Exhaust gas scrubber concept to meet future SO_2, soot, and CO_2 emission reduction requirements

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Future legislation for the emissions of SO_2 and PM from ships will be gradually tightened in the years to come. Exhaust gas scrubbers seem to be a very attractive economic solution compared with the costs of switching from heavy fuel oil to low sulfur fuel. A modular and flexible exhaust gas scrubber design is suggested for facing the different emission limits and different ambient conditions on a ship voyage.

KEY WORDS

Scrubbing, scrubber, seawater, freshwater, SW, FW, SO_2, CO_2, sulfur, sulphur, dioxide, NaOH, sodium hydroxide, soot, PM, HFO, MDO, distillate, MARPOL Annex 6, SECA, ECA, absorption, IMO, MEPC, wash water

INTRODUCTION

Due to legislative requirements, certain Flue Gas Desulphurization (FGD) or scrubber techniques are being adapted from their usual land based applications to marine applications. The most important challenges to consider in this respect are especially:

- Problems with bunkering, handling and storing chemicals onboard a ship.
- Size and weight of equipment to fit into different ship designs.
- Changing engine loads and hence variation of exhaust gas volume flows to clean.
- Changing sea water temperature and sea water alkalinity as a ship moves around the world.
- Changing legislative requirements regarding sulfur emissions as a ship pass ECA borders.
- Rules regarding discharge water from FGD.
- Possible strict rules regarding PM emission in certain areas and harbors.
- Availability of trained technical crew personnel.
- Access to service and spare parts onboard and in harbors world wide
- Approval of equipment and documentation for its operation on board.

So-called exhaust gas scrubbers or just scrubbers seem promising for application onboard ships. In particular, two different systems are seriously being developed for marine applications: seawater (SW) and freshwater (FW) scrubbing. With SW scrubbing, the natural alkalinity of the SW is applied to neutralize the sulfuric acid absorbed. With FW scrubbing, addition of a neutralizing agent (most likely NaOH) is continuously added for the neutralization.

A modular and flexible exhaust gas scrubber design with high degrees of operational flexibility as well as future possibilities for upgrading the equipment is believed to be necessary when facing the above listed challenges.

From an economic point of view, exhaust gas scrubbers as an alternative to switching from heavy fuel oil (HFO) to e.g. marine diesel oil (MDO) will be very attractive. By comparing current costs for HFO on 199 USD/ton with those for MDO on 474 USD/ton (Rotterdam, December 4., 2008) and by assuming a fuel consumption of 190 kg/MWh, the additional operation costs for switching fuel will be USD 12.540 for 24 hours operation of a 10 MW engine. The pay back time of the exhaust gas scrubber equipment could then be only 1-3 months of operation (excl. installation).

Maximum 5- 10 % reduction in NOx emission is obtainable in a scrubber under normal conditions. However, a promising method for reducing the NOx emission with more than 50 % is by re-circulation of exhaust gas (EGR) to the engine[1]. The key for EGR is a scrubber, which is able to remove the soot particles and SO_2 from the exhaust gas as these substances otherwise would damage the engine when the gas is re-introduced. Scrubbers for EGR should be placed at the high pressure side of the engine turbo charger while scrubbers for cleaning the main exhaust gas flow should be placed at the low pressure side.

LEGISLATIONS

SO_2 emissions

Regulations for the Prevention of Air Pollution from Ships were adopted in the 1997 Protocol to MARPOL 73/78 and are included in Annex VI of the Convention. The Protocol entered into force on 19 May 2005.

MARPOL Annex VI sets limits on SO_x and NO_x emissions from ship exhausts. The annex includes a global cap of 4.5 % (w/w) on the sulfur content of fuel oil and contains provisions allowing for special Emission Control Areas (ECA's) to be established with more stringent controls on emissions. In these areas, the sulfur content of fuel oil used onboard ships must not exceed 1.5 % (w/w). Alternatively, ships must fit an exhaust gas cleaning system (EGC) or use any other technological method to limit SO_x emissions[2]. The Baltic Sea Area has been designated as ECA under the regulations and has been implemented and operational since 19 May 2006. The North Sea ECA has been in operation since 22 November 2007[3].

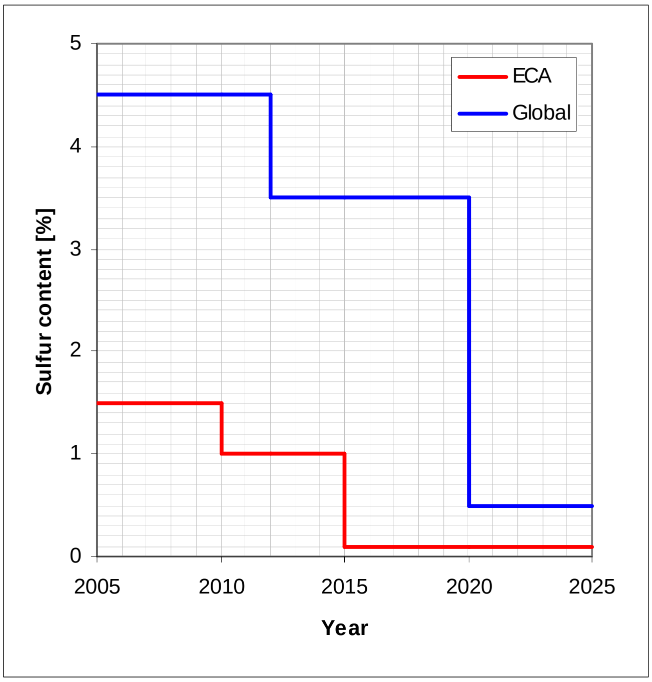

Figure 1: Limits of sulfur content in fuel oil decided by MEPC 57.

The Marine Environment Protection Committee (MEPC) met for its 58th session in October 2008 and finally agreed on the future sulfur limitations for ships as shown in figure 1. As an alternative to actually lowering the sulfur content in the fuel, exhaust gas scrubbers are allowed to be used to give equivalent reductions. The global limitation to 0.5 % might be delayed until 2025 – depending on the fuel availability in 2018. The necessary sulfur reductions by exhaust gas scrubbing are shown in figure 2 as a function of the fuel sulfur content. If, as an example, the sulfur content in the fuel oil is 3 %, a scrubber has to remove 67 % of the SO_2 in the exhaust gas within ECA until 2015. After this period, removal efficiencies exceeding 97 % are required within ECA. Only moderate removal efficiencies around 83 % are necessary in order to comply with the global cap on 0.5 % after 2020. The sulfur emission limits are in contrast to the TIER III limits for NO_x not related to the building year of the ship.

Similar rules are enforced by EU Directive 2005/33/EC, in which also the English Channel and all passenger vessels on regular services to and from EU ports are designated ECA with operational effect from August 2007[4].

If IMO approves simplified application procedures for countries to declare territorial waters an ECA (October 2008), also North America, northern Europe, Bay of Biscay and some of the Mediterranean and the Caribbean are likely to be designated as ECA[5]

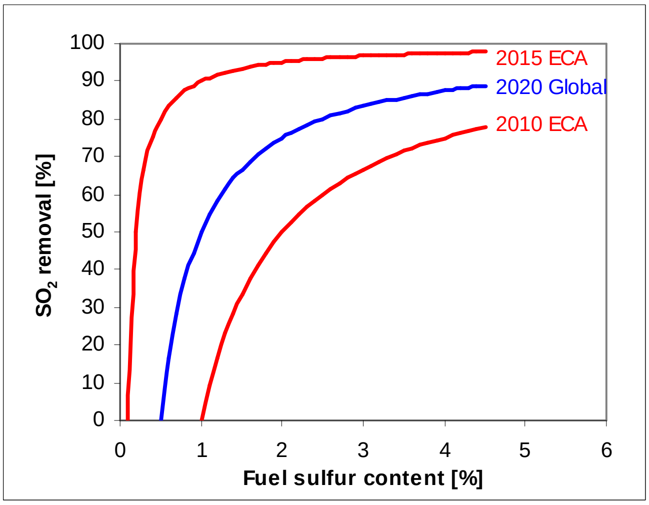

Figure 2: Required SO_2 removal by exhaust gas scrubber as a function of the sulfur content in the fuel oil.

Wash water

In the wash water criteria suggested by a work group under IMO[6], a minimum pH-value of 6.5 is allowed for the overboard discharge. Dilution with additional seawater is allowed if necessary.

The most challenging requirement will be the maximum content of soot particles in the discharge water. Visually, the water turns black as it gets in contact with the exhaust gas. More specifically, this is reflected by the concentration of Poly Aromatic Hydrocarbon (PAH) and the so-called turbidity of the discharge water. Under normal operation, the PAH concentration should not exceed 50 µg/L PAHphe (phenanthrene equivalance) above the inlet water concentration. The PAH limit is normalized for a wash water flow rate of 45 t/MWh where the MW refers to the MCR or 80 % of the power rating of a fuel oil combustion unit. This limit would have to be adjusted upward for lower wash water flow rates (e.g 100 µg/L @ 22.5t/Mwh), and vice-versa. The maximum continuous turbidity should not exceed 25 NTU (nephlometric turbidity units) or equivalent units, above the inlet water turbidity. Residues generated by the EGC unit should be delivered ashore to adequate reception facilities. Such residues should not be discharged to the sea or incinerated on board.

The suggested wash water criteria does not contain any maximum allowable sulfate level because the amount of sulfate which in theory could be formed if ship exhaust gas scrubbers were in operation on all ships, would be insignificant compared to the amount of sulfate which naturally occurs in water (figure 4). In addition, sulfur in the form of sulfate is harmless and a natural constituent of organisms.

The above requirements are only suggested to be effective when an EGC System is operated in a ports, harbors, or estuaries. At open sea, it will probably be allowed to discharge the scrubber water without cleaning.

PM emissions

The EPA (Environmental Protection Agency) Tier 2 and the identical EU Stage 3 emission limits for removing soot particles or Particular Matter (PM) are also a significant challenge – especially when applying high sulfur fuel oil because the engine PM emission increases as the sulfur content in the fuel oil increases[7] (on a mass basis but not necessarily on a number basis).

CO_2 emission

Although to date no mandatory Green House Gas instrument for international shipping has been adopted, IMO has given extensive consideration to the matter and is currently working in accordance with an ambitious work plan, due to culminate with the adoption of a binding instrument for all ships in 2009[8]. The energy consumption and hence emission of CO_2 therefore also has to be taken into account when considering methods for reducing SO_2 and PM emissions.

SCRUBBING TECHNOLOGIES

In a historic perspective, the emission of SO_2 started to increase during the industrial revolution and continued to do so until the 1970's when regulatory legislation of industrial emissions was introduced and flue gas desulphurization technologies became common.

Hydrated lime

Direct injection of dry hydrated lime to a flue gas is a very simple method to reduce gaseous SO_2 emissions. It largest application is found on cement plants, where white powder of hydrated lime is blown into a hot flue gas to react with SO_2 according to following scheme:

$$SO_2(g) + Ca(OH)_2(s)\ \ (g) \rightarrow CaSO_3(s) + H_2O$$

In these applications, the formed calcium sulfite is finally collected in an existing dust filter and returned to the process as part of the powdered raw materials. The SO_2 removal efficiency is known to improve with the specific surface area of the hydrated lime, the particle-flue gas contact time, and if the powder is well-distributed into the flue gas[9]. The main draw back of the method is:

- the cost of the hydrated lime
- the exponential increased consumption of hydrated lime as higher removal efficiencies are needed. In practice it is almost impossible to reach removal efficiencies of more than 50-70 %
- the need for particle filters to catch the lime after the absorption
- the handling and storage of the hydrated lime.

For these reasons, the method is considered unsuitable for cleaning engine exhaust gas from ships.

Limestone

Wet scrubbers are well-know from particular coal fired power plants where they have been a preferred solution to remove SO_2 from flue gasses for decades. The flue gas is usually cleaned by circulating slurry of water and limestone under the formation of gypsum, which is collected and dewatered. A large part of the gypsum is sold and used as e.g. filler in Portland cement. SO_2 removal efficiencies exceeding 98 % are not unusual in these applications. The chemical reactions taking place can formally be written as follows:

$$SO_2(g) + CaCO_3(s) + \tfrac{1}{2}\, O_2(g) \rightarrow CaSO_4(s) + CO_2(g)$$

Coal dust particles are usually collected in an electrostatic filter or bag filter prior to the scrubbing process[9] whereby contamination of the slurry and finally gypsum product is avoided. Again, due to the need of particle filters and storage and handling of the powdered materials, usual scrubbing with limestone is considered unsuitable onboard ships.

Sodium hydroxide dissolved in fresh water

In other land based installations, liquid sodium hydroxide is used as a neutralizing agent instead of the limestone:

$$SO_2(g) + 2\, NaOH(l) + \tfrac{1}{2}\, O_2(g) \rightarrow Na_2SO_4\,(l) + H_2O(l)$$

The sodium sulfate formed is usually dissociated in the discharge water from the scrubber. From a process point of view, it is easier to use liquid sodium hydroxide than limestone because handling of the limestone and gypsum powders are avoided. However, the applications are limited to smaller installations due to the costs of the sodium hydroxide.

From both theory and practice, it is well-know that the SO_2 removal efficiency increases with:

- higher water to gas flow ratios
- higher pH-values of the slurry
- lower exhaust gas temperature
- gas - liquid contact time and mixing.

The above scrubbing technology using a diluted solution of sodium hydroxide in FW is promoted by Wärtsilä to remove SO_2 from ship exhaust gas[10]. Sodium hydroxide is a commercial commodity and could be bunkered from trucks via filling connections in bunker stations. Wärtsilä estimates that the costs of the sodium hydroxide to reduce a 2.7 % sulfur fuel down to an 0.1 % equivalent, will correspond to between 2 – 17 € per ton of fuel.

Seawater

The pH of surface SW usually ranges from 8.1 to 8.9. Using the natural alkalinity of SW to neutralize absorbed sulfur dioxide is well-known from Inert Gas Systems (IGS) onboard ships but also from several land based installations. IGS have been supplied for more than 40 years to the tanker industry[11] and SW scrubbers are today an integrated part in many of these systems. A typical scrubber in an IGS system is shown in figure 3. The flue gas is first drawn downwards through a venturi scrubber which efficiently removes soot particles above the size range 1-10 µm. The water system and absorber unit will be further explained in figure 5.

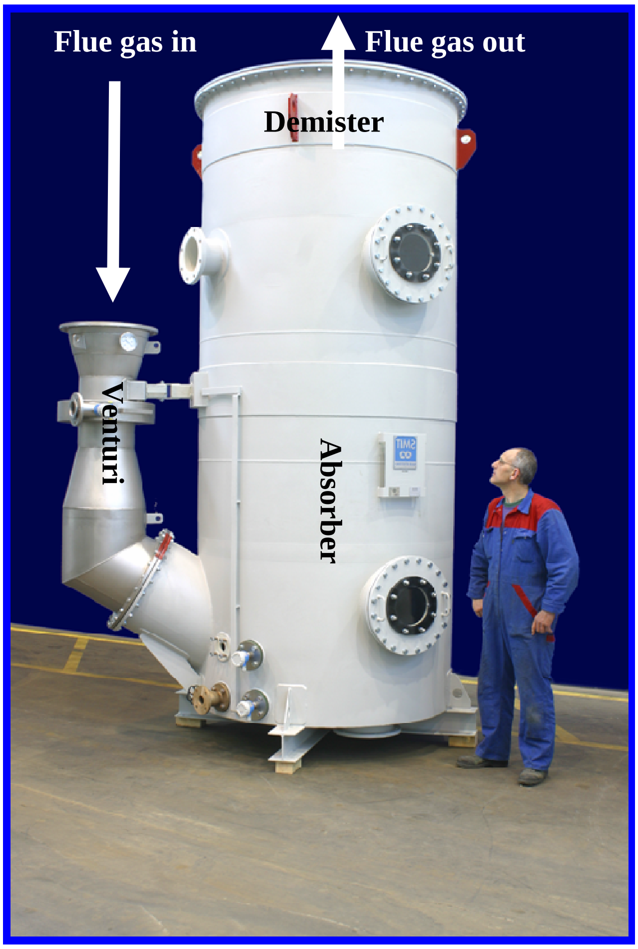

Figure 3: Scrubber in IGS systems able to treat about 15000 Nm^3/h of gas.

With absorption in seawater, the SO_2 first pushes to the acid sulfate equilibrium balance in the water:

$$H_2SO_4 \leftrightarrow H^+ + HSO_4^-$$

$$HSO_4^- \leftrightarrow H^+ + SO_4^{--}$$

The hydrogen ions then push the natural carbonate balance in the water as follows:

$$H^+ + CO_3^{--} \leftrightarrow HCO_3^-$$

$$H^+ + HCO_3^- \leftrightarrow H_2CO_3$$

$$H_2CO_3 \leftrightarrow H_2O + CO_2(g)$$

The net result is formation of bisulfate and sulfate ions in the water and gaseous carbon dioxide, which is released to the atmosphere. The amount of the carbonate (CO_3^{--}) and bicarbonate (HCO_3^{--}) as well as other minor anions originally present in the water to react with hydrogen ions determines the so-called alkalinity or buffering capacity, which in turn is a measure of the amount of SO_2, which can be absorbed in the water. In practice, the total alkalinity of a water sample can be found by measuring the amount of sulfuric acid needed to bring down the pH to a value of 4.2[12] (sufficient reaction time to reach chemical equilibrium is needed). The content of salt in the seawater (salinity) is somehow linked to the alkalinity as the content of carbonate (negative ions) increases with increasing amount of positive ions as sodium, magnesium, calcium and potassium (figure 4). As shown in table 1, the Bothnian Bay part of the Baltic Sea is as an example characterized by having low salinity and alkalinity.

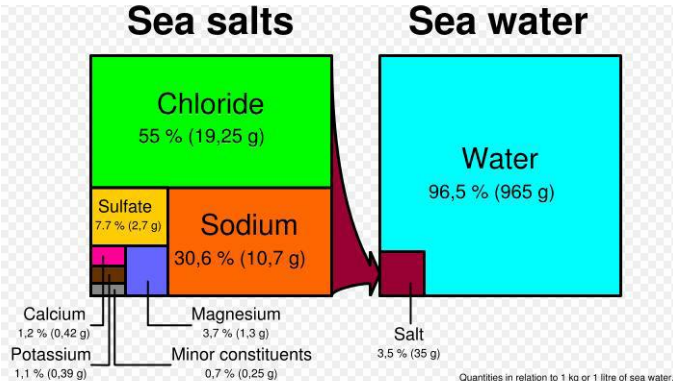

Figure 4: Concentration and composition of salt in typical sea water[13].

Table 1: Alkalinity and salinity of selected areas[14].

	Alkalinity (µmol/kg)	Salinity % (w/w)
Open ocean	2300	3.5
Kattegat	1950	1.8
Baltic proper	1650	8
Bothnian Bay	800	4
River fresh water	210	<0.1

SW scrubbers to treat engine exhaust gas have been tried on two ferries (Pride of Kent and Zaandam) and are promoted by Krystallon and Marine Exhaust Solutions. In their design, the scrubber is made in stainless steel and as an integrated silencer.

SW versus FW scrubbing

The obvious advantage of using SW instead of FW with sodium hydroxide is the elimination of chemicals needed onboard a ship. The main disadvantage is that the water flow may be 10 times higher than in the case with FW + sodium hydroxide, whereby significantly larger quantities of water have to be pumped around and cleaned before being discharged to the sea. This adds to the installation and operation costs of water pumps. In addition, SW is more corrosive which adds costs to the material and which excludes the use of some water treatment units.

Some disagreement exists regarding the usability of SW scrubbers in brackish water with low alkalinity (e.g. in the inner part of the Baltic Sea). Wärtsila claims that using FW + sodium hydroxide is a significant advantage in these areas to achieve high SO_2 removal efficiencies[10]. On the other hand, Krystallon claims that their SW scrubber works both in SW and in water run off from glaciers being close to brackish water[15]. From a more theoretical assessment, it is concluded that larger water volume flows are required in brackish water than in open sea water in the case of SW scrubbing[14]. An explanation for some of the confusion regarding the efficiency of SW scrubbing in brackish water could be the coupled effect with seawater temperature. At low temperatures, as in the Krystallon case close to glaciers, significantly more SO_2 will condense from the gaseous phase whereby the removal efficiency will increase dramatically and thereby compromise for the lower alkalinity of the water.

MODULAR AND FLEXIBLE DESIGN CONCEPT

To cope with the gradually stricter emission rules as well as rather unclear rules regarding PM emissions, a modular and flexible scrubber system as sketched in figure 5 is under evaluation.

WHR system

The exhaust gas is first cooled to about 160-180°C in a traditional waste heat recovery boiler (WHR), whereby its thermal energy is converted to steam, which in turn can be expanded in a steam turbine to produce electricity. Due to the risk of condensation of sulfuric acid in the WHR unit, the exhaust gas is usually not cooled below 160°C. Electrical power outputs equivalent to 7-15 % of the main engine power output are obtainable with a WHR system.

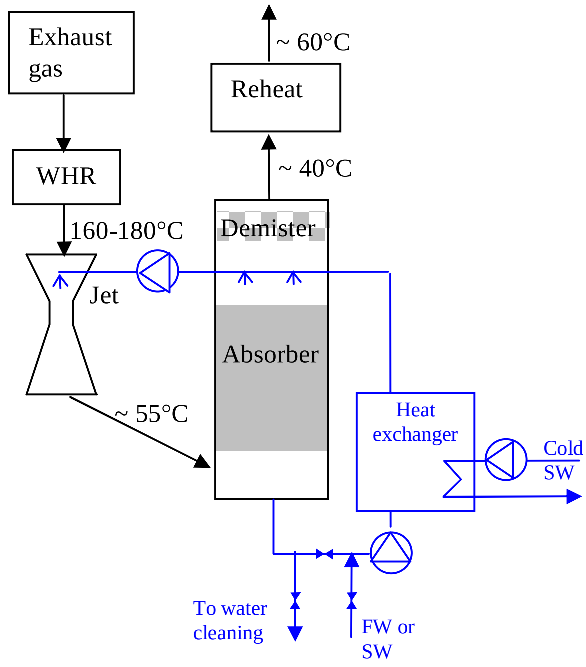

Figure 5: Sketch of a combined waste heat recovery and scrubber concept.

Gas scrubbing equipment

Following figure 5, the exhaust gas is cooled down to approximately 55°C by injection of water to the jet unit. As the 55°C is the dew point of the exhaust gas, a significant amount of the SO_2 will be absorbed prior to the absorber unit. However, the main SO_2 removal takes place in the absorber unit in which the exhaust gas flows upwards in counter-current with water-absorbent distributed by aid of spray nozzles at the top of the absorber. A demister catches any possible water droplets drawn with the upward flowing exhaust gas.

Exhaust gas reheat

In order to avoid condensation in the funnel as well as visible smoke, the exhaust gas is reheated by approximately 20°C. Only relatively few square meters of heat exchanger surface is necessary for this purpose. Hot water for the reheating heat exchanger can be taken from the engine cooling system rather than from the WHR water-steam circuit as the later would cause the electrical power output from the steam turbine to drop. The water from the engine jacket is usually around 80°C (Johan Kaltoft, MAN Diesel, personal communication).

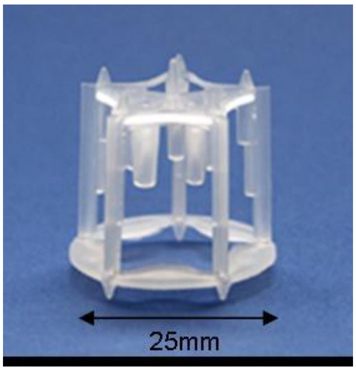

Figure 6: Example of packing material in the absorber unit.

Operational flexibility

Most challenging for the adoption of land based scrubbers to marine applications is the changing requirements to the SO_2 removal efficiency. As was shown in figure 2, the SO_2 reduction efficiency will depend on:

- Whether the ship is within or outside ECA
- The age of a ship (will it be in service after 2015-2020?)
- Fuel sulfur level

In addition to this, the scrubbing efficiency will also depend on:

- Seawater temperature.
- Engine load.
- Water flow to the absorber.
- Seawater alkalinity / NaOH dosage

Once a scrubber system is installed on a ship, only limited degrees of freedom are left for adjusting the operation of the scrubber to comply with the actual reduction requirements and changing ambient conditions. The only possibility of improving the scrubbing efficiency is to increase the water flow to the absorber, add more NaOH, or - as a last option - to lower the engine load and hence the exhaust gas flow to be cleaned.

An option for being able to handle the changing reduction requirements and different ambient conditions is of course to oversize the scrubber and the water system, so it is possible to obtain > 98 % SO_2 removal efficiency even under the worst possible conditions. This is however not believed to be an attractive solution as this will add costs to the investment and operation of the scrubber. In particular, the power consumption of the water pumps will be excessive in cases where the reduction requirements are only moderate (e.g. outside SECA until 2020) and when the conditions are optimal (i.e. high alkalinity and low seawater temperature).

A combination of a moderately designed scrubber and water circulation system together with the option of fuel switching /fuel blending could be an attractive solution. A system able to switch between SW scrubbing at open sea to FW scrubbing in e.g. harbors is another possibility.

Modular design

A main feature of the setup is the modular design, which means that some of the components can be leaved out while other components can be replaced in the future when stricter emission limits will come in force.

For older and smaller ships, it may not be economic attractive to install a WHR system onboard. In that case, one will simply leave out the WHR unit and cool the exhaust gas equivalently by injecting water to the 280-350°C exhaust gas after the engine. The water system should be designed for the increased water usage while the remaining system will be similar to an installation with WHR system.

Another feature is the possibility to replace the jet scrubber with a venturi scrubber if higher PM removal efficiencies are required. As was shown in figure 3, venturi scrubbers are applied on a large scale in Inert Gas Systems for efficiently removing soot particles larger than approximately 1-10 µm from a flue gas. A usual pressure drop for a venturi in these applications is 7000 Pa. The particle removal efficiency will increase if a higher pressure drop across the venturi is accepted. However, as the engine fuel consumption increases with increasing pressure drop through the scrubber, a compromise between PM and CO_2 emission must be met. To ensure a constant pressure drop and hence constant PM removal efficiency across the venturi at different engine loads (gas flow rates), a venturi with an adjustable throat can be applied. However, more than 50 % reductions in PM are still obtainable with a jet scrubber because the exhaust gas is cooled below its dew point temperature whereby water condenses on the soot particles and whereby most of the soot particles will grow in size and end up in the scrubbing water.

Table 2: Pressure drop

	Pressure drop [Pa], Possible range	Pressure drop [Pa], Usual operation
WHR	500-1500	1100
Jet	10-30	20
Venturi	5000 - 15000	7000
Absorber unit (incl. demister)	300 - 500	450
Reheat	50-500	100

The allowable engine back pressure drop is usually 2500 - 3000 Pa for four-stroke and 3000 Pa for two-stroke engines. Higher pressure drops are obtainable but this will cost on the fuel consumption and cause a higher temperature on the engine exhaust valves (Johan Kaltoft and Flemming Bak, MAN Diesel, personal communication). Typical pressure drops through the individual components are given in table 2. The pressure drop through the WHR + Jet + Absorber scrubber solution could be about 1670 Pa, which is acceptable for both two and four stroke engines. As the noise reduction through the scrubber is expected to eliminate the need of a silencer, the silencer pressure drop is not considered. At higher pressure drops, a fan can be installed to help drawing the exhaust gas through the equipment. In most cases it is however recommended to let the engine do the work rather than a fan in order to avoid the losses through an electrical generator and a fan as well as the investments.

CO_2 account

The scrubbing process will cause some additional fuel consumption or CO_2 emission due to the power requirement for operating the scrubber. However, the additional CO_2 emission due to scrubbing has to be compared with the alternative of removing the sulfur from the fuel oil at refineries. Table 3 shows a rough estimate of the CO_2 emission associated with burning high sulfur fuel oil and emitting the SO_2 as today together with 3 different cleaning alternatives.

Scrubbing with SW will increase the CO_2 emission by approximately 2.7 % because the entire SO_2 will end up in the seawater instead of being disposed at land and due to the additional power requirement for operating water pumps and for blowing exhaust gas through the scrubber. In the light of the CO_2 differences estimated in table 3, there will only be little difference between SW and FW scrubbing. FW scrubbing will not cause as much CO_2 released from the sea, but on the other hand generate CO_2 for producing and transporting the sodium hydroxide.

By switching from HFO to distillate, the CO_2 emission emitted by the ship itself will decrease because distillate is containing more energy and less carbon than HFO. However, a significant contribution to the CO_2 emission will come from refining the HFO into distillate resulting in a net increase on 5.1 % CO_2. The energy consumption for removing the sulfur at refineries has assumed to be equivalent to a 10 % loss of fuel. This value has been chosen by considering that the most applied process for removing the sulfur at refineries is by so-called hydrodesulfurization (HDS), which is a very energy demanding process. HDS is a catalytic process that converts organic sulfur to hydrogen sulfide gas by reacting crude oil fractions with hydrogen gas at pressures from 10 to 200 bar and at temperatures from 290 to 455°C, depending upon the feed and level of desulphurization required. In addition, also the energy released by burning the sulfur in an engine is lost. More exact information about the energy loss associated with HDS is however requested.

As explained in the previous sections, scrubbing can also be applied in connection with Waste Heat Recovery (WHR). As estimated in the last column in table 3, this combination will actually result in a 9.0 % reduction in the CO_2 emission. Waste Heat Recovery is having an even higher potential than the 11 % used in the table, but this will be a compromise between investments and savings due to the fuel savings. Also note that 11 % saving in fuel due to a WHR plant in addition to the 11 % reduction in CO_2 also will lead to 11 % reduction in the absolute emissions (e.g. in the unit kg/MWh) of SO_2, NO_x, and PM. This reduction is however not acknowledged by current legislation as the sulfur is limited by a maximum percentage while the absolute amount emitted is not considered.

Table 3: Estimated CO_2 emission in case of using HFO and not abating the SO_2 emission as today (used as reference), in case of scrubbing with seawater, in case of switching from HFO to distillate oil, and in case of scrubbing with seawater combined with waste heat recovering.

	No abatement	Scrubbing (SW)	Distillate	Scrubbing (SW) + WHR
Fuel:				
Fuel consumption [kg/MWh]	180	184	171	164
Fuel lower heating value [kJ/kg]	40500	40500	42619	40500
Carbon content [kg CO2/kg fuel]	3.16	3.16	3.15	3.16
Sulfur content [% S (w/w)]	2.7	2.7	0.1	2.7
kg CO_2/MWh:				
Generated by the engine	570	581	540	518
Released from sea water[3]	9	14	0	9
Desulphurization of heavy fuel oil	0	0	68	0
Total	579	595	608	527
Additional CO_2	**0.0 %**	**2.7 %**	**5.1 %**	**-9.0 %**

Assumptions:
Fraction of SO_2 emission disposed at land: 30 %
Fuel saving due to Waste Heat Recovery system: 11 %
Additional fuel consumption due to scrubber: 2 %
Fuel loss due to desulphurization of crude oil: 12 %
S to CO_2 conversion factor in sea water: 2 mol/mol
SO_2 removal efficiency: 100 %

PLANNED TESTS

A test rig consisting of a WHR boiler, a modified IGS scrubber, and a reheat section coupled to a MAN 1 MW 4-stroke engine is under construction (figure 5).

A test plan includes further investigations of the SO_2 and PM removal efficiency as a function of the following changes:

- With and without WHR unit.
- SW compared to FW scrubbing.
- Jet compared to venturi.
- Venturi pressure drop.
- Temperature
- Water flow rate
- pH-value.

CONCLUSION

Future legislation for the emissions of SO_2 and PM from ships will be gradually tightened in the years to come. Only 0.1 % sulfur in the fuel is allowed in ECA from 2015 and only 0.5 % is allowed in territorial waters after 2020 or at latest 2025 depending on the fuel availability in 2018.

With current fuel prices, the costs for switching from HFO to MDO will be USD 23.688 for 24 hours operation of a 10 MW engine. As the pay back time for the scrubber equipment might be as low as 1-3 months (excl. installation), SW and FW scrubbers will in many cases be an attractive solution compared to fuel switching.

As the exhaust gas has to be cooled down to or below its dew point temperature for efficient removal of SO_2 and PM, combining a WHR system with a scrubber is an obvious solution. A WHR system is also attractive in case of fuel switching due to its possible fuel savings of up to 15 % and the higher fuel price. The savings in fuel consumption due to a WHR system results in similar reductions in CO_2, SO_2, NOx and PM emissions.

Initially, the scrubber could be supplied with a jet. If required, this jet can be replaced with a venturi, which is very effective in removing soot particles.

Further investigations of SW versus FW scrubbing, the influence of gas temperature, water temperature, water flow rate, and water pH value will be carried out through November 2008 to January 2009.

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