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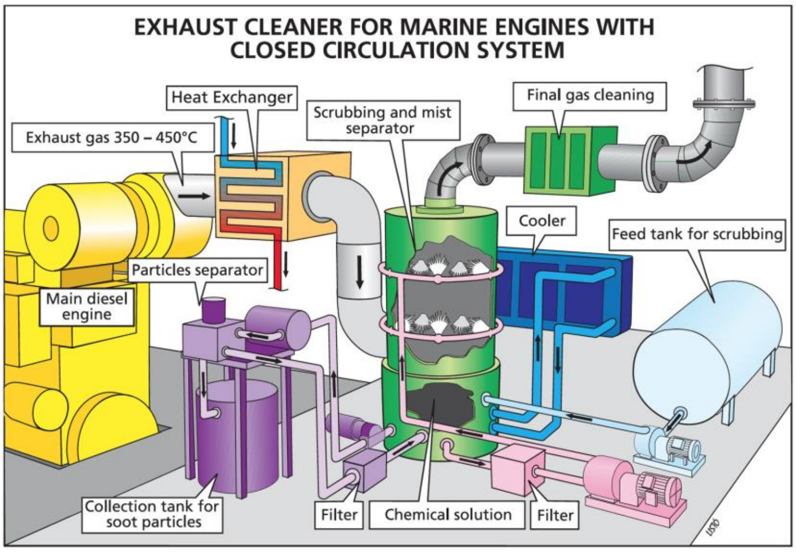
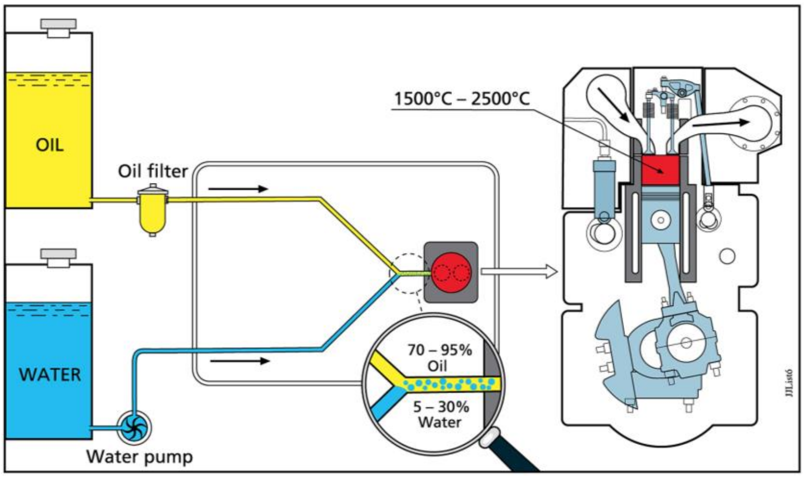
Removal of undesirable Gases and Soot-Particles from Marine Engines Exhaust Gas



Post-Treatment



Pre-Treatment

Icelandic Transport Authority

2018

An introduction to exhaust gas cleaning

An introduction to cleaning processes and exhaust equipment

The process of exhaust cleaning involves the removal of undesirable pollutants to air, from, for example, ship emissions. The cleaning procedure generally occurs prior to or subsequent to emission from the engine and results in a significant reduction in the discharge of pollutants.

The majority of vessel engines operate on fossil fuel. Smaller ship engines generally burn marine diesel while heavy fuel oil is a common fuel for larger and more powerful vessel engines. Heavy fuel oil is markedly thicker than marine diesel; it is also less refined and cheaper, thus making it a favourable option for shipping companies burning significant amounts of fossil fuel.

Combustion within engine combustion chambers produces emissions when fossil fuel is burned, for example in ship engines. This type of pollution can have harmful short-term and long-term effects on the environment, as well as on human and animal health. For some time now, the international community has increasingly implemented stricter regulations and standards in order to decrease these emissions. One means by which to meet international requirements is the cleaning of diesel engine emissions.

Carbon dioxide (CO_2), sulphur oxides (SOx) and nitrogen oxides (NOx) are the principal undesirable constituents of ship engine emissions. In addition, exhaust gas contains particulate matter (PM), a mixture of extremely small particles which can enter the bodies of animals and humans via inhalation. The most toxic gas contained in diesel engine emissions is carbon monoxide (CO); however, its levels are lower than those of gasoline engine emissions. Exhaust gas cleaning is an effective type of post-treatment, a means by which to process for the substances discussed above. Water in Fuel Emulsion is type of pre-treatment, where water is added to the oil, just before it enters the engine combustion chamber. These methods are simple yet effective and both have delivered excellent results with regard to the removal of undesirable gases from engine exhaust[1].

The most common exhaust gas post-treatment involves the use of clean water or seawater and the addition of substances to cleaning solution, specifically to rid the exhaust gas of carbon dioxide (CO_2) and nitrogen oxides (NOx). Water cleaning is an efficient post-treatment method for removing particulate matter and sulphur oxides (SOx), both of which are almost completely purged from the exhaust gas.

Exhaust Gas Cleaning is a process of post-treatment to achieve a reduction in engine exhaust emissions while Water in Fuel Emulsion, is a type of pre-treatment where water is added to the fuel prior to its entry into the engine combustion chamber.

Wet scrubbers**,** which provide post-treatment via a water cleaning process, are becoming standard parts of vessel engine rooms, mainly due to the fact that the equipment and the cleaning process are simple and efficient. The cost of the scrubbing system is acceptable when it is included during vessel construction however, when this is not the case, the cost of retrofitting an older ship can be considerable. Where the engine room allows for a retrofit, specifically with regard to space and setup, simple and relatively inexpensive yet effective equipment can usually be added to older and existing vessels.

Furthermore, many engine manufacturers now offer Water in Fuel Emulsion systems as standard equipment addons to main and auxiliary ship engines. The most common mixing ratio of water to fuel is 20% upon addition to the engine combustion chamber.

Both processes are essentially technically uncomplicated and effective, producing exhaust gas that is completely rid of some undesirable constituents such as particulate matter and sulphur compounds.

Environmentally energy sources and energy carriers

Replacing fossil diesel with environmentally friendly and renewable energy sources significantly reduces the toxic substance content of exhaust gas. For these alternative energy sources, the energy density and characteristics compared to fossil diesel are variable but in an Icelandic context, biodiesel made from rapeseed is the most relevant. Indeed rapeseed is quite easily cultivated in Iceland. Biodiesel and rapeseed oil have an energy density similar to that of fossil diesel and ship engines only require minor changes prior to the combustion of these fuels.

Other environmentally sound energy carriers are also worth mentioning, in particular those produced via other energy sources, such as electricity. Some of these energy carriers are suitable for ship engines and can contribute to the reduction of undesirable emissions, including methanol, dimethyl ether (DME) and hydrogen. While all of the aforementioned produce emissions containing less toxic gases compared to fossil diesel, their energy density is considerably lower. This is most common for cases of fuel additives, with environmentally friendly fuel (rapeseed diesel) or energy carriers (methanol)[2]. Recent years have seen various pilot projects involving electric vessels, with promising results.

One important aspect regarding the use of energy carriers is toxicity. In such cases, environmental pollution is a risk, should the substances be released to air or soil.

Energy sources and energy carriers can also, in a way, benefit from exhaust gas cleaning despite being environmentally friendly. Carbon dioxide (CO_2) and nitrogen oxides (NOx) are prime candidates for removal from related exhaust gas while sulphur and particulate matter are not significant issues for environmentally sound energy sources and energy carriers. In this respect, the overall environmental impact is positive[3].

Exhaust gas testing and future utility

In 2006, the Icelandic Maritime Administration (predecessor to the Icelandic Transport Authority) was responsible for the design of abatement technology which allowed for the removal of sulphur, particulate matter, carbon dioxide (CO_2) and nitrogen oxides (NOx) from ship engine emissions. The demonstration project, „Vessel engine exhaust treatment,“ ensued. The equipment involved a post-treatment scrubbing system, a process by which the exhaust gas was treated with water spray prior to release to the atmosphere. The Icelandic Transport Authority took over the project when the Icelandic Maritime Administration was discontinued.

Essentially, the project goal was to develop and construct a treatment system for engine exhaust from the combustion of fossil diesel and Icelandic rapeseed diesel.

The project made use of widely accepted methods and relied upon the experience and expertise of international pioneers within the field in addition to their published results. Equipment and procedures where tailored to befit Icelandic conditions and an effort was made to create a simple yet effective scrubber delivering pollution reduction and suitable for vessel engine rooms.

The Icelandic Maritime Administration‘s exhaust treatment system at Nesjavellir in 2006

Testing revealed that a great deal of undesirable compounds and gases remained in the spent water following the scrubbing treatment and the level of soot, carbon compounds and sulphur compounds within the exhaust gas was reduced. As an illustration, the scrubbing system completely removed sulphur dioxide (SO_2) and hydrogen sulphide (H_2S) thus averting their emission to air. The spent exhaust water was subsequently piped through a specific filtering unit in order to purify the turbid water[4]. Sulphur oxides and hydrogen sulphide generally originate from the combustion of fossil diesel, aluminium production (SO_2), and also arise from high temperature geothermal power plants (H_2S).

Following this project, the idea was conceived to test a similar type of exhaust treatment system aboard a cargo ship owned by an Icelandic fishing enterprise.

The Icelandic Transport Authority and associates were tasked with designing and building a simple exhaust treatment system comparable to the first one. It would be tested on a diesel generator with an output of 500 – 1000 kW for post-treatment evaluation of the engine exhaust content.

Once results are in and should they correspond to the shipowner‘s requirements and expectations, a system could be designed according to specification for the company‘s larger engines.

Exhaust gas post-treatment

General post-treatment methods of exhaust gas

Exhaust after treatment for a main engine (and for exhaust from generators and boiler, when applicable) involves the exhaust emissions being sprayed and scrubbed in an exhaust gas tower (an exhaust separator). The spray water is either normal water or a chemical mixture. Finally, the liquid is cleaned via filtration so that it may be recycled back to the scrubbing process.

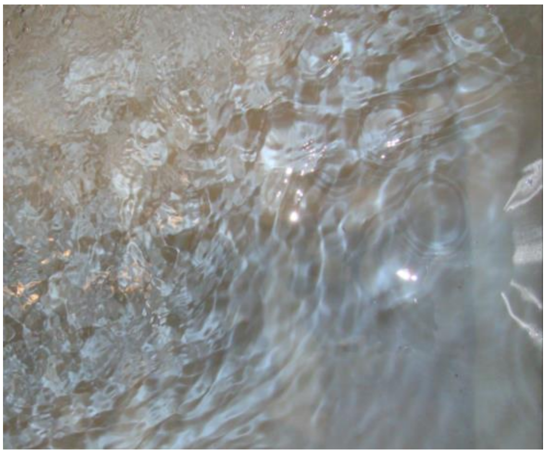
Only water is used for the removal of sulphur oxides (SOx) and particulate matter from exhaust emissions and the process allows for a reduction of 90 - 95%. If the intention is also to remove carbon dioxide (CO_2), a small amount of calcium is added to a chemical mix, yielding a 20 - 25% reduction in the exhaust content. The addition of carbamide (urea) to the chemical mixture enables a 25 - 35% cut in nitrogen oxides (NOx) in emissions content.

The water or mixture can be filtered in order to remove the exhaust gas substances which, in turn, are treated as hazardous waste and disposed of in accordance with the law and supporting regulations.

Wet scrubbing

Scrubbing refers to the application of water during the process of exhaust gas cleaning. Seawater is often a suitable scrubbing agent as it is abundant around the vessel and indeed, it is commonly used in systems designed as such.

The inlet gas, once collected from the engine exhaust pipe following heat exchange, is sprayed with water within a specifically designed scrubbing tower. The spray causes water droplets to capture soot particles, for example, and drop to the bottom of the tower instead of being discharged to air along with the exhaust via the ship funnel. The wet soot particles are left at the tower bottom wherefrom they are transferred along with the spent scrubbing water through a separator. There, the particulate matter and contaminants are filtered from the water which is reused in the cleaning cycle.



Clean water prior to entering scrubbing tower

The same water after one scrubbing treatment in scrubbing tower

Soot in a filter (system without scrubbing equipment)

Soot in a filter (system with scrubbing equipment)

On the whole, the wet scrubbing process reduces the emission of soot (Black Carbon), carbon dioxide (CO_2), sulphur oxides (SOx) and nitrogen oxides (NOx). The application of wet scrubbing treatment alone decreases the discharge of soot particles by 90%, of sulphur compounds by up to 98% and the emission of CO_2 and NOx by less than 10%[5].

Wet scrubbing also captures sulphur and removes it almost entirely. Moreover, the process reduces the emission of carbon dioxide (CO_2) and nitrogen oxides (NOx) and affects other undesirable gases but to a lesser extent.

An essential part of the treatment process is the transfer of spent water through a separator where it is rid of the undesirable substances removed from the exhaust. This measure eliminates hazardous compounds and allows for the water to re-enter the cycle. Finally, the hazardous waste is disposed of according to relevant legal framework.

Exhaust gas cleaning via chemical treatment

Specific compounds can be added to the water in order to improve the efficiency of the wet scrubbing treatment, creating a specialized chemical solution. The wet scrubbing process itself remains the same but the chemical addition significantly increases the removal of carbon dioxide (CO_2) and nitrogen oxides (NOx).

The chemical solution is made up of water, calcium and carbamides (urea). The mixture is sprayed at the exhaust gas within the scrubbing tower. The calcium reacts with carbon dioxide (CO_2) and is precipitated as sand-like matter which is later removed via filtration. The urea reacts with nitrogen oxides (NOx) and produces mostly harmless nitrogen compounds[6].

A 98% decrease of sulphur compounds and a 90% reduction in particulate matter is achieved when a solution of water, calcium and urea is applied, which is the same reduction as yielded by the sole use of water spray. However, the reduction in nitrogen oxides (NOx) amounts to 35% and 25% for carbon dioxide (CO_2), quite an acceptable level of reduction of these exhaust constituents.

Following the scrubbing process, the substances removed from the exhaust gas are separated from the chemical solution via filtration and disposed of in the same manner as other hazardous waste as regulations stipulate.

Post-treatment process for exhaust gas

During this type of process, the engine exhaust gas enters the scrubbing tower. Upon introduction to the tower, the exhaust gas is sprayed with a liquid. This causes soot particles and other exhaust constituents formed during fuel combustion to adhere to the liquid droplets (water, for example). The matter removed from the gas settles to the bottom of the tower along with the scrubbing liquid. From there, the contaminants and the liquid are conveyed through a filtration system.

A specialized separator receives the particulate matter, which is then collected in a soot tank while the rest of the constituents are left in filters. The filters are replaced regularly and as required. The filtered liquid can be recycled to the scrubbing tower, which gives the process its name, closed loop exhaust gas scrubbing. Finally, the cleaned exhaust gas is released to air and thus completes each cycle.

The engine pressure conveniently serves as a driver for the exhaust gas into the scrubbing tower. Once the gas has been scrubbed, the products are clean air in addition to the remnants of scrubbed substances at the bottom. Due to the remaining air pressure from the engine, the purified air flows upward and is emitted from the scrubbing tower as light smoke while the scrubbed matter settles to the base.

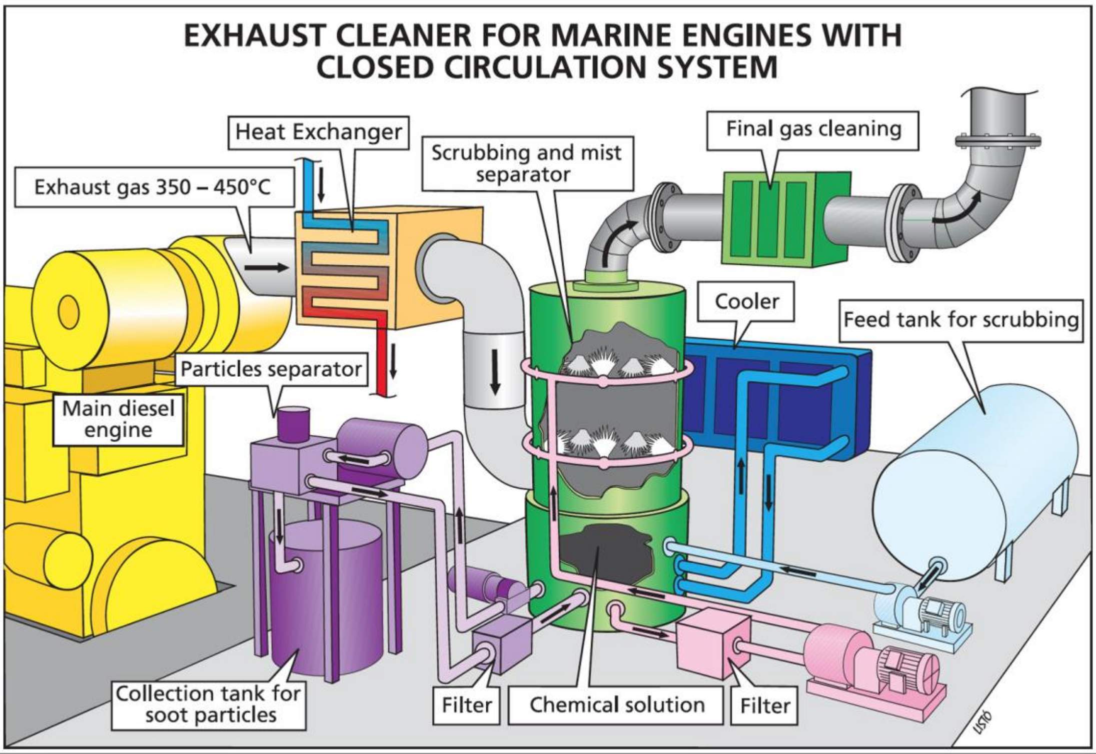
The scrubbing procedure should take engine fuel consumption and type of fuel into account. The level of undesirable substances in exhaust gas is proportional to the amount of fuel burned and, moreover, fuel viscosity and sulphur content affect the scrubbing process.

The pressure and gas temperature at the entrance to the scrubbing system are factors that must be determined. Engine speed of rotation and even slight back-pressure can affect the scrubbing efficiency but only to a small extent. The correct amount of scrubbing fluid is also an important aspect and the optimal exhaust gas velocity entering the scrubbing tower at variable loads is between 0.6 and 1.2 m/s. The required volume of water spray per scrubbing unit or cycle is 6 to 10 litres. Acceptable diameter range for sprayed water droplets is 0.1 to 1.0 mm. Variable engine load should also be taken into account.

The processes can be adjusted according to scrubbing design and location aboard the vessel and should correspond to engine power and consumption. Post-treatment of exhaust gas can vary depending on whether the scrubbing agent is water or a chemical solution. Using the latter can alter the cycle, requiring a longer scrubbing time as not only does the method remove a greater share of gases but also may have a more complex filtration system. Overall, and considering all of the above, it is safe to contend that exhaust gas post-treatment is quite straightforward.

Exhaust post-treatment equipment

Post-treatment equipment to process exhaust gas requires a scrubbing tower and a liquid spraying system for water and chemical solutions. The engine exhaust pipe is connected to the scrubbing tower via a heat exchanger which allows for the utilization of heat to warm water. The heat exchanger also reduces the exhaust gas temperature prior to its emergence into the tower, where it is sprayed by a spraying system equipped with a water separator. The cleaning solution is collected at the bottom of the tower where a piping system and separator for soot and other solids filters the liquid. The liquid also comes into contact with a cooler which chills it following the scrubbing. A filling tank replenishes the system with liquid, replacing the amount removed along with the purified exhaust gas. A final process rids the gas of any remaining impurities.



The figure illustrates exhaust gas post-treatment scrubbing with water or chemical solution

Closed-loop exhaust gas scrubbers are rather uncomplicated apparatus and can easily be placed in vessel engine rooms. Setup and system design are the only factors that require modification.

Exhaust gas post-treatment results

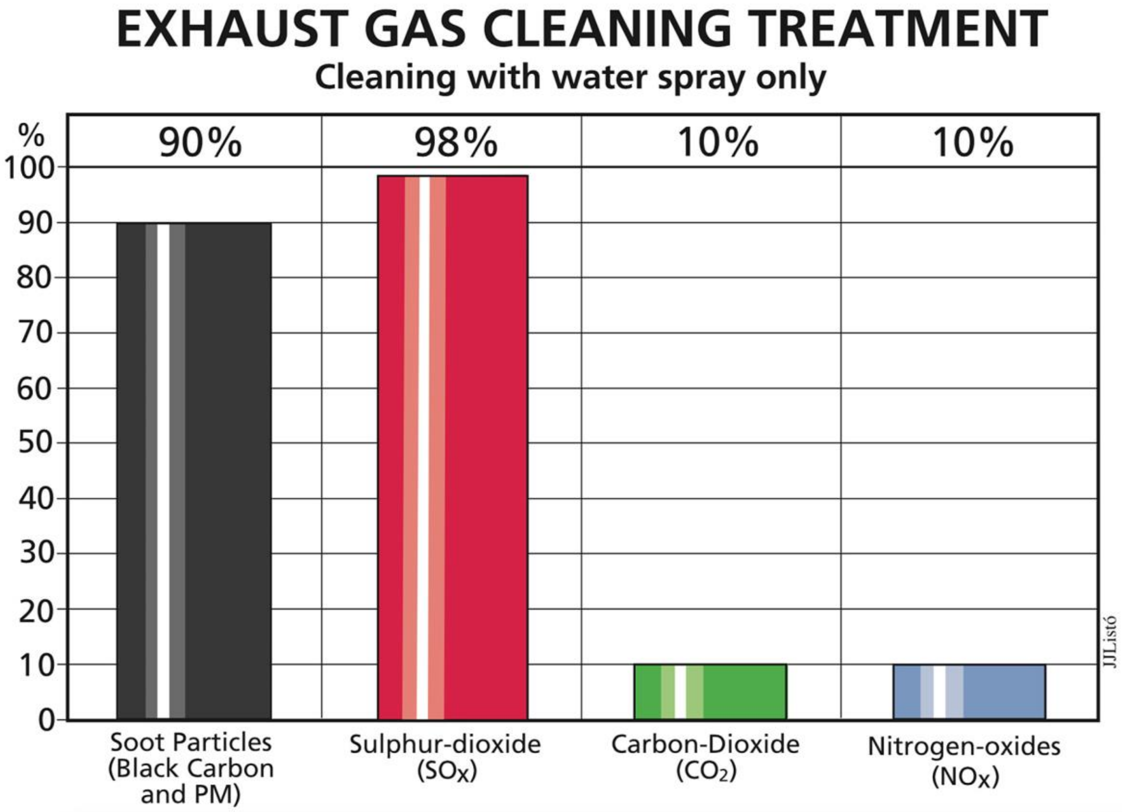
For each kg of common fossil diesel burned in a ship engine, between 3.16 and 3.18 kg carbon dioxide (CO_2) are emitted. In the case of fossil diesel containing 1% sulphur (S), the exhaust gas produced by combustion will consist of 0.02 kg sulphur dioxide (SO_2) per kilogram diesel oil. Assuming a normal ship engine load, one can expect the exhaust to contain up to 0.04 kg nitrogen oxides (NOx) for the same amount of fossil diesel oil. The nitrogen oxides are mostly NO (90 – 95%) and NO_2 (5 – 10%). Particulate matter (soot) is also produced by incombustible fossil diesel oil, and even a small amount of soot can pose a risk to human and animal health.

Thus, the combustion of 1 kg diesel oil generally yields:

- 3.18 kg CO_2,
- 0.02 kg SO_2 (for 1% S content in oil),
- Up to 0.04 kg NO_X gases (NO and NO_2)
- Particulate matter (quantity dependent on engine type and fossil diesel viscosity)

The scrubbing process, spraying the exhaust gas with only water or seawater, produces the removal of the following constituents, respectively:

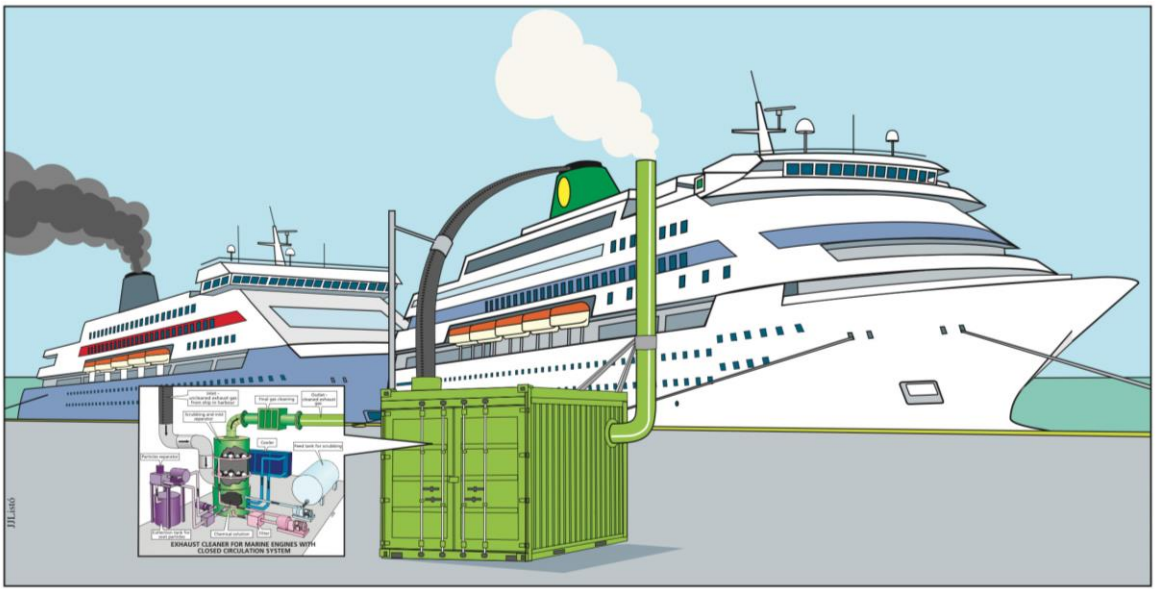
- 90% Soot (PM or Black Carbon)
- 98% Sulphur dioxide (SO_2)
- 10% Carbon dioxide (CO_2)
- 10% Nitrogen oxides (NOx)



Using water spray exclusively removes the greater part of soot and sulphur dioxide

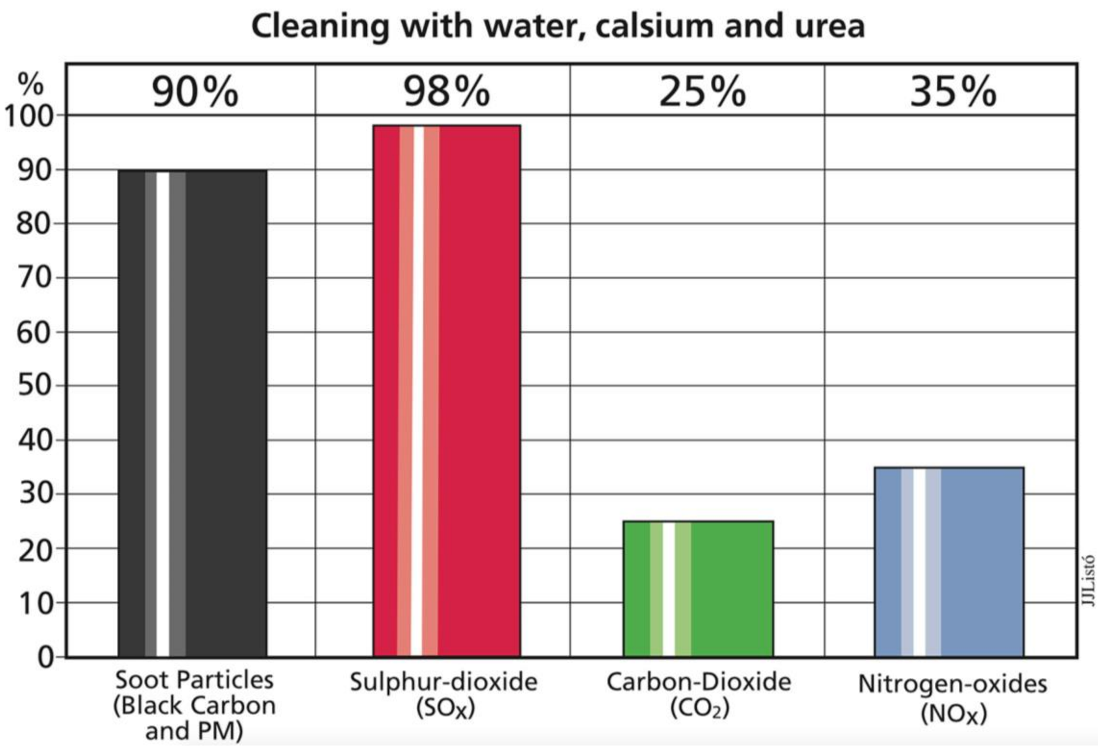
The results of exhaust gas scrubbing utilizing water spray are quite noteworthy due to the large extent to which sulphur dioxide (SO_2) and particulate matter are removed from the exhaust gas. Indeed the decrease in carbon dioxide (CO_2) and nitrogen oxide (NOx) content is acceptable, thus the option of using a mobile container housing wet scrubbing equipment is one for serious consideration. Cruise ship funnels could be connected to a duct leading into the container where, for example, particulate matter would be removed from the exhaust gas.

Arranging a simple scrubbing system port side to treat exhaust gas could be an alternate solution to the utilization of shore power for large passenger ships with generators burning diesel oil while at berth. That is, channelling exhaust gas from vessel generators through a simple wet scrubbing system set up in a container on the quay may be a means by which to significantly reduce pollution issues related to large passenger vessels powered by diesel generators. This solution could be adopted and used with substantial results until onshore power system infrastructure linked to landside grid reaches its potential as a technical and cost effective method for ship-owners.



Particulate matter can easily be removed from exhaust gas via water spraying in an especially equipped container

Exhaust gas scrubbing systems using chemical solutions are more effective with regard to the removal of carbon dioxide (CO_2) and nitrogen oxides (NOx). The level of particulate matter and sulphur dioxide purging is the same as for the system operating with water spray only. Due to the addition of calcium and urea to water, the removal of carbon dioxide and nitrogen oxides is multiplied.



Water spraying with added calcium and urea significantly increases the removal of CO_2 NOx

The proportional cleaning of exhaust emissions using a chemical solution is as follows:

- 90% Soot (PM or Black Carbon) (same as water spraying)
- 98% Sulphur dioxide (SO_2) (same as water spraying)
- 25% Carbon dioxide (CO_2)
- 35% Nitrogen oxides (NOx)

The only difference between using water spray only for exhaust gas post-treatment and the chemical solution is the increased efficacy with regard to carbon dioxide and nitrogen oxide when applying the chemical solution. Moreover, by designing and building a simple wet scrubbing unit, the removal of particulate matter and sulphur dioxide can be guaranteed as both methods eliminate the same amount of soot and sulphur and do so almost completely. Thus it is clear that exhaust gas post-treatment is a solution to particulate matter and sulphur emissions related to vessel engines, at sea and at port.

Exhaust gas pre-treatment

Water in Oil Emulsion as a pre-treatment method for exhaust gas

Exhaust gas pre-treatment refers to a cleaning process that occurs within the engine combustion chamber. That is, the cleaning takes place before undesirable substances produced during engine combustion are transferred to the exhaust pipe which transports the exhaust gas to air. Water in Oil Emulsion is one of the most effective methods for removal of these compounds from the exhaust. It involves spraying the oil with water, just prior to its introduction to the engine combustion chamber[7].

The temperature inside the combustion chamber can reach up to 2750°K (2500°C) but only for brief periods at a time. When it has reached 1600°K, nitrogen oxides (NOx) start to form and the longer the heat within the combustion chamber remains over 1600°K, more nitrogen oxides are produced. Upon entering the chamber with the oil, the water initially has a cooling effect and immediately reduces the formation of nitrogen oxides (NOx). The combustion of the fuel creates intense heat inside the combustion chamber, causing the water molecules to divide into oxygen (O) and hydrogen (H_2). Following the split, the fuel combustion is impacted by both the oxygen and hydrogen, reducing the formation of particulate matter which in effect simply unburnt fuel which the heat has transformed to soot.

Water in Oil Emulsion is an extremely effective method for cutting soot, reducing its exhaust level by half. The impact of the treatment on nitrogen oxides (NOx) is also considerable, providing removal roughly proportional to the amount of water sprayed into the combustion chamber. For 20% water in oil emulsion, one can expect a 20% reduction in nitrogen oxides (NOx) in the exhaust. This process also reduces exhaust gas levels of sulphur oxides and carbon dioxide, but to a lesser extent.

When the share of water reaches 20% compared to fuel, the option of using seawater instead of freshwater becomes an issue worth exploring, in order to save the space taken up by freshwater aboard the vessel. Under certain conditions, seawater can be partially used for the Water in Oil Emulsion treatment but salt from the seawater tends to corrode the sleeve and the piston in the combustion chamber. Thus the utilization of pure seawater is not generally recommended for the process.

Freshwater can be produced aboard the vessel by distilling seawater. By these means, all of the water required for the Water in Oil Emulsion can be produced as needed and specific tanks for the emulsion water are not needed. However, engine manufacturer approval must be sought for the liquid intended for use for the application of the Water in Oil Emulsion treatment.

In recent years, many engine manufacturers have incorporated Water in Oil Emulsion treatment within their equipment, most commonly applying 20% emulsion. In cases where the standard equipment includes pre-treatment with Water in Oil Emulsion and the post-treatment method of wet scrubbing, the removal of undesirable compounds formed during diesel fuel combustion is greatly improved[8].

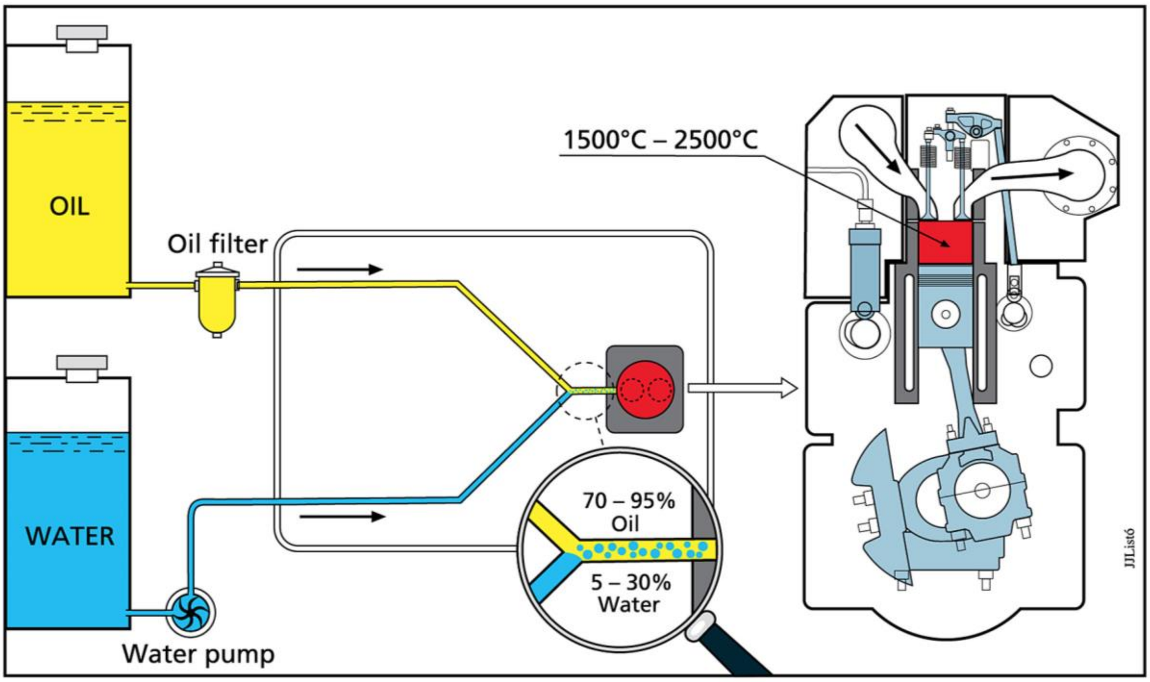
Methodology for pre-treatment with Water in Oil Emulsion

Theoretically speaking, a 50% water-to-oil emulsion can be applied but the engine fuel injection system will generally restrict the emulsion ratio to 10 - 20%. Some cases, however, will allow for an emulsion of up to 40%. A 20% proportion of water in oil emulsion is the most commonly used, with droplet sizes of less than 5 µm. While the emulsifying equipment can be set specifically to the desired emulsion percentage and droplet size, the appropriate and constant water injection into the combustion chamber is an essential factor for a successful pre-treatment with Water in Oil Emulsion[9].

Due to the immiscibility of water and oil, the two liquids must be emulsified and this process occurs just before they are injected into the combustion chamber. In this manner, the proportion of water entering the combustion chamber along with the oil can easily be decided. This is an extremely efficient method, specifically for the reason that no modification to the ship‘s main engine is necessary as the water injection does not adversly affect the energy output or fuel consumption[10].

The oil must be filtered prior to the mixture of the liquids; the filter would separate the water intended for the emulsion.

Water in oil emulsion method



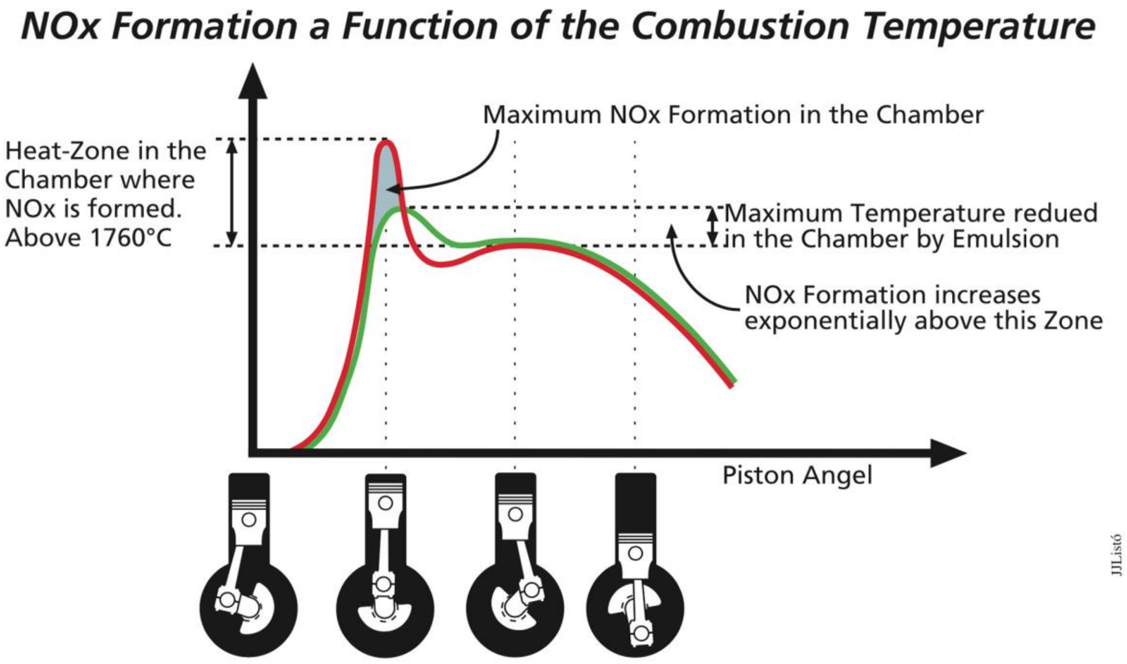
Water is mixed with oil just prior to entering the engine combustion chamber

Pre-treatment process of exhaust gas with Water in Oil Emulsion

An endothermic reaction occurs when the water is injected along with the fuel into the engine combustion chamber, that is the temperature decreases within the chamber as the water droplets absorb heat. This temperature drop reduces the formation of nitrogen oxide (NOx) because its production is solely dependent upon the chamber temperature, specifically the maximum temperature reached while combustion takes place.

The water‘s cooling effect in the engine combustion chamber lasts only a brief amount of time and is realized when at the peak temperature in the chamber. Nonetheless, it is sufficient to reduce the emission of nitrogen oxides (NOx) by roughly the same proportion of water to oil that is injected into the combustion chamber.

The extent of particulate matter in the exhaust gas is reduced considerably as the presence of water increases the amount of oxygen (O_2) and hydrogen (H_2) in the combustion chamber. The hydrogen and oxygen are by-products of the water entering the chamber being that the high temperature level splits the water hydrogen and oxygen molecules in the water. Thus the divided water increases and completes the combustion process of the fuel. In other words, the fuel combustion is greater and closer to optimal and the soot, which is unburned fuel, is only formed to a small extent[11].



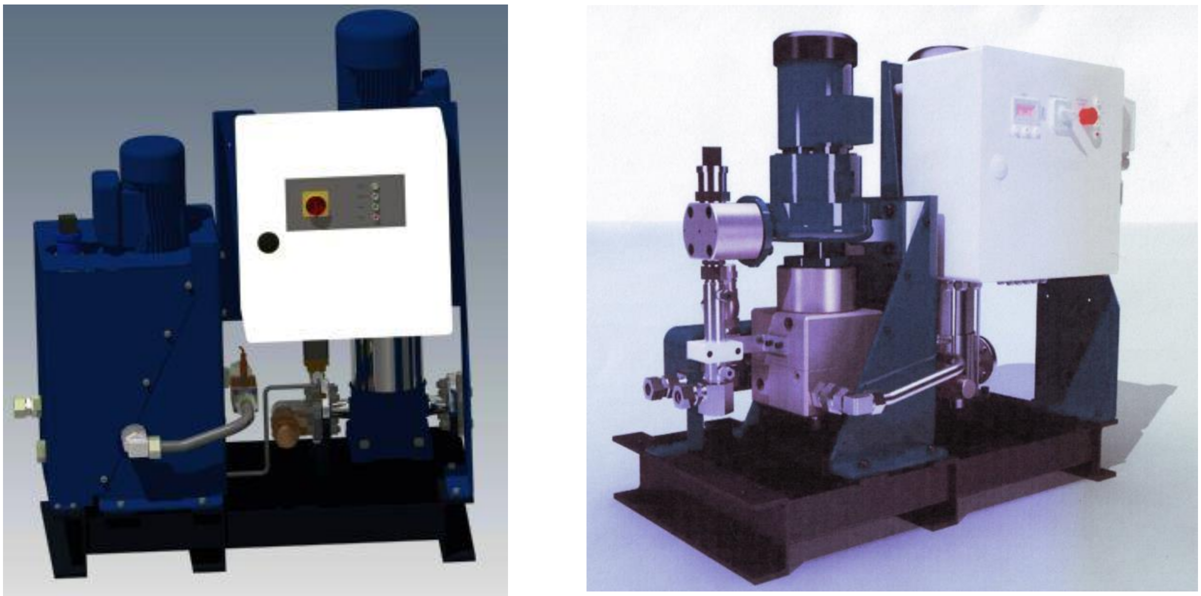
The figure demonstrates the effect of Water in Oil Emulsion on the formation of NOx compounds in a combustion chamber[12].

In summary, the emission effect of pre-treatment process is twofold: due to the water in oil emulsion and presence of hydrogen and oxygen, the production of nitrogen oxides (NOx) is reduced as a result of lowering the temperature in the combustion chamber. On the other hand, the emulsion also boosts the fuel combustion, thus reducing soot formation.

Equipment for pre-treatment of exhaust gas with Water in Oil Emulsion

The stability and efficacy of exhaust gas pre-treatment is dependent upon the type of emulsifying equipment used, the proportion of water in the emulsion and water droplet size. Therefore, using the proper pre-treatment machinery is essential and today, several manufacturers offer well developed and acceptable systems for injecting the fuel along with the fuel into the engine combustion chamber. This process produces the best results with regard to the reduction of undesirable compounds which otherwise would be discharged to air along with the engine exhaust.

As emulsifying equipment is not extensive, it can in most instances be set up in ship engine rooms, even in older vessels. It should be a valid and suitable option for ship owners interested in retrofitting their vessels with Water in Oil Emulsion equipment. The cost and arrangement thereof is well acceptable in most cases, according to manufacturers.



Emulsifying equipment[13]

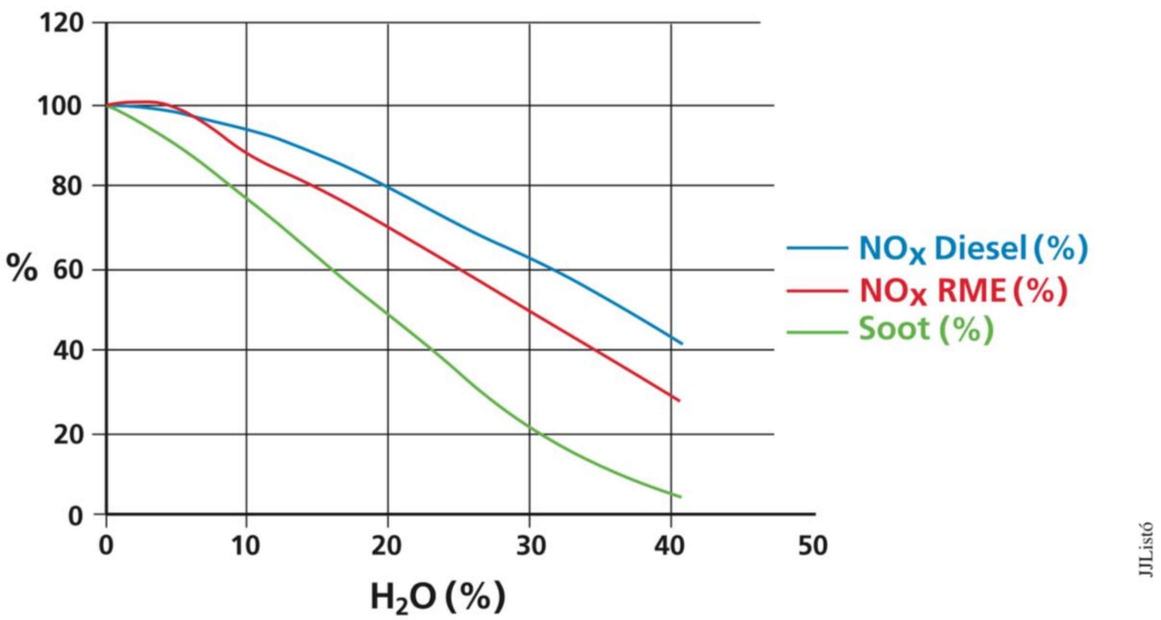
In recent years, many engine manufacturers have offered emulsifying equipment as a standard component, including it within the engine unit from the beginning. Most of them provide 20% water in oil emulsion.

Efficiency of Water in Oil Emulsion as exhaust gas pre-treatment process

The favourable results of the Water in Oil Emulsion method are quite remarkable, especially with regard to the emission reduction of nitrogen oxides (NOx) and particulate matter. The emulsion seldom exceeds 40% water content; usually the proportion of water is 20% upon entrance into the engine combustion chamber. In fact, the emission reduction is roughly linear and the emulsion method is most effective as regards the reduction in particulate matter emissions. This is good news, to some extent at least, as particulate matter (Black Carbon) poses a particular threat to the Arctic region, home to highly vulnerable ecosystems.

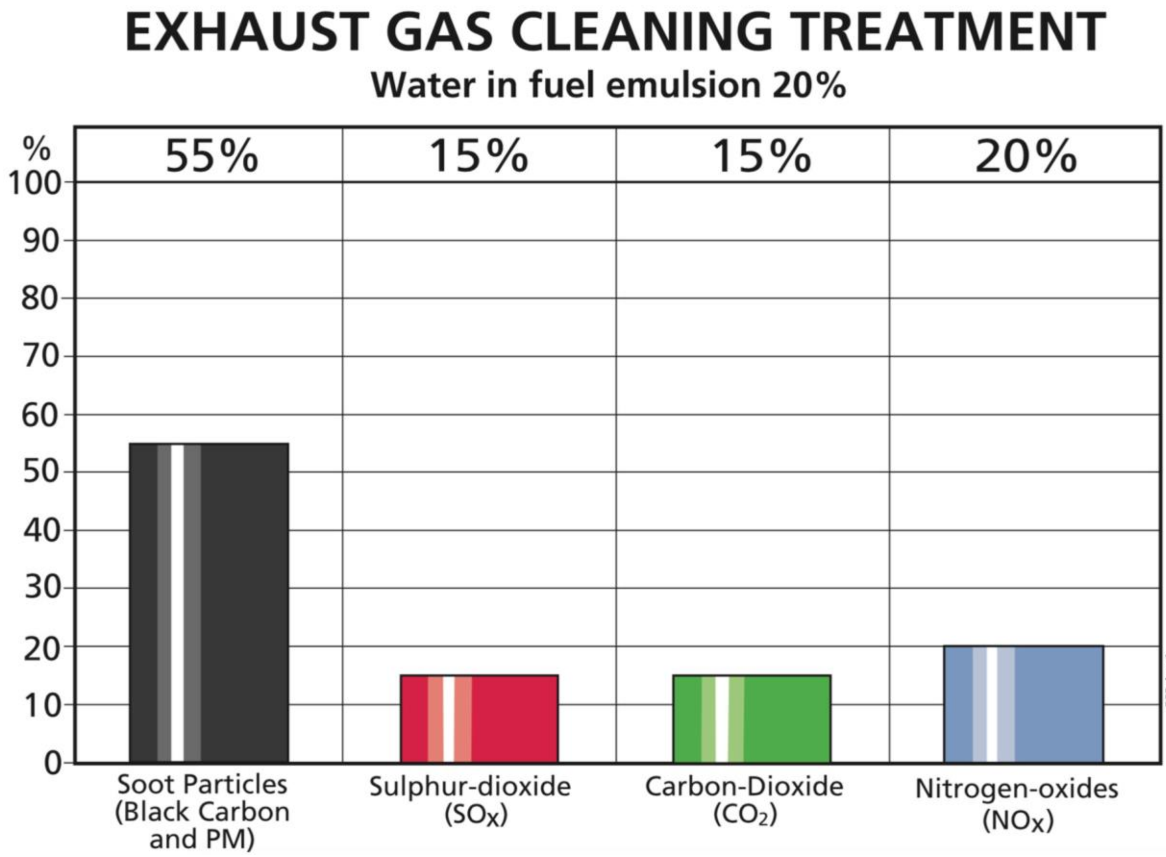
Water in Oil Emulsion is quite effective in reducing nitrogen oxides (NOx) in rapeseed diesel (Canola oil), also a notable result. Under normal combustion conditions, nitrogen oxide emissions are slightly higher compared to those of fossil diesel because rapeseed diesel contains 11% more oxygen. However, a small amount of water in oil emulsion, around 5%, reduces NOx emissions below the levels formed due to fossil diesel combustion. Nitrogen oxide emissions continue to decrease as water content increases in the emulsion.

Because rapeseed diesel exhaust gas does not contain any particulate matter and carbon dioxide has been absorbed during cultivation of the plant yielding the oil, Water in Oil Emulsion is the most suitable method for the reduction of undesirable compounds related to rapeseed combustion.



Nitrogen oxide (NOx) and soot (PM) emission reduction using Water in Oil Emulsion methodology[14]

Exhaust gas is almost completely rid of particulate matter when using 40% water content in emulsion but this can also be achieved with exhaust gas post-treatment using Water in Oil Emulsion. Indeed, even applying an emulsion of 20% significantly reduces particulate matter emissions.



20% Water in Oil Emulsion

The proportional cleaning of exhaust emissions due to the combustion of fossil diesel using exhaust gas pre-treatment and 20% Water in Oil Emulsion is as follows:

- 55% Soot (PM or Black Carbon)
- 15% Sulphur dioxide (SO_2)
- 15% Carbon dioxide (CO_2)
- 20% Nitrogen oxides (NOx) (fossil diesel)
- 25% Nitrogen oxides (NOx) (rapeseed diesel)

A 20% Water in Oil Emulsion level corresponds to a 20% reduction in nitrogen oxide (NOx) emissions to air. Particulate matter is more readily removed from the exhaust gas in this way.

Alternative methods for exhaust gas cleaning

An introduction to alternate exhaust gas cleaning methods

Exhaust gas from vessel main engines can be treated and purified in a number of ways. Some methods have gone through years of development, such as *the exhaust gas recycling system* and *scavenge air moistening*.

There are other, less tested and developed options and yet others still at the experimental stage. It will be interesting to examine these once they have been fully realized and production has started.

Exhaust gas recycling system

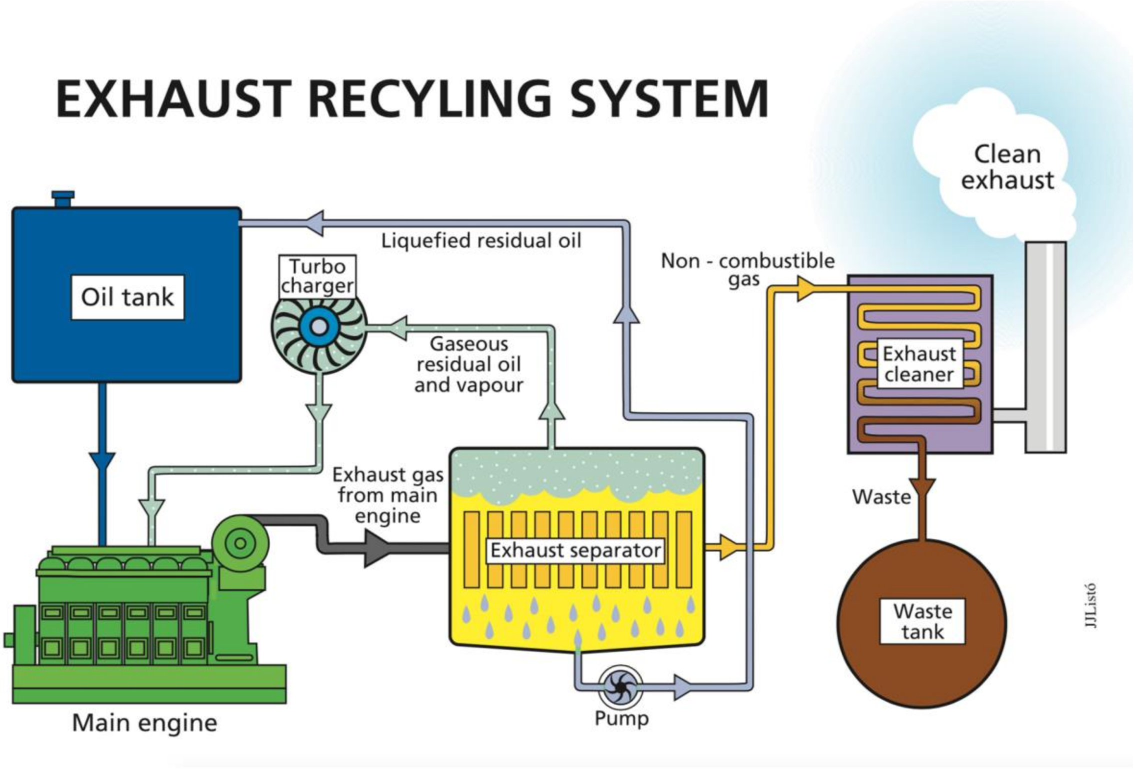
A method worth mentioning involves the collection of exhaust gas, transfer through an exhaust separator where uncombustible gas and exhaust gas are separated. Residual oil in gaseous and liquid form is recycled by pumping it back into the engine. This method is called an Exhaust Gas Recycling System.

The separator receives the exhaust gas which else would be emitted via the ship‘s funnel or smokestack. There, the gas is cooled and separated into incombustible and combustible parts. The combustible portion is further divided into gaseous and liquid substances (residual oil and water vapour). The incombustible part can be transferred to exhaust gas cleaner.

Uncombusted oil (liquid residual oil) is pumped from the separator to the fuel tank and from there it enters the combustion chamber once again.

A turbo charger then draws water vapour and particulate matter, which is uncombusted carbon compounds (gaseous residual oil), back into the engine along with clean air. In this manner, part of the exhaust gas is repeatedly recycled through the combustion chamber. Here, the water vapour could be used for Water in Fuel Emulsion. Thus an Exhaust Gas Recycling

System can be applied as a pre-treatment and as a post-treatment of exhaust gas in a collective process.



A simple diagram depicting an exhaust gas separator and exhaust gas cleaning

The exhaust gas separator also carries incombustible gas to an exhaust gas purifier for removal of toxic compounds before the gas is released to air as clean exhaust. The toxic substances are disposed of in accordance with the law and supporting regulations. The result is a significant decrease in toxic gases which otherwise would have been emitted to air following combustion in the vessel‘s main engine cylinder.

Scavenge air moistening - SAM

Scavenge air moistening - SAM is a process where the intake air for the engine is cooled in order to reduce combustion chamber temperature. In turn, the temperature decrease reduces the extent of nitrogen oxide (NOx) formation. Research has demonstrated that SAM reduces nitrogen oxides (NOx) levels by up to 50%, a remarkable result for this relatively simple and easily installed process. However, its reduction effect is essentially restricted to nitrogen oxide (NOx) emissions[15].

Alternate noteworthy exhaust gas treatment processes

Examples of other methods currently being tested for vessels include:

- Plasma, which mostly involves nitrogen oxide (NOx) reduction. This method is relatively well developed and executed.

- Separator; where a centrifugal separator is used to filter particulate matter from exhaust gas.
- Catalyst method, where exiting exhaust gas is run through a catalytic converter.
- Adsorption; particulate matter is removed from exhaust gas via suction before being released to air.
- Various chemical processes have been realized to varying degrees.

Most of these methods are relatively recent and will likely undergo some changes following further development and research.

Furthermore, electric filters for finer particulate matter are worth a mention. While these have been shown to rid exhaust gas of up to 99% of particles, the filters are rather voluminous and expensive to manufacture. Currently, water spraying is the preferred solution to remove particulate matter and a simple and inexpensive one.

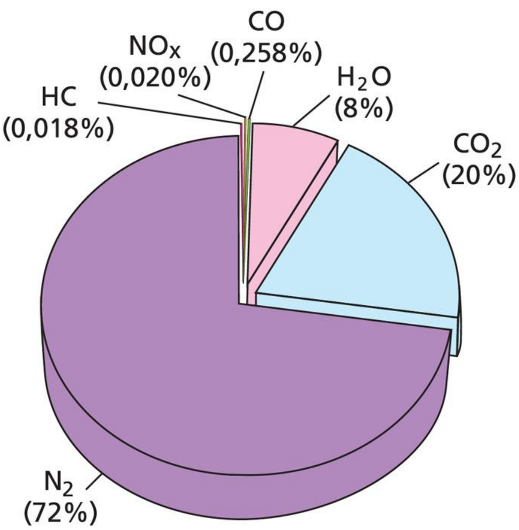
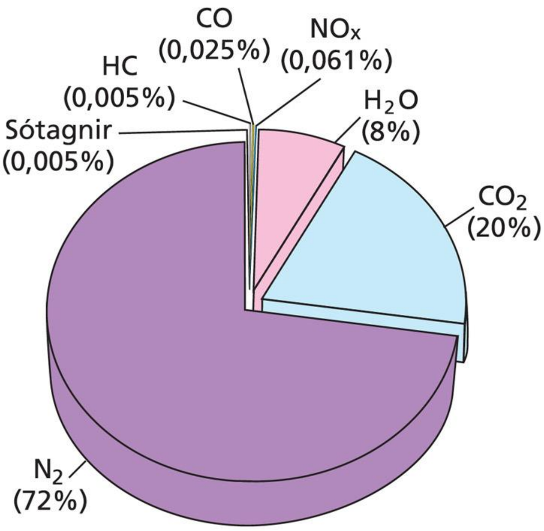
In recent years, several other interesting and simple means by which to remove contaminants and undesirable gases from exhaust gas have emerged. The easiest methods involve mixing a small amount of an additive with the fuel. Upon combustion the additive reacts with carbon dioxide (CO_2) and nitrogen oxides (NOx), producing a reduction in the emission of these constituents. Most of the additives also have properties for fuel combustion improvement and yield decreased particulate matter emission levels[16]. The methodology is extremely interesting, specifically if a significant reduction in undesirable emissions from vessel engines can be achieved with these developed additives[17]. Perhaps the simplest future additive will be water (H_2O), once a researcher successfully and permanently mixes it with oil.

The removal of undesirable substances and gases from exhaust gas

An introduction to the removal of undesirable substances and gases

Diesel engine exhaust gas contains soot (PM), unburned hydrocarbon (HC), nitrogen oxides (NOx), sulphur oxides (SOx), carbon dioxide (CO_2), carbon monoxide (CO), nitrogen (N_2), water vapour (H_2O) and residual oxygen and argon, as well as several other trace elements. Gasoline engine exhaust contains the same substances but to a differing extent. Particulate matter produced by a gasoline engine is extremely fine and the amount of the toxic gas carbon monoxide (CO) is ten times that of diesel engines. However, diesel engines produce three times the quantity of nitrogen oxides (NOx). The proportion of unburned hydrocarbon (HC) from gasoline engines compared to diesel engines is four to one.

The diesel motor is considerably more economical than the gasoline motor with regard to energy density and energy efficiency. That is, it consumes less fuel and emission production is lower when considering displacement per unit and for this reason, the diesel motor is by far the most common option for vessels of all sizes.

Gasoline motor (Otto motor)	Diesel motor
	
Combustion emissions for a gasoline motor	Combustion emissions for a diesel motors

Combustion emission comparison gasoline and diesel motors[18]

The minimum allowed content of various substances for diesel engine emissions differs from country to country. In Iceland, regulations on minimum limits related to transport have been implemented. As examples of lowest allowable limits for nitrogen oxides (NOx) and carbon dioxide (CO_2), one can compare those of the USA to EU country limits. American legislation is significantly stricter when it comes to nitrogen oxides (NOx) while the European Union generally focuses more on the reduction of carbon dioxide (CO_2) than nitrogen oxides (NOx). The minimum for nitrogen oxides is 43 milligrams per km (70 milligrams per mile) in the USA but 80 milligrams per km within the EU, that is 86% higher. For carbon dioxide, the current EU limit is 130 grams per km and beginning in 2020, the margin will be reduced to 95 grams per km. Currently, the minimum is at 165 grams per km and no decisions have been made for changing it in the near future. This difference between the US and EU allowable emission limit for carbon dioxide is approximately 20%. Assuming an unaltered American minimum for carbon dioxide (CO_2), the difference will be 75% in the year 2020, compared to EU countries, that is for land transport[19].

Tier	Ship construction date, on or after	Nitrogen oxide (NOx) emission in grams per (kWh)		
		n < 130 rpm	n = 130 to 1999 rpm	n ≥ 2000 rpm
I	January 1, 2000	17.0	$45 \cdot n^{(-0,2)}$	9.8
II	January 1, 2011	14.4	$44 \cdot n^{(-0,23)}$	7.7
III	January 1, 2016	3.4	$9 \cdot n^{(-0,2)}$	2.0

IMO regulation on nitrogen oxide emissions (NOx) [20]

Emission restrictions for sea-going vessels address nitrogen oxides (NOx) and sulphur oxide content (SOx): the International Maritime Organization (IMO) has introduced emissions standards for nitrogen oxides (NOx) known as Tier I, Tier II and Tier III. The requirements apply to engine rated speed, not power output.

In the case of sulphur oxides (SOx), the IMO has set a cap on allowed vessel fuel content. The regulations are part of MARPOL (MARine POLlution) Annex VI on sea areas where sulphur compound emissions are restricted (*SECA – Sulphur Emissions Control Area*), allowing for a fuel content maximum of 0.1% sulphur compounds, starting in 2015. For other areas, the limit is 3.5% until 2020, followed by a cap of 0.5% for sulphur content in fuel oil. Iceland has ratified MARPOL Annex VI.

Allowed sulphur oxide (SOx) content in diesel fuel		
Date	**SOx in ECAs**	**Global SOx**
2005	1.5%	4.5%
2010.07	1.0%	
2012		3.5%
2015	0.1%	
2020*		0.5%

IMO regulations on sulphur oxide (SOx) emissions. *Date decided in 2018.

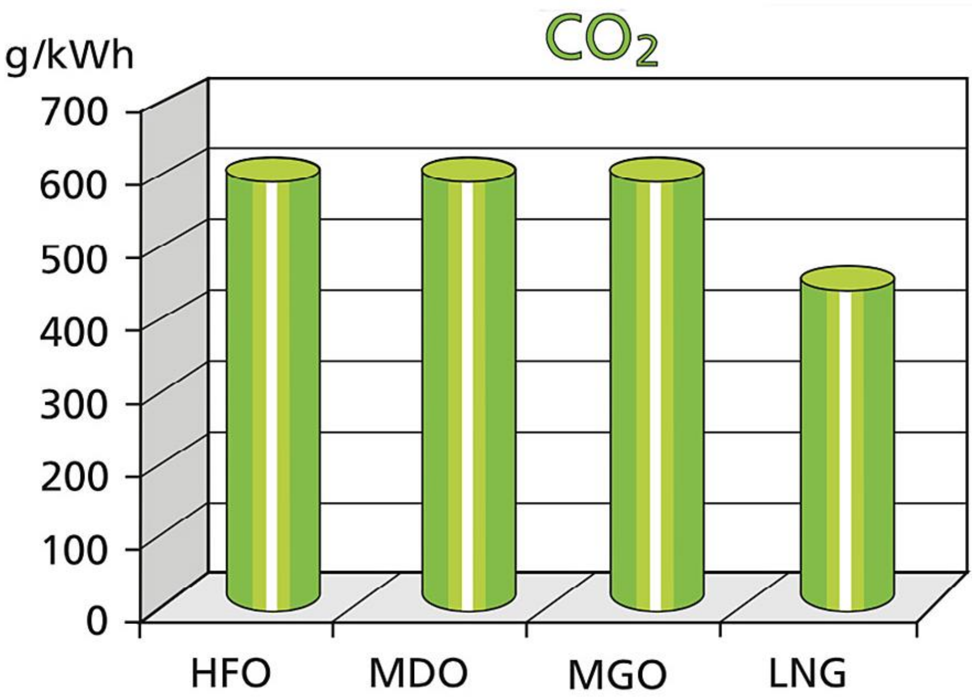
The combustion of 1 kg diesel oil yields an emission composition of:

- 3.18 kg carbon dioxide (CO_2)
- 0.02 kg sulphur dioxide (SO_2) for 1% sulphur (S) content in oil
- Up to 0.04 kg nitrogen oxides (NOx) as nitrogen monoxide (NO) and nitrogen dioxide (NO_2)
- Amount of soot depends on fuel type and viscosity.

Carbon dioxide (CO_2) cleaning

The extent of carbon dioxide in engine emissions is directly proportional to the quantity burned in the engine combustion chamber. That is to say, the more fuel efficient the engine, the lower the carbon dioxide emission. Reducing fuel consumption can be brought about by increasing pressure within the combustion chamber and thus also the combustion temperature. This action raises the temperature from 650°C to 2500°C at a pressure of 175 bar. Together, the elevated temperature and pressure yield a greater fuel efficiency, less fuel consumption and carbon dioxide (CO_2) emissions[21].

Carbon dioxide (CO_2) emissions are roughly the same for fossil diesel, heavy fuel oil (HFO), marine diesel oil (MDO) and marine gas oil (MGO). The combustion of fossil gas, which has been cooled to below minus 162°C (LNG) and thus has liquified and reduced its volume by 1:600, produces 10% less carbon dioxide than the other fossil fuels. However, the energy density of LNG is 65% of the energy density of the other fuels, so overall, the extent of carbon dioxide emissions is almost the same for these fossil fuels.



Carbon dioxide (CO_2) emission comparison for fossil fuel combustion[22]

Post-treatment of exhaust gas is the best method for removal of carbon dioxide (CO_2). The exhaust gas is scrubbed using a chemical solution containing a small amount of calcium (CaO). The scrubbing can remove up to 25% of the carbon dioxide (CO_2) from the exhaust gas.

The quantity of calcium used depends on the engine type and fuel viscosity. Its disposal is simple as the product of calcium and carbon dioxide is similar to sand. It can be separated from the scrubbing liquid and destroyed according to relevant regulation.

As a long-term solution, the most interesting method involves binding carbon dioxide (CO_2) with hydrogen. The hydrogen would need to be produced via electrolysis prior to mixing with carbon dioxide. Methanol is the product, which can easily be used as a fuel in other equipment aboard the ship, aside from the vessel engine. The heat of combustion is 41.9 MJ/kg for diesel oil but 22.7 MJ/kg for methanol, about half the energy density. In order for this to be a viable future option, a small scale chemical plant would be required for production of hydrogen and methanol aboard the ship. This specific process is the one applied at the Icelandic company Carbon Recycling International[23].

The proportional removal of carbon dioxide (CO_2) from exhaust gas due to the combustion of fossil diesel using the methods of post- and pre-treatment is as follows:

- 10% Only water scrubbing post-treatment
- 25% Water scrubbing post-treatment with calcium and urea
- 15% Only Water in Oil Emulsion (20% water) pre-treatment
- 35% Post- and pre-treatment (water scrubbing (calcium and urea) and 20% Water in Oil Emulsion)

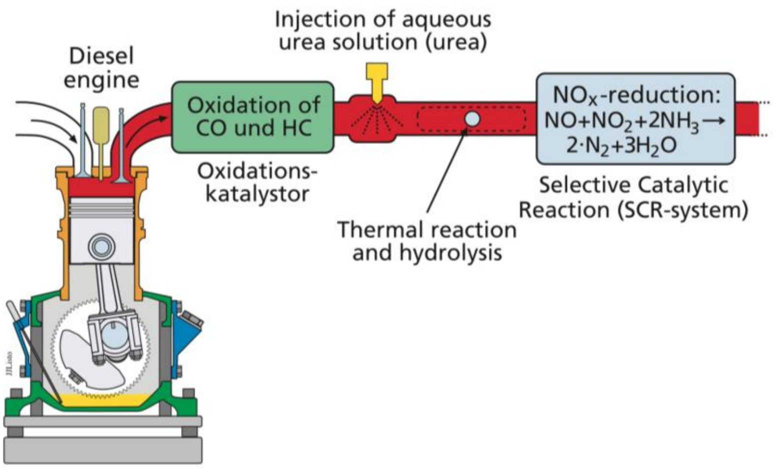
Nitrogen oxide (NOx) cleaning

Nitrogen oxides (NOx) are produced at high temperatures within the engine combustion chamber irrespective of the fuel type. Starting at a temperature of 2000°K and over or around 1760°C in the combustion chamber, nitrogen oxides (NOx) are produced. While the considerable heat in addition to increased pressure and a greater quantity of air results in a desired reduction in carbon dioxide (CO_2) content in the engine exhaust gas, the conditions generate a greater amount of nitrogen oxides (NOx) in exhaust[24].

The nitrogen in air reacts with oxygen in the engine combustion chamber to produce nitrogen monoxide (NO) and nitrogen dioxide (NO_2). Thus the chemical compound nitrogen oxide (NOx) is a synonym for both nitrogen monoxide (NO) and nitrogen dioxide (NO_2). The quantity ratio is generally 90 to 95% nitrogen monoxide to 5 to 10% nitrogen dioxide (NO_2)[25].

Nitrogen monoxide (NO) is a colourless and odourless gas capable of causing paralysis and blood poisoning in humans and animals. Nitrogen dioxide (NO_2) is a reddish brown colour and badly odourous gas which can adversely affect the respiratory tract. It can also contribute to the acidification of the oceans but normally positively affects the growth rate of plants.

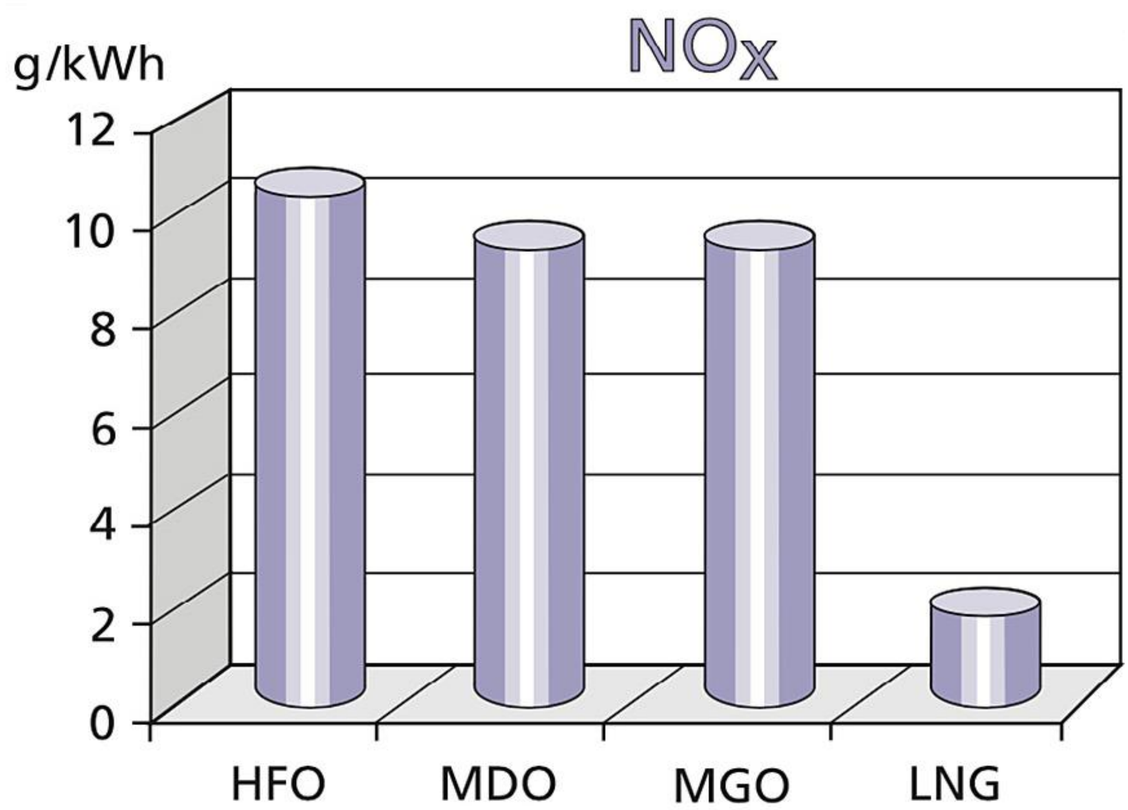
Nitrogen oxide (NOx) gases can be difficult to remove but they can be dissolved in seawater or fresh water. The first step is to convert as much of the nitrogen monoxide (NO) into nitrogen dioxide (NO_2) as possible, as the latter is soluble in water. Nitrogen monoxide (NO), on the other hand, is only slightly soluble in water and its solubility decreases with water temperature. Both of these gases can be converted into nitrogen gas and water vapour using enzymes and chemicals such as ammonia (NH_3) or urea. They can also be oxidized into nitrate before processing the solution to produce nitrogen fertilizer. Nitrogen monoxide (NO) can be transformed into nitrogen dioxide (NO_2) with ozone gas (O_3), then using a specialised catalytic converter to create nitrogen (N_2) and oxygen (O_2) from the nitrogen dioxide (NO_2). This completes the cycle and the nitrogen oxides (NOx) are back to their original form, as they entered the engine combustion chamber[26].



The figure demonstrates a stepwise method for removing nitrogen oxides (NOx) from vessel engine exhaust gas[27]

In some cases, scrubbing equipment is installed for the sole purpose of cleaning nitrogen oxides (NOx). This type of set up is often referred to as stepwise scrubbing for nitrogen oxides (NOx) and is commonly used in inland water vessels or in the vicinity of populated areas. It could also be useful aboard larger land vehicles and machines such as trains, tractors and larger trucks and freighters.

Although this specific scrubbing system is meant to rid exhaust gas of nitrogen oxides, it also removes a considerable share of soot (PM) and sulphur oxides (SOx) in addition to some carbon monoxide (CO). For carbon dioxide (CO_2) however, the extent of removal is significantly lower than for common post- and pre-treatment equipment.



Comparison of nitrogen oxide (NOx) emission due to the combustion of various fuels[28]

Roughly the same amount of nitrogen oxides (NOx) is produced from the combustion of fossil diesel fuels such as heavy fuel oil (HFO), marine diesel oil (MDO) and marine gas oil (MGO), between 9 and 10 g/kWh. Usually, the amount is 0.04 kg per kg fossil diesel oil combusted. For LNG, the quantity of nitrogen oxides is less, or under 2 g/kWh which has made LNG quite an interesting fuel option as the emission of nitrogen oxides (NOx) is less than that of fossil- and rapeseed diesel. Despite its lower energy density relative to conventional fossil diesel, LNG should be viewed as a worthy fuel alternative since diesel engines require no modification in order to operate on LNG.

The proportional removal of nitrogen oxides (NOx) from exhaust gas due to fossil diesel combustion with exhaust gas post- and pre-treatment is as follows:

- 10% Only water scrubbing post-treatment
- 35% Water scrubbing post-treatment with calcium and urea
- 20% Only Water in Oil Emulsion (20% water) pre-treatment
- 50% Post- and pre-treatment (water scrubbing (calcium and urea) and 20% Water in Oil Emulsion)

Sulphur oxide (SOx) cleaning

The chemical compound sulphur oxide (SOx) is a synonym for the different combinations of sulphur and oxygen. Sulphur dioxide (SO_2) is the most common; thus these compounds are almost one and the same**.** Sulphur dioxide (SO_2) is a colourless gas the scent of which can be detected once it reaches a certain level in the air.

Fossil diesel contains sulphur (S) to a varying degree. Currently fuel producers are required to almost completely remove sulphur from diesel oil due to the fact that when combusted, fossil diesel containing sulphur, causes the emission of sulphur oxides (SOx) to air. Subsequently, the international community has implemented regulations pertaining to a few ocean areas, *SECAs - Sulphur Emission Control Areas*, where the emission of sulphur oxides (SOx) is restricted to an allowed level of sulphur in fuel. The maximum allowed content of sulphur in fuel can not exceed 0.1%. For other ocean areas, the maximum allowed sulphur content in fuel is 3.5% and will remain until 2020, when it will be reduced to a maximum of 0.5%.

All fossil fuels contain sulphur (S), the level of which depends on its origin and type. Upon engine combustion, the sulphur (S) in the fuel is completely converted to sulphur dioxide (SO_2), which is soluble in water and seawater. For example, at 20°C, 40 parts of sulphur dioxide (SO_2) dissolves in one part water. This turns into sulphate (SO_4), which must be filtered from exhaust gas in order to prevent it from reaching the ocean as acid rain.

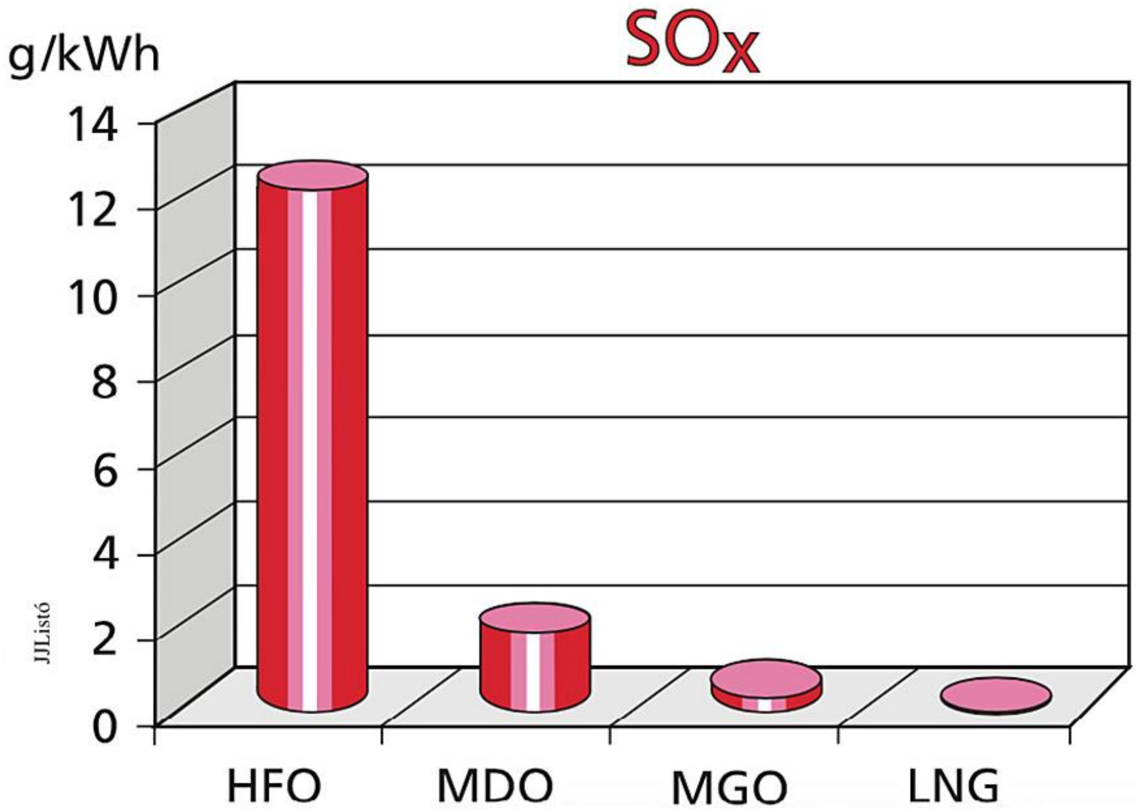
The most effective means by which to remove sulphur dioxide is via exhaust gas post-treatment, that is with water scrubbing only. The process efficiency is 90 – 99%. It is safe to assume over 90% cleaning using a relatively simple spray nozzle and drop catcher. The sulphate in the spent water can be processed to produce the fertilizer ammonium sulphate ($(NH_4)_2SO_4$)[29].

Obviously, the best way to reduce sulphur dioxide (SO_2) emissions related to engine exhaust gas involves removing sulphur from the oil at the production facility.

Sulphur oxides have other sources aside from vessel fuel. Specifically, volcanic eruptions can contribute up to 450 kg sulphur dioxide (SO_2) per second, that is a total of 40 thousand tonnes per day.

An aluminium smelter produces 16 tonnes of sulphur dioxide (SO_2) per day and the European Union releases a daily 14 thousand tonnes per day[30].

Thus there are several factors contributing to the quantity of sulphur dioxide (SO_2) in the atmosphere, aside from vessel engine emissions. These can however be removed from the exhaust gas in a simple manner, using only water scrubbing post-treatment of the exhaust gas.



Comparison of sulphur oxide (SOx) emission due to the combustion of various fuels [31]

The emission of sulphur oxides (SOx) due to fossil fuel depends on its sulphur content. Heavy fuel oil (HFO) most commonly contains the greatest amount of sulphur compared to other fuels, with 12 g/kWh of sulphur oxides (SOx). Marine diesel oil (MDO) and marine gas oil (MGO) cause smaller emissions than heavy fuel oil and sulphur oxide emissions are negligible due to LNG.

For fossil diesel containing 1% sulphur, 0.02 kg sulphur dioxide (SO_2) is produced for each 1 kg of fuel. Currently, fossil diesel content is restricted to 0.1% in SECA areas, which is equivalent to 0.002 kg sulphur dioxide (SO_2) for one kg combusted diesel oil. For global oceans, the maximum allowed sulphur content in diesel oil is 3.5%, leading to an emission of 0.07 kg sulphur dioxide (SO_2) per kg fuel. In the future, the maximum allowed sulphur content in diesel oil outside the SECA areas will be 0.5%, or 0.01 kg sulphur dioxide (SO_2) for each 1 kg diesel combusted.

The proportional removal of sulphur oxides (SOx) from exhaust gas due to fossil diesel combustion with exhaust gas post- and pre-treatment is as follows:

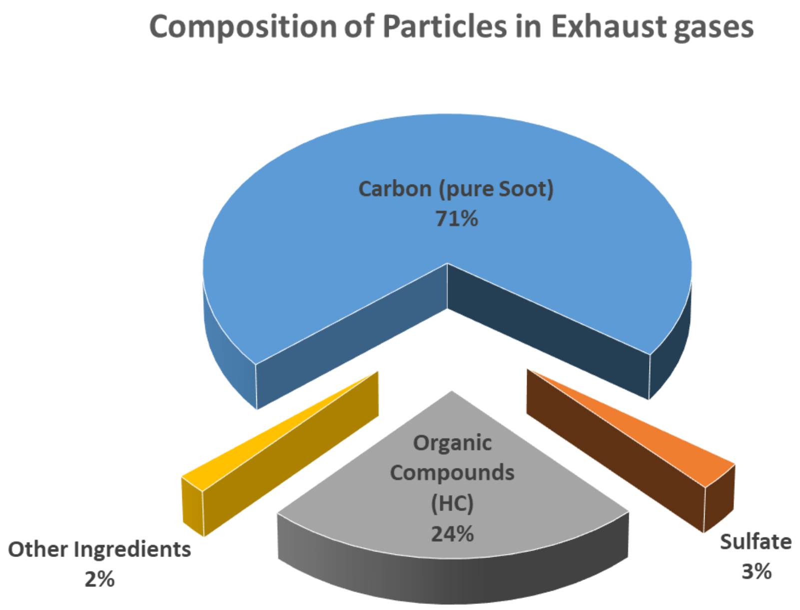
- 98% Only water scrubbing post-treatment
- 98% Water scrubbing post-treatment with calcium and urea
- 15% Only Water in Oil Emulsion (20% water) pre-treatment
- 99% Post- and pre-treatment (water scrubbing (calcium and urea) and 20% Water in Oil Emulsion)

Particulate matter (PM) cleaning

Soot is made up of pure carbon (C) and is part of diesel engine exhaust. It is usually produced due to incomplete combustion of the fuel. It is part uncombusted oil created as a result of lack of oxygen in the combustion chamber and does not reach air along with the exhaust gas.

The solid particles contained in exhaust gas, such as soot, are often referred to as Black Carbon or BC. These compounds can adversely affect ice sheets in the Arctic in that the particles settle on the ice, warming up by absorbing sunlight and melting the surrounding ice. The particles do not necessarily originate from vessels navigating Arctic regions but can be transferred there via air currents. In this way, southern regions can contribute to melting of ice sheets in the Arctic Ocean.

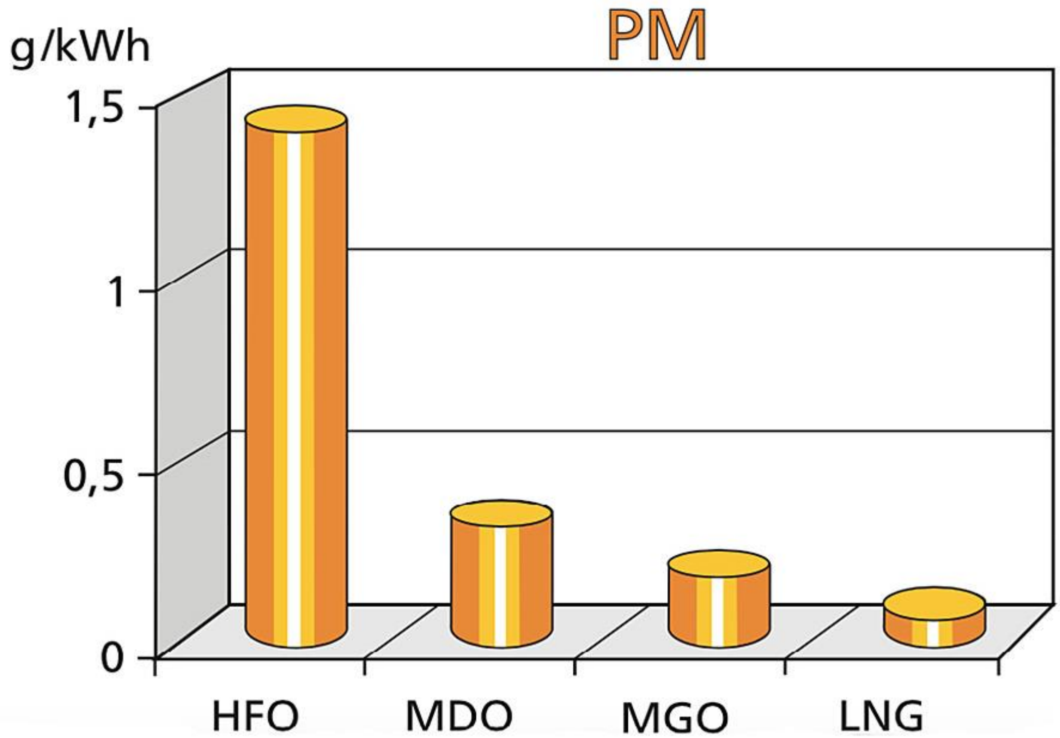
The international community has set its focus on Black Carbon emissions and minimizing their discharge from anthropogenic sources. The consequences are known and fortunately, so are also various ideas for how to solve the problem. The fact that a simple wet scrubbing process could completely rid exhaust gas of soot means that this problem will be eradicated within a few years.



The figure demonstrates soot composition in vessel engine exhaust gas[32]

Exhaust gas soot is mostly made up of carbon (C) as pure soot and organic compounds as uncombusted oil as hydrocarbons (HC) in addition to a small share of sulphate (SO_4) and other trace elements.

Soot and uncombusted oil as volatile organic compounds (VOC) can reenter an exhaust gas system where air is added to the exhaust and soot and fed back into the combustion chamber to be burned again. The amount of exhaust gas is controlled according to how the engine runs, its ignition, idling and load. During this extra combustion process, the soot and unburned fuel is converted to carbon dioxide (CO_2) and water vapour.



Comparison of soot (PM) emissions due to the combustion of various fuels[33]

Soot emissions in diesel engine exhaust gas are generally the greatest for the combustion of heavy fuel oil (HFO), which has the highest viscosity, the least amount of refining at the oil refinery and the longest carbon chain. Other types of fuels such as marine diesel oil (MDO) and marine gas oil (MGO) cause a similar amount of soot formation but LNG has very little. Thus LNG is a desirable fuel option where soot emissions are the focus because their negative impact can be permanent, and especially harmful in vulnerable habitats such as the Polar Regions.

The proportional removal of soot or particulate matter (PM) from exhaust gas due to fossil diesel combustion with exhaust gas post- and pre-treatment is as follows:

- 90% Only water scrubbing post-treatment
- 90% Water scrubbing post-treatment with calcium and urea
- 55% Only Water in Oil Emulsion (20% water) pre-treatment
- 99% Post- and pre-treatment (water scrubbing (calcium and urea) and 20% Water in Oil Emulsion)

Removal of other substances

Other constituents of exhaust gas are present only to a small extent. In heavy fuel oil that has been processed and cleaned using catalysts, these are quite varied. As an example, there are aluminium, vanadium, sodium, silicium, nickel and lead, among others.

Carbon monoxide (CO) is produced in diesel engine combustion chambers and usually it is discharged to air along with the exhaust gas. Carbon monoxide (CO) is a highly toxic gas created as the combustion becomes increasingly incomplete and also due to unusually high engine load. SO_3 can form during combustion of heavy fuel oils (HFO) containing a large amount of sulphur and other substances related to the refining process, such as vanadium. Combined with water vapour, SO_3 can in turn produce sulphuric acid (H_2SO_4), which can adversely affect engine parts. This can be avoided by using alkaline lubricant.

Engine combustion is never fully complete in the sense that no products of combustion are emitted to air and several factors influence the quality thereof. The extent of carbon monoxide (CO) can reach up to 10% of the exhaust gas due to gasoline engines, especially during idling. In diesel engines, the share of carbon monoxide is normally significantly less than 1%, and when bio oil is used, such as rapeseed oil, the carbon monoxide (CO) proportion is still smaller. Due to its toxicity, the carbon monoxide danger level is commonly set at 50 ppm in many countries, or 0.005%.

Another toxic gas related to oil consumption is hydrogen sulphide (H_2S). Hydrogen sulphide is not produced due to oil combustion and thus is not an exhaust gas constituent. According to oil product manufacturers, the risk of its formation is linked to evaporation from oil containing sulphur (S). Its inhalation can be harmful, it can adversely affect the respiratory system and it is very explosive. Furthermore, hydrogen sulphide is believed to be a carcinogen, specifically via inhalation and skin exposure. Hydrogen sulphide danger levels or exposure limits in a work environment are 10 ppm or 0.001%, making its toxicity greater than that of carbon monoxide (CO)[34].

Vessel engine exhaust gas can easily be rid of carbon monoxide (CO) using a simple post-treatment of common water scrubbing and wet scrubbing with a chemical solution, which yields a reduction of over half the original quantity.

Exhaust gas pre-treatment via Water in Oil Emulsion is not nearly as effective towards the removal of carbon monoxide and not at all, in some cases.

Water scrubbing easily removes hydrogen sulphide (H_2S) from the oil evaporation. However, this type of cleaning is more complicated and has not been widely used[35].

Treatments of other emissions

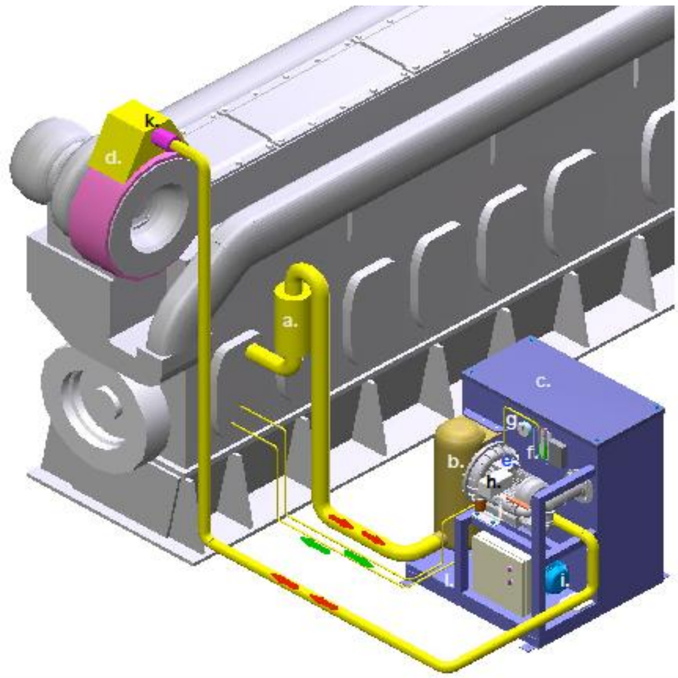
An introduction to the treatment of other emissions

There are various pollution sources aboard ships. Firstly, there are emissions due to fossil fuel combustion and evaporation of different oil based substances. There is also pollution related to air conditioning units, evaporation from enamel, paint and other surface treatments. Crew and passenger smoking have been steadily decreasing and while asbestos is hardly used at all anymore, other fibres may be present. The vessel cargo can be a source of pollution, dangerous goods such as gas, oils or radioactive substances. In recent years, the presence of electromagnetic fields has been defined as a type of pollution aboard ships.

Any work aboard, in addition to the operation of vessel systems, can also involve pollution sources. This is the case, in particular, with evaporation from oils and fuel as these substances can contain undesirable and toxic vapours.

Cleaning of lubricant vapour in vessel engine rooms

Through research grants, the Icelandic government supported a project involving the removal of gaseous lubricant in vessel main engine crankshafts. The equipment cleans the main engine crankshaft by suctioning any vapourised lubricant into a cleaning mechanism where it is separated into gaseous and liquid lubricant. The latter product is transferred back to the crankshaft while the gaseous part is passed through a turbo charger back to the main engine, where it is burned along with the fuel oil.



Equipment which suctions gaseous lubricant oil from the vessel's main engine crankshaft and recycles the lubricant.

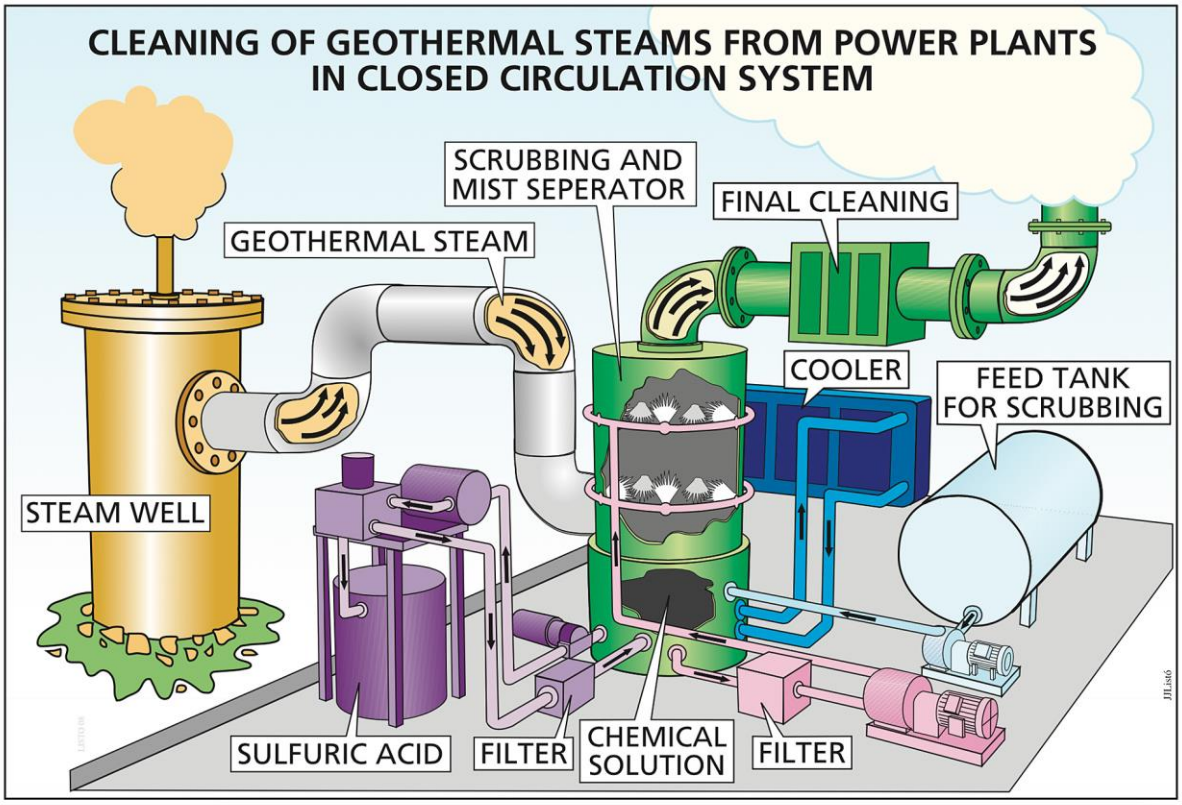
This methodology also reduces lubricant use aboard the ship by up to 50%, by means of recycling the lubricant that otherwise would leak from the crankshaft back to the engine. Moreover, lubricant vapour, which is toxic and can be harmful to humans and even carcinogenic[36] is dispersed to a lesser extent around the vessel engine room.

Removing the vapourised lubricant from air using the process described is likely simpler than cleaning the engineer‘s lungs after having inhaled the toxic vapour. An engine room saturated with lubricant can reduce the engineer‘s concentration, increasing the risk of fatigue and accidents aboard the ship. Healthy working conditions are a basic human right.

Treatment of geothermal steam from power plants

Another relevant topic is the purification of geothermal steam due to power plants and geothermal areas. Hydrogen sulphide (H_2S) from geothermal power plants is an emission constituent whose removal is worth considering as it is a gas heavier than air. It is not a greenhouse gas but can adversely affect humans and the environment

Hydrogen sulphide emissions have been an inevitable part of geothermal utilization in Iceland. Its natural outflow from geothermal fields also impacts the hydrogen sulphide concentration in air.



The figure demonstrates a theory for the removal of hydrogen sulphide (H_2S) from geothermal steam.

Hydrogen sulphide (H_2S) is specific to volcanic regions (as in the smell of hot springs). Some of it is produced due to decomposition, additionally, hydrogen and solid sulphur combined form hydrogen sulphide at 600°C. Its concentration in air is monitored due to the widespread geothermal utilization around the country[37].

There are several methods for the removal of hydrogen sulphide (H_2S) from air. First of all, there is general water scrubbing where hydrogen sulphide is transferred through a scrubbing tower, an equivalent process to cleaning engine exhaust gas using a simple, common water scrubbing post-treatment technique. The hydrogen sulphide is filtered out of the chemical solution and disposed of according to regulation. This water scrubbing method is worth taking into consideration as it is efficient and leads to minimal discharge.

Other means by which to remove hydrogen sulphide (H_2S) from air involve, for example, oxidizing hydrogen sulphide to create hydrogen dioxide (SO_2). Another reaction will, in turn, produce sulphate (SO_4) or SO_2 can be reduced to solid sulphur (S), which requires disposal in a landfill according to regulation.

Yet another methodology for the treatment for hydrogen sulphide (H_2S) concerns converting it to another substance, such as an insoluble salt (ionic compound). This can be achieved via a specific sea water scrubbing process, producing practically insoluble salts which may be landfilled without a negative impact on the environment.

These ideas are based upon the premise that the hydrogen sulphide (H_2S) has been processed from geothermal steam (exhaust gas) and is carbon dioxide (CO_2) free[38].

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