion efficiency	Dust removal efficiency	Absorption efficiency	Reference photo
				Inlet (mg/Nm^3)	Outlet (mg/Nm^3)	Inlet	Outlet				
Company A	Parallel flow	140	1,800	0.13 – 0.26	0.013 – 0.0026	–	–	–	90% or more	–	1, 2
Company B	Countercurrent flow	216	1,500	–	0.011	–	–	93 – 96%	–	–	3
Company C	Countercurrent flow	140	1,800	0.200	0.004	–	–	–	95 – 98%	–	4
Company D	Parallel flow	200	900	0.2 – 0.4	0.01 – 0.005	–	5ppm or less	–	95 – 99%	5ppm or less	5, 6, 7
Company E	Parallel flow / countercurrent flow 2 tower system	114	900/900	2 – 5 kg/hr	95% or more removed	1,800 kg/hr	5ppm or less	–	95% or more	5ppm or less	8
Company F	Parallel flow / countercurrent flow 2 tower system	125	250/150	–	–	90 – 95%	5ppm or less	–	–	5ppm or less	–
Company G	Parallel flow Liquid / liquid	Flow diffraction simulation	500 x 2 units	Diameter 20m spherical reaction tank (tank internal volume 4,000m^3)				–	–	–	9, 10, 11, 12 Completely mixed in 20 minutes

The scrubber delivered to Company A was for waste gas that included foul odor elements and dust particles made up of fume-type rubber deterioration inhibitors. Tests were conducted using a MU Scrubber with a diameter of 140 mm as the test unit. Based on the test results, the actual unit that was delivered was scaled up to a diameter of 1,800 mm. That actual unit had a processing gas volume of 50,000m^3/hr and an inlet dust concentration of 0.1 - 0.2 wtppm (0.13 - 0.26 mg/Nm^3) and an outlet dust concentration of 0.01 - 0.002 wtppm (0.013 - 0.0026 mg/Nm^3). **Photo 1** shows the state of the inlet prior to maintenance which is conducted once each year. Operators were disappointed to discover absolutely nothing growing (very clean) on or adhering to the blades.

Photo 2 shows the state of gas-liquid mixing following passage through the MU-SSPW element by means of natural gravity downflow. Clearly visible in the photo is the waterfall-like white turbidity resulting from the mixed gas-liquid phase flow that incorporates the surrounding air. The production of microbubbles and the generation of negative ions and ultrasonic waves helps to increase dust removal efficiency and reaction efficiency.

Photo 1 Photograph of interior before maintenance

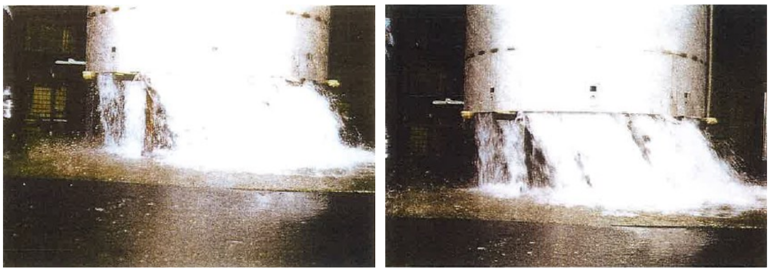

Photo 2 Status of gas-liquid mixing after passage through element by means of natural gravity downflow (top, top right, bottom right)

Although it was not the falling of Newton's apple, the birth of the MU Scrubber that utilizes natural free-fall energy occurred as a union of the cascade and the MU-SSPW. The new packing element has a mixing function that surpasses double film performance. It is characterized by offering high performance and being maintenance-free, and it also has both energy-saving and space-saving attributes. It can also be used for both parallel flow and countercurrent flow operations.

Company B uses the MU Reactor steam distillation tower which operates continuously to disperse and capture the organic compounds included in industrial wastewater. The wastewater includes small quantities of calcium compounds. Previously a sieve tray method was used, and two towers were used alternately while tower interior maintenance was conducted. The use of the MU Reactor pressure reducing distillation tower equipped with MU-SSPW elements achieves a dispersion efficiency of 95% with a single tower. It also enables continuous operation, with no calcium compounds sticking to or growing on the elements and — at a low pressure loss of 2 kPa or less — with no major changes in pressure loss (**Photo 3**). Conventional distillation towers require strict verticality, but the MU Reactor can be designed with less sensitivity to verticality. It has been used for measurements of radon in seawater at the South Pole with a ship hull inclination of 30°. This flexibility helps to keep civil engineering and construction costs low.

The MU Scrubber installed at Company C is used to remove fine particle dust from the many different types of metallic particles emitted from multiple incinerators. **Photo 4** shows the 1,800 mm diameter MU-SSPW element installed in the MU Scrubber.

Photo 3 Overall appearance of dispersion tower

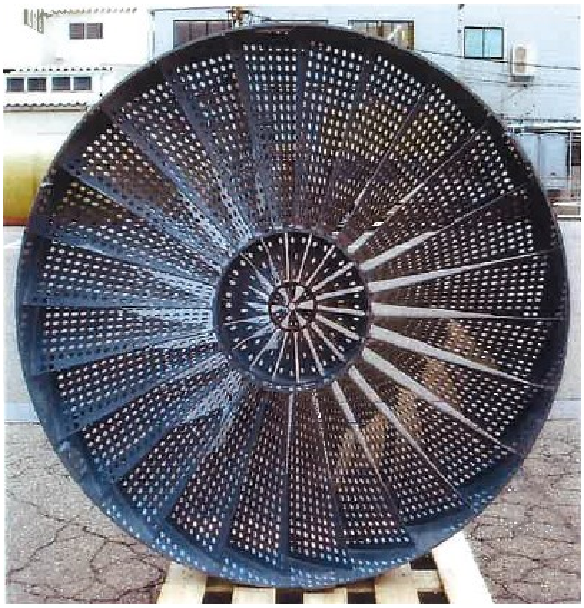

Photo 4 MU-SSPW element with diameter 1,800 mm

Company D uses a MU Scrubber to treat waste gas containing silicon and titanium compounds emitted from a production plant. **Photo 5** shows the state of the emission of waste gas into the atmosphere prior to the installation of the MU Scrubber. **Photo 6** shows the state of emission following the installation of the MU Scrubber. Almost no white smoke can be observed. **Photo 7** shows a SEM photograph of the silane oxides contained in the circulating liquid. The scale is 200 μm.

Photo 5 Prior to installation of MU Scrubber

Photo 6 Following installation of MU Scrubber

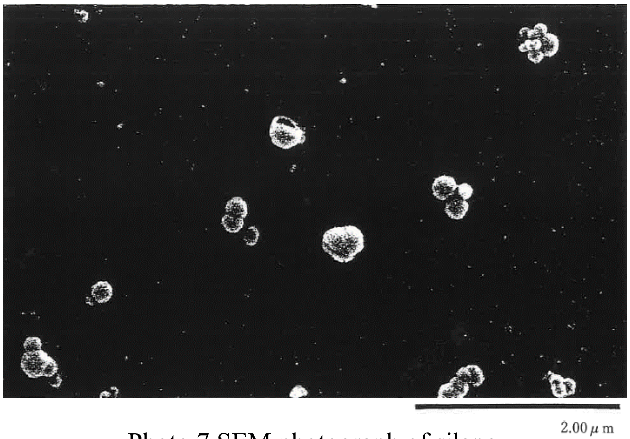

Photo 7 SEM photograph of silane oxides in circulating liquid

Company E absorbs the HCl in waste gas and captures it in the form of a 30% HCl aqueous solution (**Photo 8**). The system is made up of a fumed silica dust removal tower used with parallel flow operation and a multi-stage absorption tower used with parallel flow operation to absorb and capture 30% HCl. The dust removal tower and absorption tower are equipped with MU Mixing Elements. The on-site engineers say that, at or below a certain concentration, the MU Scrubber has experienced no trouble with clogging resulting from silica sticking to or growing on the pipes and inside of the elements in the system, which is heartening. This system ensures continuous operation of 8,000 hours each year.

Photo 8
HCl capture unit

Company F uses its unit as an absorption unit for highly concentrated gaseous NH_3 that contains small quantities of silica compounds. In the first tower, an absorption tower that uses parallel flow operation, the highly concentrated gaseous NH_3 is absorbed using large quantities of water at almost gas-liquid equilibrium. Subsequently, the NH_3 is absorbed again in the second tower, an absorption tower that uses countercurrent flow operation, and the fine particle silica compound dust is removed before emission into the atmosphere. The reaction product heat can be absorbed due to the high liquid-gas ratio. This is an ideal treatment unit for HCl, NH_3 and other highly concentrated gases.

Company G is a major Taiwanese chemical company. This application is not directly related to this paper but was included from the standpoint of scaling up. This company adopted the MU Eductor liquid-liquid mixer (**Photo 11**) as the world's first main unit reaction tank for its C5 plant with a total investment of approximately JPY 20 billion. This spherical reaction tank (**Photo 10**) has a diameter of 20m and an internal volume of 4,000m^3.

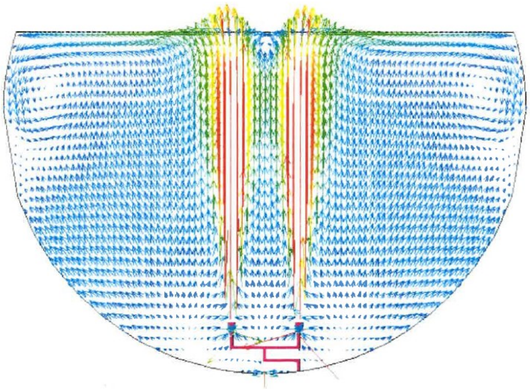

Photo 9 Simulation of wave diffraction

The execution design of the MU Eductor was determined through a flow diffraction simulation (**Photo 9**) with various trials of the supply quantity of liquid to the eductor and the suction volume from the area around the main body, as well as the liquid properties, specific gravity, viscosity, pressure, temperature and other factors. Based on the results, two MU Eductors with a diameter of 500 mm and a height of 750 mm were mounted at prescribed positions inside the spherical reaction tank. **Photo 12** shows the author in attendance at startup, at the moment when the reaction time was reduced to an even greater degree than expected. Currently, the MU Eductor achieves complete mixing in a short period of time and aids in the manufacture of high-quality industrial products. We would like to express our great respect to the owners and engineers who adopted the MU Eductor for use as the main unit in the C5 plant, a world first. The MU Eductor was also featured as a technical topic in the journal *Kagaku Sochi* (Plant and Process), April 2015, pp 4-5.

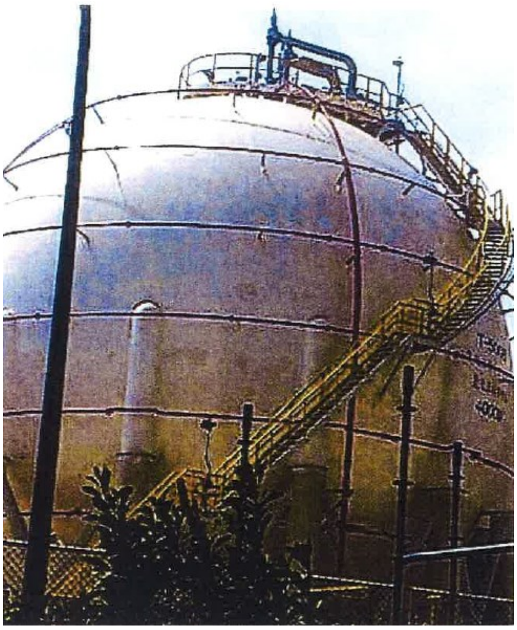

Photo 10
Spherical reaction tank with diameter 20m

This has been a simple discussion of the ease and reliability of scaling up the MU Scrubber, MU Reactor and MU Eductor which use the MU Mixing Element and MU-SSPW Element.

In the future, we intend to work diligently on scaling up the MU Aerator gas-liquid contactor for CCS, CCUS, COG, gaseous NH_3 and gaseous CO_2 and seawater, as well as diameter 3m, 5m and 10m large versions of direct absorption equipment for the CO_2 in the air and so on that are suitable for use in absorption towers and dispersion towers.

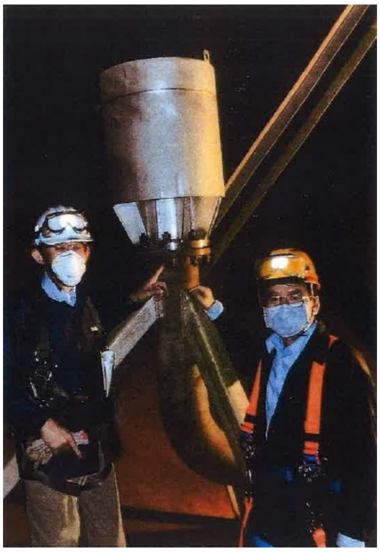

Photo 11
Company G P.M. and MU Eductor designer

Our future goal is to provide a new and revolutionary technology that combines the features of the MU-SSPW Element and the MU Eductor to collect radioactive fine particles emitted from radioactive waste incinerators in order to reduce atmospheric emissions to as close to zero as possible, and to reduce radioactive material in treated water to as close to zero as possible for discharge into the ocean.

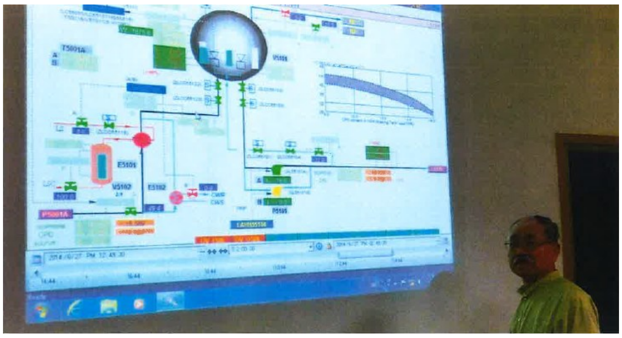

Photo 12
The author (President Kojima) in attendance at startup

7. Conclusion

Finally, there is no competition without freedom; no progress without competition; no evolution without progress; and no disruptive technical innovation without evolution. The authors would like to express their heartfelt gratitude to everyone who disclosed data.

We were reminded of the MU-SSPW by the trickle of water and wind blowing through countless holes opened through weathering of the surface of the tuff wall of *Yamadera* (Mountain Temple).

"Up here, a stillness—
The sound of cicadas
Seeps into the crags"   (translated by Arthur Binard)

—Basho—

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