Different Industries – Different Technologies?
– Seawater Scrubbing for Power Plants and Cruise Ships –

Christian Fuchs

1. Restrictions for exhaust gas scrubbers .....................................................666
2. Additives for closed loop exhaust gas cleaning systems .........................666
3. Coal fired power plant Longyearbyen ......................................................667
4. Exhaust gas scrubber for ships .................................................................670
   4.1. Offline and inline arrangement ..............................................................671
   4.2. Open loop operation .........................................................................676
   4.3. Closed loop operation .......................................................................678
5. Conclusions and outlook ........................................................................679

1958 the international maritime organization (IMO) was founded to promote safety at sea more effective by forming an international body with the main shipping nations as members. Today there are 174 members of all important maritime states.

The first task of IMO was to agree in 1960 on the International Convention for the Safety of Life at Sea (SOLAS), the most important regulation dealing with all matters of marine safety.

Workgroups of the IMO discuss and agree on specific matters, for example, the Marine Environment Protection Committee (MEPC) is defining and regulating all emissions at sea, be it to water or be it to air.

In 1997 decision was taken to protect the oceans from SO₂ and NOₓ emissions from the engines, it took until 2005 to have the regulation agreed between the 174 member states and in force for dedicated sensitive area SECA areas (Sulphur Emission Controlled Areas) with a validation date in January 2015. In January 2020, the regulation will be in force worldwide.

Thus, the shipping companies are forced to bunker low sulfur fuels (LSHFO or MGO), to use alternative propulsion energy like LNG, battery power for electric engines, to install scrubbers to reduce the environmental footprint or to pay substantial penalties.

One very bad example for the pollution of air with the exhaust gas of HFO driven 2-stroke engines is the MS Yang Ming Utmost, which polluted on 04. October 2014 the port of Hamburg and the area of many square kilometers with a poisonous sud cloud.
The fuel used in the ship engines is HFO, Heavy Fuel Oil, which is waste and residue of refineries and contains up to 3.5 % Sulphur and other unwanted pollutants like for example Heavy Metals.

Beginning 2020, the S-contents in HFO will be limited on the seas worldwide to a maximum of 0.5 %. Latest to that date, the ships need conversion to Exhaust Gas Cleaning Systems (EGCS) in order to travel the oceans legally, because it is widely assumed that not sufficient low sulphur fuel will be available.

1. Restrictions for exhaust gas scrubbers

It is not an easy task to install a scrubber aboard of a ship, where is no unused space, no room for additional components, for tanks and where additional weight reduces the loading capacity of the ship and slows it down.

Height limitation is also an issue. If the scrubber cannot be installed below the top deck, it might interfere with the ships navigation and communication systems. Height is principally limited by the height of the existing stack.

Wherever the scrubber is being installed, the static of the ship is concerned by a change of loads. This has a major impact, because a ship is not only subject to static and vertical loads, but also due to the complex ship movement as heaving, swaying and surging there are also horizontal loads and turning moments.

In case a closed loop EGCS is installed there is also a requirement for process tanks and storage tanks, which mostly will be integrated in the ship structure as integral tanks.

Finally yet importantly, the scrubbing water needs to find a dedicated and safe way on board and, more important, off board again.

Any of these modifications require the involvement of static calculations about the ship structure, specialized companies offering calculation of the required modifications to the system ship and offering guarantees for these calculations.

Just to illustrate that these problems are of serious nature you have to understand that for a scrubber treating the exhaust gas flow of a 24 MW engine, we have to design for 150,000 m³/h exhaust gas flow of up to 250°C, a process tank of 20 m³, an additive tank of 50 m³ and a discharge tank, which in worst case might have up to 2,000 m³.

2. Additives for closed loop exhaust gas cleaning systems

If the EGCS is operated in open loop, the additive used for the neutralization of the exhaust gas is seawater, which is pumped from the sea to the scrubber and then released back to the sea. Here certain conditions for the water discharge need to be maintained, e.g. pH, turbidity and PAH concentration.

In certain sensitive areas of the sea like for example harbors, open loop operation is not permitted anymore (or will be in future) and the EGCS needs to switch to closed mode.
A closed loop EGCS may use the same additives, which are common for land-based power plants. In fact, there are experiences with caustic soda, dry hydrated lime and magnesia milk. No experience up to date exists with limestone milk or sodium carbonate.

However, and this is the advantage of the open loop technology, when you can use seawater as an additive there is no weight loss for additives or residues to be stored aboard, there is no requirement for additional tanks or components and the complete system saves weight, space and complexity.

To better understand the seawater scrubbing technology for the open loop scrubbers, we want to have a closer look at the coal fired Longyearbyen power plant on Spitsbergen, the largest island of the Svalbard archipelago, northernmost part of Norway.

3. Coal fired power plant Longyearbyen

Spitsbergen has a population of 2,700 people, from which more than 2,000 are located in the Longyearbyen region, the capitol village of the islands. The second main local mammal is the polar bear, of which we count 3,500 in this part of the Barents Sea.

Commercially today, Spitsbergen is depending mainly from tourism, after periods of whaling and coal export.

As the climate of the archipelago is arctic, a safe and redundant power and energy supply is mandatory. Today heat and electricity are generated by the Longyearbyen hard coal fired power plant, which combines two boiler and one flue gas cleaning system, while only one boiler is in operation. Redundancy of the heat and energy generation is 100 %, the flue gas cleaning part is only one single line with a bypass.

The required coal comes from local mines, but any required additive would have to be transported by ships, making the safe supply subject to many uncertainties.

The complete installation is in-house due to the extreme climate conditions.

The discussions with the customer about the use of seawater scrubbing technology were very interesting, since this technology is not very common in this remote part of the world.
Finally the decision pro seawater scrubbing was made out of two reasons:

- Lowest OPEX
- Safe availability of the additive

The flue gas cleaning system is a wet scrubber with a packing, arranged after dedusting with an ESP and a quench for the cooling and saturation of the gas. The stack has a FRP pipe and a steel pipe, which in normal operation is not in use. Only in emergency, when the ESP and the scrubber are bypassed, the hot exhaust gas is diverted to the *hot* pipe.

This bypass is increasing the safe operation of the boiler for heat and power generation even in case of problems with the flue gas cleaning system.

The only additives required for the generation of heat and power are the coal, which is from local mines and ammonia for the SNCR, which needs to be transported to Spitsbergen in tankers. The other additive, which is required for desulphurization, is seawater, which is available free from the Barents Sea.

The power plant is relatively small and produces 11 MW\textsubscript{el} and 16 MW\textsubscript{th} with a steam flow of 40 t/h at 460 °C. The stack is 90 m high. The boiler plant was commissioned in 1982 and was delivered by Burmeister & Wain from Copenhagen.

The design gas flow is approximately 45,000 Nm\textsuperscript{3}/h\textsubscript{t} at a temperature of 160 °C. The local coal contains a low amount of sulphur, for design this value was increased to 5,000 mg/Nm\textsuperscript{3} dry. Emissions are limited contractually with an annual load.
### Table 1: Design data of the flue gas cleaning system of the Longyearbyen plant

<table>
<thead>
<tr>
<th>item PFD</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
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<tbody>
<tr>
<td>designation</td>
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<td>boiler outlet</td>
<td>ESP outlet</td>
<td>booster fan outlet</td>
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<tr>
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<td></td>
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<td>163</td>
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<tr>
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<tr>
<td>flow rate dry at 6 % O₂ dry</td>
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<tr>
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<tr>
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<tr>
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<td>mg/Nm³ dry</td>
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<tr>
<td>SO₂</td>
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<tr>
<td></td>
<td>mg/Nm³ dry</td>
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<td>5,000</td>
<td>5,000</td>
</tr>
</tbody>
</table>

The Flue Gas Cleaning System produces only one contractual residue: Fly ash from the ESP.

### Table 2: Residues of the Longyearbyen plant

<table>
<thead>
<tr>
<th>designation</th>
<th>residues from ESP</th>
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</thead>
<tbody>
<tr>
<td>references</td>
<td>3</td>
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<tr>
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<tr>
<td>temperature</td>
<td>160</td>
</tr>
<tr>
<td>density</td>
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</tr>
</tbody>
</table>

However, there is also a flow of seawater to the scrubber and, after scrubbing, from the scrubber back to the sea.

It is obvious, that this flow and the contained elements are also subject to emission control.

For the wash water discharge it is not just one measuring point, you are obliged to measure both inlet and outlet conditions and calculate the difference values, this is what is legally considered as a discharge from the ship:

- Oil or oil-sludge < 15 ppm – absolute value
- pH value > 6.5 – absolute value
- Turbidity < 25 NTU (Nephelometric Turbidity Units) – differential value
- PAH (Polyaromatic Hydrocarbons) < 50 µg/l normed to 45 m³/h / MW – differential value
Table 3 clearly shows, that there are no real changes in the composition of the washwater before and after scrubbing, the only main difference is the pH-value, which is alkaline before and strongly acidic after the scrubber. This value requires a neutralization or at least a dilution of the washwater to reach the accepted pH 6.5.

The salt concentration before the scrubber is approximately 3.5 % as it is also after the scrubber.

### 4. Exhaust gas scrubber for ships

Why scrubbing the exhaust gas of ships?

The following Figure illustrates the main shipping routes and therefore the pollution caused by the ships, which burn heavy fuel oil for propulsion, which also discharge polluted water along their routing and all this with legal justification.

In the early days of shipping, there were no marine rules at all for safety and environment. The open oceans were not belonging to any state and therefore there was no state legislation. This changed slowly and today the IMO has the power to define rules, which have to be taken into the national legislation of all member states.

One example are the SOLAS guidelines, but also water discharge, waste incineration on board and last but not least the emissions of exhaust gas from the engines.

As mentioned in the beginning, sulphur contents of fuel has been limited to 0.1 % in certain areas from January 2015 and will be limited worldwide starting January 2020 to 0.5 %.

The first experience with the SECA limitations in the North Sea is that the pollution has decreased by more than 50 % in the Channel and close to Heligoland. These results prove that using LSHFO or also the equivalent of using scrubbers is making a significant change for the environment.
The main difference between using HFO 3.5 % unscrubbed or scrubbed with seawater is the prevention of acid rain. The sulphur salt concentration in the sea does not change at all when using a scrubber, but the local impact of acid rain on life at sea when not scrubbing is immense!

The costs of low sulphur fuel is approximately double to the fuel with sulphur, so it might be an attractive financial approach to install a scrubber to reduce the OPEX of the ship.

Fuel consumption for propulsion is approximately 170 kg to 200 kg per MWh. Considering that a regular ferry has 20 MW engines for propulsion, 4 MW engines for electricity, an hourly consumption of 4 t/h HFO is average. With 3.5 % sulphur in the fuel, this is equivalent to 280 kg/h SO₂ emissions!

If you imagine that, we can consider approximately 50,000 ships to be travelling the oceans and they all burn HFO with 3.5 % sulphur at the rate we have indicated above, the damage done to life at sea is dramatic!

4.1. Offline and inline arrangement

The Exhaust Gas Scrubber will be installed either in a new built or a retrofit ship. Here we have the first deciding factors for the scrubber design.

When you look at new built, there is a specific planning possible, scrubber dimensions, supporting structure and weights can be built in tailor-made.

A retrofit is a completely different story: There is no room left for the scrubber and the static design of the ship has been done. To incorporate a scrubber at a later stage means much more complications, because the structure needs to be changed in wide areas to make room for the necessary components.
If you do a retrofit the *easy* way, decision is made for an Inline-Scrubber, which will take the place – at the dimensions – of the silencer. The silencer of the engine is taken out, the scrubber is installed instead. The benefit is clearly, there is no lost space on the ship. The drawback is that the design of the scrubber is made to fit in the available space and not necessarily to the required performance. An Inline Scrubber usually has less performance compared to an Offline Scrubber, which on the opposite is larger in diameter and height. Furthermore the Inline Scrubber needs to be designed in an sound reducing way to achieve the same sound reduction as the silencer, but at the same time needs to have scrubbing ability. One Inline Scrubber generally scrubs one engine’s exhaust gas, meaning if there is a main engine and three auxiliary engines, in the worst case four scrubbers need to be installed.

The Offline Scrubber, to the opposite, is designed for performance. Compared to the Inline Scrubber it is usually of bigger diameter and height, and it is sometimes not easy to find a space on board, but if you find the space, the benefit is an easy installation, a low pressure drop, high performance and the possibility to use a corrosion free compound material for the scrubber housing.

![Inline versus offline scrubber](image)
The Offline Scrubber has a weight disadvantage compared to the Inliner, because it is just additional weight and there is a completely new supporting structure required. The Inliner is neutral in weight, because the silencer is taken out instead and the support for the silencer is sufficient for the scrubber as well.

![GA drawing offline scrubber](image-url)
The weight disadvantage is a real issue for the loading capacity on smaller ships, but for the big ships of 360 m length and a maximum load of 140,000 DWT and more it is helpful and stabilizes the ship.

One other main advantage of the Offline design is, that a specific compound material, a fiber reinforced plastic (FRP) can be used.

The exhaust gas is diverted from the main stack with a bypass duct and introduced to a quench, to cool down to saturation temperature. At this temperature, the use of FRP is safely possible, meaning, that the corrosion, which is a serious problem for any alloy is eliminated.

If it comes to installation, an Offline Scrubber can be installed within a few hours, compared to an Inline Scrubber, which requires serious lifting and installation works.

In case of this 13,000 TEU container ship the integrator and shipyard prepared a complete module housing the scrubber, but also the quench, the bypass, the sealing dampers, the emission monitoring equipment etc. This installation work take place on the dock, in preparation, without the ship being present. Docking days are are Off-Hire days for the ship, very expensive and need to be limited to an absolute minimum.

The scrubber module then is lifted into place, bolted to the resilient mounting to protect the structure from the engine’s vibrations. This action involving a heavy crane takes only a few hours, compared to the lifting of an inline scrubber and all other equipment into the structure of the ship.

Here the Offline Scrubber is in clear advantage to the Inline Scrubber.

Figures 6 and 7: Installation offline scrubber
Figures 5 to 10 clearly show the different design of the inline and offline technology:

The design follows the available space principle and results in a slim and tall scrubber. The exhaust gas velocity is higher here, as high as 4 – 5 m/s, resulting in a limited reaction time inside the scrubber to allow for the migration of SO₂ from gas to water of less than 2 seconds.

Furthermore, the Inline Scrubber has to reduce the exhaust sound of the engine, because it replaces the silencer. Required sound reduction is by approximately 35 dB/A, this is a guarantee value. The LAB solution is a specially designed inlet and outlet piece, which reduces the sound level by the required amount, but increases the exhaust gas pressure.

The exhaust gas pressure is a critical characteristic for the engines. Mainly in use are two-stroke engines, which are able to fire the heavy fuel oil, but which are sensitive against a backpressure in the exhaust gas flow. The backpressure already is created by the turbocharger, the exhaust gas boiler, possibly a SCR – DeNOx and the resistance of the duct routing. Usually a value of 15 mbar remains available for the pressure drop of the scrubber itself, which needs to be considered.

Finally, there is a further drawback for the Inline Scrubber: In SECA areas the scrubber is in operation, in non-SECA areas is switched off to save costs. In this situation, because there is no bypass for the Inline Scrubber, the hot exhaust gas passes through...
the scrubber at the original temperature, which can be as high as 340 °C. The pumps are not spraying any water to cool down the exhaust, meaning that the material of the scrubber itself, but also all sensors, valves, dampers and sealings have to withstand this high temperature.

As mentioned before, from January 2020 on the worldwide limitation of sulphur will lead to the fact that the scrubber will not be switched off in open water any more.

4.2. Open loop operation

Generally, a scrubber can be operated in open loop or in closed loop. The possibility to switch between both modes is called Hybrid.

An open loop system consists of the scrubber itself and pumps to provide the necessary seawater for the reaction, that is all. The clear benefit of this simple system is the low Capex and low Opex, while fulfilling the Marpol regulations for most areas.

Usually this system is already designed as Hybrid-ready, meaning that pumps are manufactured from high grade alloys, designed to withstand high temperatures and low pH values, which are linked to the closed loop operation.
Seawater Scrubbing for Power Plants and Cruise Ships

Flue Gas Treatment

The operators clearly prefer open loop mode, because in this mode the only additive used is free seawater with its natural pH value of approximately 8.0. Seawater is taken from the ocean, pumped to the scrubber to react with the sulphur contents of the exhaust gas and then released back to the sea without further treatment. The difference between inlet and outlet conditions of the seawater is continuously monitored and has to comply with the Marpol regulations; these are the same regulations the power plant in Longyearbyen has to follow.

Open loop scrubbing is permitted in SECA zones and worldwide, if the SO\textsubscript{x} contents of the exhaust gas is equal to the limitation in this area.

Nevertheless, even the open loop technology is not as bad as it’s image! Acid rain is prevented, which causes local damage to life at sea, plants and humans. First studies show that the pollution in the area close to the main routes is reduced by 50 %, as explained above.

For the thousands of ships travelling the oceans a scrubber sometimes is the only possibility to reduce the environmental footprint of the ships. Other and cleaner solutions like LNG are very difficult, if not impossible to integrate on a ship, which has been constructed following other guidelines than the reduction of emissions.

Unfortunately, HFO contains other pollutants and not only sulphur, like Heavy Metals and Polyaromatic Hydrocarbonates. Even if the concentrations of these pollutants comply with the Marpol Annex VI regulation, these pollutants can be found in the wastewater discharge after scrubbing. Here is a lot of development necessary to clean

Figure 11: Piping and instrumentation diagram offline scrubber open loop

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the wastewater streams from the scrubber, before releasing the water back to the sea. The scrubbing water flow to be treated could be as high as 3,500 m³/h, which makes a filtration on board difficult.

4.3. Closed loop operation

Exhaust gas scrubbing using closed loop is the best technology to clean the exhaust gas from sulphur, dust and heavy metals, which tend to stick to the dust particles. The created sludge is disposed off safely to a tanker truck in the next harbor and can be treated professionally onshore.

Figure 12: Piping and instrumentation diagram offline scrubber closed loop
In certain areas like the Baltic Sea there is no sufficient alkalinity, the North Sea tide-land is a particular sensitive area and in many harbors being a secluded area open loop scrubbers are banned. Closed loop is accepted in most of these areas.

The technology of closed and open loop is very similar. The scrubber is identical, the scrubbing pumps are the same, maybe made from a better material. The main difference between both technologies is that open loop uses seawater for scrubbing and closed loop uses it for cooling the washwater only, while scrubbing is done in a closed circuit with the use of an alkaline additive. Additional equipment are the cooling pumps, the heat exchanger to extract heat out of the washwater and the wastewater treatment for the bleed.

The heat exchanger is essential to cool down the washwater to prevent salt incrustation, in particular at the nozzles.

The wastewater treatment is a membrane system taking out solids and crystals out of the bleed. It can also be designed for neutralization, the additive is available anyway.

There is also a requirement for additional tanks to support the reaction like the process tank to allow for additional water in the scrubbing circuit, clearly the additive tank, but also a dilution tank, to store the scrubber bleed until a further filtration or disposal is permissible.

5. Conclusions and outlook

Scrubbing the exhaust gas from propulsion engines on ships is proven and environmental technology. As always, there exist cleaner solutions, which have serious disadvantages on a ship: They consume more weight and space, they may cost more money, they offer limited autonomy or they may expose the ship to a high risk of fire and explosion.

LNG is a clean fuel, but the engines need a conversion to be able to operate with this fuel. The storage tanks are huge and require special insulation and safety measures.

Hybrids operating on batteries and electric drives need to reload the batteries; they can only operate within a limited range.

Figure 13:
Exhaust gas scrubber for a cleaner environment
Looking at new built, all of these options are possible including the scrubber solution, but for an existing ship, usually a scrubber is the only viable option. Here still is the option between open and closed loop, which finally will be decided by IMO in the coming years by a more stringent control of the scrubber bleed.

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The aim of this study is to demonstrate such discrepancies or dependencies between attainable emission reductions and the emissions-generating energy input necessarily incurred by flue gas treatment technologies in attaining those reductions.

The study initially focuses on current investigations and assessments related to this issue, as well as on the legal emission requirements. Due to the wide range of components involved in flue gas treatment systems and their consequent numerous combination possibilities, six different system Variants are presented and compared. It is notable in the context of the present study that both single and two-stage or multi-stage systems are considered in the set of Variants, which differ not only in their structure and additive use but also in their separation capacity. These six basic Variants reflect the systems frequently employed in practice and represent non-congruent procedural steps with their respective target emission levels. Based on the fact that each of these Variants is already in operation in thermal waste incineration plants, the assessment draws on many years of existing operative experience.

The individual energy demands for the Variants described are determined on the basis of mass, material and energy balances.

Evaluation criteria for energy demand at the different emission reduction ratios are educed from the formulation of emissions-related energy indicators. This establishes a set of tools with which to assess emissions-generating energy demand in the context of emission reduction ratios.

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