# Practical Design of Marine SOx Scrubber for Mega-Container Ships

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*From January 2020, the International Maritime Organization (IMO) will implement a stricter limit for sulfur in fuel oil of ships operating in all sea areas based on their regulations. This report presents the practical design of a SOx scrubber that can stay within this limit with a treatment capability for large-output engines of ultra-large container ships. By marinizing the rectangular flue gas desulfurization system for onshore boilers, which Mitsubishi Hitachi Power Systems, Ltd. (MHPS) has improved over the years, we have given the SOx scrubber advantages in terms of the installation layout, especially in large container ships, also enabling it to be installed without reducing the cargo capacity. The system we offer has a high sulfur removal efficiency and is compliant with the regulations of all sea areas including Emission Control Areas (ECAs) which are subject to the particularly strict emission regulations.*

## 1. Introduction

Regulations on SOx emissions into the air environment have conventionally focused on fixed, onshore emission sources such as thermal power plants.

Regarding ships operating offshore, the IMO regulations, which came into effect on January 1, 2015, mandate the use of fuel oil with a sulfur content not exceeding 0.1% in pollutant ECAs such as the North Sea in Europe, as well as the Baltic Sea and coastal sea areas in North America. For ships operating in global sea areas excluding ECAs, the use of fuel oil with a sulfur content not exceeding 0.5% will become compulsory from January 1, 2020 (**Figure 1**).

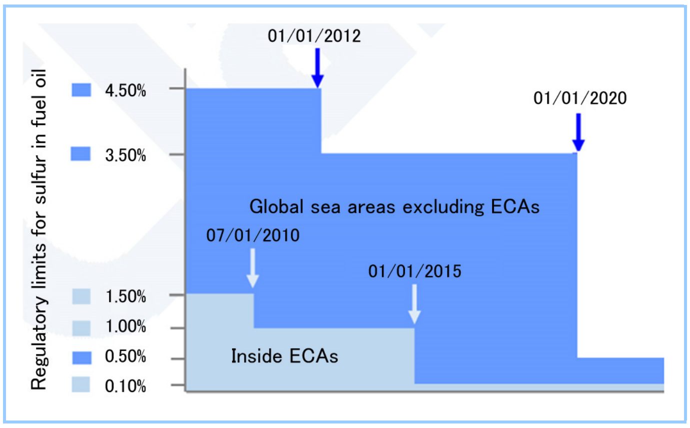


**Figure 1 Regulatory limits for sulfur in marine fuel oil**

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Meanwhile, an approved alternative method for using low-sulfur fuel oil is the combustion of conventional heavy oil in the diesel engines used for propulsion and power generation, followed by the use of exhaust gas cleaning systems (EGCS) by which the level of sulfur oxides in the combustion flue gas is reduced to or below the regulatory limit. As SOx regulation guidelines for similar measures, MEPC.259(68): 2015 Guidelines for Exhaust Gas Cleaning Systems (hereafter referred to as the IMO EGCS Guidelines) have been adopted.[1)] Given the circumstances in which low-sulfur fuel is more costly than conventional heavy oil and its supply capacity is unclear in anticipation of the demand that will grow in the coming years, there is increasing demand for EGCS enabling the continuous use of conventional heavy oil with a sufficient supply capacity at lower prices. Many marine equipment manufacturers and flue gas desulfurization unit manufacturers have entered this market.

## 2. Seawater desulfurization system for thermal power plants

In Japan, stricter emission standards for air pollutants have been gradually implemented since the 1960s as countermeasures against aggravating environmental issues. Flue gas desulfurization system manufacturers have taken up the challenge to conserve the environment by designing and supplying environmental equipment mainly for domestic/overseas thermal power plants.

The major technologies used to desulfurize flue gas from thermal power plants are the wet process, dry process, and semi-dry process (**Table 1**).

**Table 1 Overview of major desulfurization technologies in thermal power plants**

| Desulfurization method | | Process overview |
|---|---|---|
| Wet process | Alkali absorption method (typical examples)<br>○ Limestone-Gypsum method<br>○ Seawater method<br>○ Caustic soda method<br>○ Magnesium hydroxide method | (1) Absorb $SO_2$ with an alkaline aqueous solution or slurry<br>(2) Oxidize the produced sulfites to sulfates, as needed<br>(3) Collect the products for reuse or disposal<br>(4) There are several different processes depending on the alkali in use<br>(5) The major processes are the limestone-gypsum method and the seawater method |
| Semi-dry/dry process | Spray-dry method | (1) Spray slaked lime slurry into the reaction tower to turn $SO_2$ into powdery substances such as calcium sulfite<br>(2) Collect using the precipitator and dispose of the collected matter |
| | Activated carbon method | (1) Adsorb $SO_2$ with activated carbon<br>(2) Thermally desorb the adsorbed $SO_2$ to collect highly-concentrated $SO_2$ and turn it into gypsum, sulfuric acid, etc. |

Among these technologies, we will address wet flue gas desulfurization with seawater, which is suitable for flue gas treatment for ships.

**Figure 2** is a system flow diagram for seawater desulfurization. In a desulfurization system using seawater, the alkaline components (e.g., $HCO_3^-$) naturally contained in seawater are utilized for desulfurization, instead of using chemicals like limestone and magnesium hydroxide as absorbents for sulfur in flue gas.

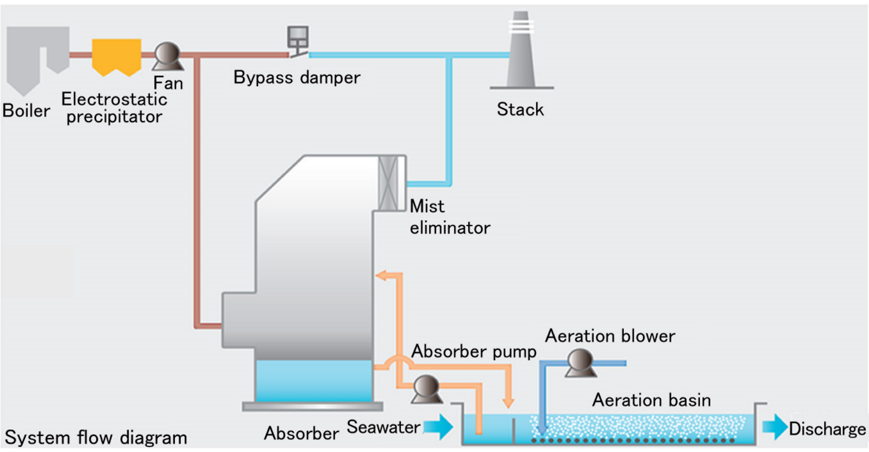


**Figure 2 System flow diagram for seawater desulfurization**

In recent years, because of its simple configuration and desulfurization being possible even when there is difficulty in preparing absorbents or handling by-products, this system has been increasingly adopted by power plants in emerging countries such as India and those in Southeast Asia and the Middle East. The principle of seawater desulfurization is the absorption of $SO_2$ in flue gas into seawater inside the absorption tower, followed by the oxidation treatment of the formed sulfite ions ($HSO_3^-$) through contact with large quantities of air in the oxidation tank to produce harmless sulfate ions ($SO_4^{2-}$). As sulfate ions are contained abundantly in seawater, there is little impact on the marine environment. In the oxidation tank, pH is adjusted by means of neutralization and aeration and the reduced level of dissolved oxygen is recovered by oxidation, before the treated seawater is ultimately discharged into the sea. The reactions are as follows:

Absorption: $SO_2 + H_2O \rightarrow H^+ + HSO_3^-$

Oxidation: $HSO_3^- + (1/2)O_2 \rightarrow H^+ + SO_4^{2-}$

Neutralization: $HCO_3^- + H^+ \rightarrow H_2O + CO_2 \uparrow$

MHPS's deliveries of seawater desulfurization systems includes one installed at a heavy oil-fired plant that treats flue gas with one of the highest $SO_2$ levels by seawater desulfurization (Saudi Arabia), and another installed at the world's largest class 1000 MW coal-fired plant (Malaysia). Making use of their proven normal operational records, we tailor the design of seawater desulfurization systems that can satisfy the diverse needs of our customers. The actual value of the rate of desulfurization by our seawater desulfurization systems for thermal power plants exceeds 99%, which is significantly higher than that required in ECAs (97.1%).

## 3. Application to marine SOx scrubber

Using seawater as a desulfurization absorbing liquid, our marine SOx scrubber employs a seawater desulfurization system that has a simple configuration and can be installed in a limited space. **Figure 3** is a system flow diagram of the marine SOx scrubber. The basic principle is the same as the desulfurization system for thermal power generation and the seawater taken from the sea is supplied to the absorption tower, directly spraying into flue gas. The system utilizes alkaline components naturally contained in seawater to remove sulfur. What differentiates this system is the post-desulfurization seawater treatment method. In the case of thermal power plants, the seawater used for desulfurization undergoes treatments such as oxidation and pH adjustment in the oxidation tank according to the requirements of each country or region, before being discharged into the sea near the power plants. On the other hand, the marine SOx scrubber complies with the IMO EGCS Guidelines and makes sure that the effluent pH, polycyclic aromatic hydrocarbons (PAHs), turbidity, etc., are within the respective limits before being discharged overboard. Each unit of the marine SOx scrubbers needs to be approved by a classification society regarding its compliance with the Guidelines.[3)]

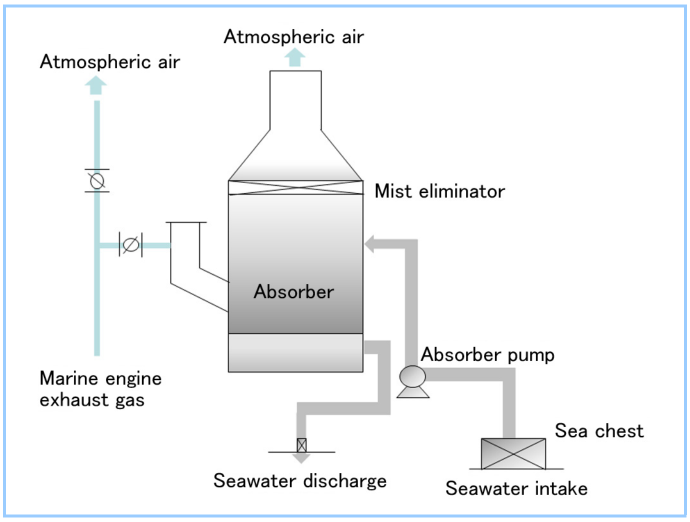


**Figure 3 System flow diagram of marine SOx scrubber**

**Table 2** lists the differences of desulfurization system design conditions between thermal power plants and large ships. When it comes to the system size, those for onshore thermal power plants are larger and require higher desulfurization performance.

**Table 2 Differences of desulfurization system design conditions between thermal power plants and large ships**

| | For thermal power plants | For large ships |
|---|---|---|
| Flue gas treatment capacity ($Nm^3/h$) | 600,000 to 4,000,000 | 23,000 to 540,000 |
| Fuel | Heavy oil/coal, etc. | Heavy oil |
| $SO_2$ level at the inlet of desulfurization unit (ppm-d) | 100 to 1800 | 700 |
| $SO_2$ level at the outlet of desulfurization unit (ppm-d) | 10 to 220 | 20 |
| $SO_2$ removal efficiency (%) | 75 to 98 | 97.1 (3.5%S → 0.1%S): ECAs<br>85.7 (3.5%S → 0.5%S): global sea areas excluding ECAs |
| Regulatory items for seawater discharge | pH, dissolved oxygen (DO), temperature, etc. | pH, PAH, turbidity, nitrates |

## 3.1 Summary of IMO EGCS Guidelines[1),3)]

Here, we will describe the regulatory items for seawater discharge, which are stipulated as the requirements particular to marine SOx scrubbers.

3.1.1 Effluent pH criteria for discharge

These criteria set the limits for the acidity of washwater effluent. The effluent at 4 m from the overboard discharge point with the ship being stationary should have a pH of no less than 6.5. Continuous monitoring is obligatory while EGCS is in operation.

3.1.2 Effluent turbidity criteria for discharge

These criteria set the limits for the turbidity of washwater effluent. The maximum turbidity difference between inlet water and discharge water should be no greater than 25 FNUs (formazin nephlometric units) or 25 NTUs (nephlometric turbidity units). Continuous monitoring is obligatory while EGCS is in operation.

3.1.3 Effluent PAH criteria for discharge

These criteria set the limits for the PAH concentration in washwater effluent. For example, the maximum difference between the PAH concentration in inlet water and that in discharge water should be no greater than 50 μg/L PAHphe (phenanthrene equivalence) at a washwater flow rate of 45 t/MWh. The stipulated limits are normalized according to the washwater flow rate. Continuous monitoring is obligatory while EGCS is in operation.

3.1.4 Effluent nitrate criteria for discharge

These criteria set the limits for the nitrate concentration in washwater effluent. The nitrate concentration should not exceed the following, whichever is greater.

(1) 12% of the NOx emissions from flue gas

(2) Nitrate concentration of 60 mg/L at a washwater flow rate of 45 t/MWh

## 3.2 Points to note in design of marine SOx scrubber

3.2.1 Countermeasures against scrubber vibrations caused by external vibrations

When installing the SOx scrubber in a ship, we have to consider countermeasures against the vibrations particular to ships. Every instrument or structure has its own frequency at which it tends to oscillate (i.e., natural frequency). When an external exciting force, which works to shake an instrument or structure, has a frequency close to the natural frequency, a phenomenon called sympathetic resonance occurs. As a result, the vibration of the instrument or structure intensifies, which may damage the structure. Therefore, it is important to understand natural frequencies by means such as numerical simulation and design a structure that can prevent the occurrence of sympathetic resonance with the exciting frequencies.

**Table 3** gives some examples of the vibratory forces on board ships and their consequent ship vibration directions. As shown in the table, the forces on board ships that cause the SOx scrubber to oscillate include the inertial force of the main engine involving the reciprocating motion of the engine piston and the rotational motion of the crankshaft, as well as the propeller vibratory force originating from the rotating screw propeller that results in surface force on the stern outer shell through seawater.

**Figure 4** shows a vibration response analysis model of the entire ship. Regarding the SOx scrubber, to simultaneously assess vibration response and fatigue strength, modeling was done by allowing the shell elements to include shaped steel parts such as stanchions and reinforced parts such as plating. The beam elements also included steel tubes such as piping, internal structural members and support structures.

**Table 3 Examples of vibratory forces on board ships and consequent ship vibration directions**

| Vibratory force | Degree | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1N | 2N | 3N | 4N | 5N | 6N | 7N | 8N | 9N | 10N | 11N |
| Inertial force of the main engine | ● | ● | | | | | | | | | |
| Vertically transmitted force | | | ● | ● | | | | | | | |
| Propeller vibratory force | | | | | | ● | | | | | |
| 10 cylinder ship | | | | | | | ● | | | ● | |
| 11 cylinder ship | | | | | ● | | | ● | | | ● |
| Major vibration direction | Up/down and bow/stern | | Bow/stern and up/down | | Torsional | Up/down | Torsional and port/starboard | | — | Port/starboard | |

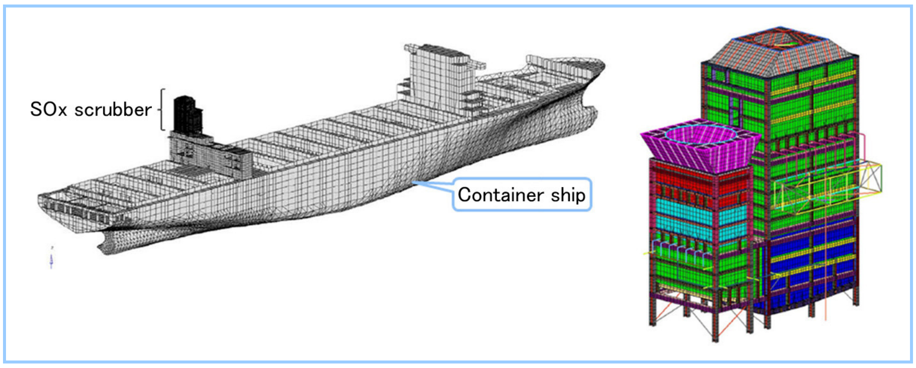


**Figure 4 Vibration response analysis model of entire ship**

The vibration response analysis results using this model show that the entire structure of the SOx scrubber, ducts, internal structural members, surrounding wall panels, and piping successfully ward off sympathetic resonance with the frequencies of external vibratory forces. It has also been indicated that the stress concentrated areas in the SOx scrubber structure have sufficient fatigue strength.

3.2.2 Material selection method

As the seawater desulfurization unit needs to have resistance to the acids absorbed from seawater and flue gas, the materials to be used should be highly resistant to corrosion. In a desulfurization unit for onshore thermal power plants, materials with high acid resistance such as resin lining materials and fiber reinforced plastic (FRP) have often been used. On the other hand, for ships with a shorter maintenance period than thermal power plants, the use of resin materials is avoided in many cases, because it takes longer for maintenance. Metals are therefore a preferable choice in most cases, and two-phase stainless steel is mainly used for the scrubber tower. As the flue gas inlet where hot flue gas comes into contact with seawater for the first time is subject to the most severe corrosive environment, the use of stainless steel with high corrosion resistance is essential. This environment is so severe that corrosion will occur within a short period of time, if the seawater spray method and structure of the flue gas inlet are not adequately considered at the same time.

## 4. Marine SOx scrubber features

### 4.1 Operable in open loop mode in ECAs

The marine SOx scrubber operates in one of the following modes: open loop in which seawater is sent as an absorbing liquid to the absorption tower in a single pass system, closed loop in which a circulating liquid containing chemicals such as caustic soda is used, and hybrid in which the other two modes are used in combination. Together with Mitsubishi Shipbuilding Co., Ltd., MHPS has employed the open loop mode for desulfurization treatment of flue gas from 30-75 MW class large-output engines, without the need for the use of chemicals such as caustic soda. The developed marine SOx scrubber also complies with the regulatory limits in ECAs.

### 4.2 Rectangular absorption tower with high volumetric efficiency

**Figure 5** is the external view of the marine SOx scrubber. As the height/width ratio of the rectangular absorption tower can be changed relatively freely, the optimal layout in the limited space of a ship becomes possible, achieving a higher volumetric efficiency than the existing cylindrical scrubbers. Especially for large container ships, the scrubber can be installed without reducing the container burden, which indicates that the rectangular shape has a considerable layout advantage. **Figure 6** depicts an image of the layout of the scrubber on board a large container ship. This is an example of a large container ship with a two-island design with living quarters separate from the engine casing in which the scrubber unit is accommodated, thus enabling the installation to be carried out without reducing the number of containers on board.

**Figure 5 External view of marine SOx scrubber**

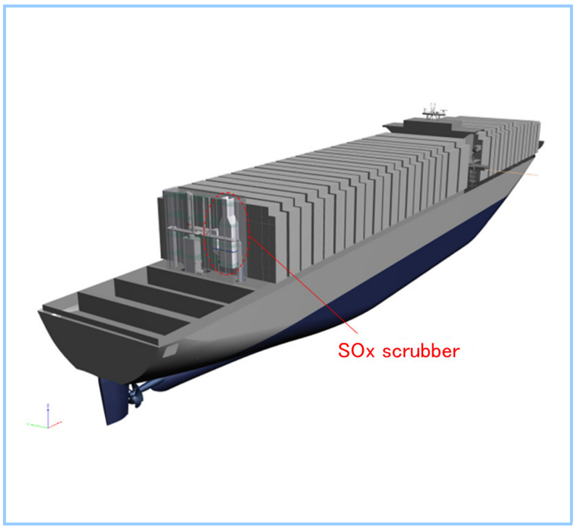


**Figure 6 Conceptual image of scrubber located on board large container ship**

## 5. Engineering for installation

Mitsubishi Shipbuilding Co., Ltd. provides the engineering service for installation to customers who want the SOx scrubber to be installed on board their planned ships more quickly, easily and securely. The company assists in their plans through the provision of service by taking advantage of its strength and shipyard experience together with the knowledge it possesses as a SOx scrubber manufacturer. While this service is also available to customers who want to retrofit the SOx scrubber to their in-service ships, an increasing number of shipbuilders are using this service for ships that they plan to construct. The company can propose an installation plan harmonious with the ship in question, whether it is newly built or already in service or whether we built the ship or it was built by another company.

With regard to the retrofitting of in-service ships, the engineering service for installation is provided according to the following steps:

(1) Reverse engineering (3D laser measurement)
(2) Basic plan
(3) Detailed engineering

(1) Reverse engineering

To do the engineering work for installation in relation to the retrofitting of in-service ships, the drawing information on the ship in which the scrubber is to be installed is required. The detailed piping drawing in particular is needed when designing the layout arrangement. However, as it is usually a working drawing used at shipbuilding dockyards, it may be unavailable in some cases. Even when the working drawings are available, the drawing information may be different from the actual ship because of post-launch modifications, etc. If this is the case, 3D laser scanning is conducted to design the layout arrangement based on the created 3D model (called a 3D as-built model).

With the 3D laser scanner, a hemisphere with a radius of several dozen meters (the scanner is located at the center of the hemisphere) is continuously irradiated by a laser pulse and the distance from each object for measurement in the hemisphere (e.g., ship shell, piping and auxiliary equipment) is calculated by comparing the phase difference between the incident and reflected waves. The point of reflection is determined based on the angle of where the laser originally came from and data of a group of several thousand points can be collected with a single measurement. The measurement is repeated until the whole area for retrofitting is covered. Combining these data together enables the positioning information to be complementary synthesized to three-dimensionally visualize these objects. The data of groups of points are converted so as to be handled as 3D CAD data.

(2) Basic plan

The basic plan starts on the basis of the information on the scrubber unit and the ship in which the scrubber is to be installed. In the retrofitting of in-service ships, the value added by the engineering work for installation is to propose a retrofit plan with minimized work over a shorter time span.

Based on the 3D as-built model of the planned ship, we plan how to lay out the components such as the scrubber tower, flue gas damper, seawater pump, scrubber control panel and sensors and decide the large-diameter piping routes such as seawater pipes and flue gas pipes. At the same time, a retrofit plan is made regarding the upper hull structure in which the scrubber tower is to be fitted, as well as for the structure of the sea chest at the bottom of the ship through which seawater is taken from the sea. Moreover, the impact of scrubber installation is examined in terms of ship stability (metacentric stability), hull strength, cargo load, onboard power consumption, etc. We proceed with the basic plan as described above and propose the optimal retrofit plan that provides a clear understanding of the impact on ship safety and performance to the customer.

(3) Detailed engineering

The details of retrofitting in relation to scrubber installation are reflected in the detailed engineering drawings such as the engine chamber layout diagram, piping system diagram, detailed piping diagram, table of electricity, electrical power system diagram, electronics layout diagram, and ship shell structure diagram. The amount of retrofitting work is thus estimated. At the same time, we proceed with certification by classification societies and the relevant authorities. The amount of retrofitting work will be used as reference information to estimate the cost at the customer's repair dockyard, while the detailed engineering drawings are used to draw up a work schedule at the repair dockyard.

## 6. Conclusion

As a response to IMO environmental regulations, the following choices are available: the use of low-sulfur fuel compliant with the regulations, the installation of a SOx scrubber, and the use of liquefied natural gas fuel. The installation of a scrubber enables the continuous use of conventional fuel, resulting in lower fuel cost than in the case of using expensive low-sulfur fuel. The period required to recover the investment in scrubber installation is estimated to be 2 to 5 years in many cases, and demand is increasing.

Given the stricter regulations to reduce the impact of marine flue gas on the air environment, we have developed a marine SOx scrubber by expanding the application of flue gas desulfurization technology for thermal power plants. This scrubber unit has specifications that satisfy the regulatory limits regardless of the sailing sea area, thereby enabling us to meet the diverse needs of our customers.

Toward the implementation of stricter regulations in 2020, we want to contribute to solutions to global issues of energy and the environment (which is one of our Vision Statements) through the provision of marine scrubbers to our customers worldwide.

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