

The Environmental Case for Seawater Scrubbing

David Hirst

Shipping Emissions

The romantic image of a luxury liner cruising blue seas amid blue skies and trailing a plume of smoke is too close to the truth for comfort. The emissions from shipping make an increasingly conspicuous contribution to air quality, health and environmental problems of Europe, and indeed, the world. Yet there are effective and safe technologies to dramatically reduce these emissions. There is a danger, however, that the widespread introduction of these technologies may be being discouraged, even blocked, by inappropriate and over-prescriptive legislation. Proposals based solely on reducing sulphur in fuel at refineries would achieve modest reductions in pollution at considerable environmental (and economic) cost, but concerns about the environmental performance of ship-board technologies for removing sulphur from exhaust gases are making legislators wary of a more innovative approach. This paper aims to address these concerns and to give a balanced view on seawater scrubbing for shipping. We present some environmental arguments for rapid and full support to the wide introduction of this technology. We believe that this is a win-win technology minimising environmental emissions at minimum cost to the industry.

Today's mercantile fleet, unlike the sailing fleets of just 150 years ago, uses fossil fuel to propel itself. For the last 70 odd years, this fuel has been predominantly oil, and burning it, in engines or boilers, creates four general kinds of emissions:

- **Sulphur Oxides, or SO_x**, come from burning the sulphur present to some degree in all oils, although there is less in the lighter fractions, such as car fuels. There are various geological cycles of sulphur, each with some impact on the environment. We explore what happens when mankind's activities modify them, and how scrubbing can minimise this disturbance.
- **Nitrogen Oxides, or NO_x**, is made when engines heat up the Nitrogen and Oxygen in air. Scrubbing does somewhat reduce these emissions (~10-15%), and it can compliment use of further NO_x reduction technologies. Despite their environmental importance, they are not discussed further in this paper.
- **Soot, or Particulate Matter (PM)**, consists of particles of many different materials, such as unburned fuel or incombustible elements in the fuel. Some of it are secondary particulates formed from SO_x, NO_x and other material in the atmosphere, which can condense in the plume away from the ship. The familiar "diesel smell" is largely due to the presence of PM. It comes in many different sizes, and there is some evidence which implicates the very small, or ultrafine, particles as the most harmful to us. Scrubbing dramatically reduces PM emissions.
- **Carbon Dioxide, or CO₂**, is an inevitable product when we get energy from burning the carbon in fuel, and it is the main culprit implicated in global warming and climate change. Among the best ways of reducing CO₂ is to use less energy. A shift of transport from air, rail or road will reduce CO₂ emissions, as shipping is a particularly efficient form of transport. We also explore the energy efficiency of methods we use to reduce the other emissions.

Natural Sulphur Cycles

Sulphur is an element we need to live and some 0.2% of our bodies are sulphur. We get the sulphur we need from our food, and plants get it from the soils in which they grow. Every

year huge quantities of this sulphur are washed from the land to the sea. Some of it is replenished from the rocks of the earth, or from volcanoes or other sulphurous sources, (when it is called brimstone). Most is replenished by rain, which carries sulphur from the sea.

In its travels from sea to rain to land, and back again, we believe sulphur also plays a crucial climate control role¹, as follows:

- Micro organisms in the sea methylate the sulphur (that is they add methane groups (CH₃) to it) and use this for their own biological processes. Other creatures may then eat them and capture this sulphur for their own uses. When they die, some of the sulphur turns to dimethyl sulphide (DMS), which is volatile, and some of it evaporates from the sea surface.
- Some of the sulphur also stays with the decaying organism, so in the past some went to make up the sulphur in the oil we now burn.
- The DMS in air provides a nucleation site for moisture to condense into clouds. Tiny particles of DMS help damp air turn into tiny droplets. The amount of DMS influences how quickly clouds are formed, and thus influences how much sunlight reaches the sea, and so how much rain falls. We now recognise this as a critical climate control mechanism.
- Much of the land upon which the DMS falls has plenty of various compounds of sulphur around already, so the ecology is not constrained by lack of sulphur. If you add more, nothing happens, except that more of it runs off back to the sea. A few ecologies are constrained by lack of sulphur, and have evolved to live with only that which falls in the rain. If more sulphur compounds land on these ecological communities, then some of the organisms in it will be able to grow bigger or faster. For most sulphur constrained ecologies, the addition of extra sulphur changes the balance of the ecology, often for the worse.

Sulphur is a naturally occurring element, obviously present all around us. The form in which it is present is a key factor determining whether it is beneficial, neutral or harmful.

SO_x in the Cycle

Mankind, in its use of sulphur, influences these natural cycles, principally by releasing SO_x into the atmosphere. SO_x, unlike DMS, is typically only abundant in air during and close to volcanic eruptions. Thus our continuous and widespread generation of SO_x presents environmental problems.

Most of the Sulphur Oxides (SO_x) we release arise when we burn materials containing sulphur, such as most oils and coals. We also create smaller quantities of SO_x, with their sulphurous smell, when we smelt sulphate ores in the extraction of metals, such as copper, zinc and lead, and it was perhaps this smelting that caused it to be one of the first air pollutants ever to be regulated.

Once released into air, SO_x will combine with water droplets to form sulphuric acid, or with other particles in air to form sulphates. Although emitted as a gas, the gas can condense to form tiny crystals of SO_x, which are (like natural DMS) nucleation sites for moisture (which then form Sulphuric Acid). SO_x can travel a many thousands of kilometres from where it is

¹ Some of the details of this cycle and their impact are still to be fully understood. Aspects of it remain topics of active scientific research.

emitted, but a “rule of thumb” is that half of total emissions will land within 720 kilometres of the source.

SO_x combines readily with ammonia in the air to create ammonium sulphate, which causes a haze, reducing visibility and increasing the amount of incoming sunlight reflected back into the sky. As well as damaging “clear air”, it thus also influences the climate. When SO_x is breathed it is irritating to nasal passages and the lungs, and is harmful to our health (as well as that of animals and plants).

When emitted SO_x lands, it is, unlike DMS, largely as sulphuric acid, giving rise to the term Acid Rain. In many ecosystems, there is enough “buffering” in the water and the soil to neutralise the acid, and it behaves much as sulphur from natural sources. In many areas, this buffering capacity arises from the limestone or chalk geology of the soil. Older, alluvial soils tend also to have greater buffering capacity. After providing sulphur to the ecosystem (perhaps with a fertiliser effect) it runs off to the sea.

If the emitted SO_x come down on buildings or statues, it rots them. Much of the loss of detail on historical monuments, particularly those of marble or limestone, is caused by reactions from acid rain dissolving the material.

Some ecosystems, particularly those associated with granite geology or thinner soils, do not have enough buffering capacity to neutralise the load of acid that lands. When this happens, the soil and freshwater environment turns more acid. As well as being corrosive, it is harmful to all life, with the harm growing as the concentration increases. Fish cannot survive in the water, and plants cannot survive in the soil. If the acid is concentrated by sudden releases, such as when snow melts, the effect can be lethal and quick. Many sensitive freshwater lakes are regularly treated with lime to neutralise the acidity and preserve the life of the lake.

Eventually, the SO_x that lands on the soil is washed down the streams, with the acid gradually neutralised by other materials carried in the rivers to the sea.

If not neutralised before reaching the sea, the massive buffering capacity of seawater rapidly neutralises any remaining acidity.

In short, SO_x in air are bad for us and on land they are often harmful. The sea is a natural sink for SO_x, and is a place where sulphur is already enormously abundant. Indeed, the ultimate fate of all the sulphur runoff from land and air is the world’s oceans.

SO_x and Seawater Scrubbing

When SO_x comes into contact with seawater there is a fast and efficient reaction between the SO_x and Calcium Carbonate (CaCO₃) in the seawater, to form Calcium Sulphate (gypsum) and CO₂. The reaction neutralises the acidity of SO_x, and consumes some of the buffering capacity of the seawater. The reaction is complete in a very short time, so the equipment to bring the exhaust gas with SO_x and the seawater into contact can be compact and still achieve high reduction efficiencies (~95%).

The key environmental benefit of scrubbing is that it short circuits the whole SO_x cycle, and returns the sulphur to the sea in the safest, quickest and least harmful way². This is the core environmental justification for scrubbing³.

² It is also currently by far the cheapest way, but the economic arguments are presented elsewhere.

³ There is a small fuel consumption penalty of some 0.5%, but there are also heat recovery opportunities that can achieve consumption savings of 2% to 5% in most vessels.

But further questions about scrubbing need answering:

- Does the SO_x harm the seawater or the creatures in it?
- Can the sulphur be burned or disposed of in other ways?
- Are there other better ways of returning the sulphur to the sea?

We then discuss the further benefits arising from scrubbing, and safely disposing of, the PMs in the emissions.

Does the SO_x harm the seawater or the creatures in it?

Adding scrubbed sulphur to the sea does change its acidity very close to the source. However, the evidence available suggests that, in foreseeable practical uses, this change is barely detectable within a meter or two of any discharge. Certainly, any increase in the concentration of sulphur is miniscule (a few parts per million) compared to the sulphur already there. No known environmental harm is caused by such small changes and many rivers already have much larger increases in sulphur concentration.

We know that there are substances that are harmful at extraordinarily low concentrations, but in this case we are concerned with an increase in concentration of substances already present, not with new substances being added. Generally the local effect increases the proportion of sulphur in the sea from 928 parts per million (0.0928%) to perhaps 929 ppm. By way of comparison, we have increased the concentration of CO₂ in our atmosphere from ~275 ppm to ~367 ppm, an increase of over 30%.

We do not yet know how far seawater can be diluted before it loses its scrubbing effectiveness, or the changes in acidity of sulphur content become large enough to cause harm. There is active research in this area. However, even enclosed harbours, with lock access, probably turn over enough seawater to handle likely discharges.

Can the sulphur be burned or disposed of in other ways?

Shipping, like other large industrial plants, is able to handle and use the difficult heavy fuels that are unsuitable for other purposes, such as domestic heating, car or lorry transport, or air transport. To do so ships use complex fuel handling and processing machinery (quite unlike the filters in, for example, cars), but the extra cost is justified by the lower costs of the fuels they can then use.

These heavy fuels often concentrate the sulphur from the original crude oils. Although some heavy fuels can be made from the low sulphur crude oils, marine fuels reported to IMO average 2.7% sulphur. (This is 27,000 parts per million, whereas low sulphur car fuels are around 50 ppm).

So if shipping were to use low sulphur fuels, what would happen to all the high sulphur fuel oils they currently use? There appear to be five possible answers:

- This fuel is shipped to other parts of the world, where regulation is less strict. However, in most possible markets, SO_x emissions are becoming a political issue, and the “Asian Brown Cloud” in part created from SO_x emissions, is threatening to impact the whole Northern hemisphere. There may be parts of the Pacific, the Atlantic and the Southern Ocean where SO_x can be emitted without significant harm, although SO_x has a complex role in atmospheric chemistry and the jury is still out on this.
- The high sulphur oil is blended with available low sulphur fuels to match required limits to the sulphur permitted in fuels. However, since the benefits of lowering the sulphur levels of high sulphur fuels are matched by the disbenefits of raising the sulphur levels of low sulphur fuels, this has no overall environmental effect.

- The fuel is burned on shore, and uses other Flue Gas Desulphurisation (FGD) technologies to remove the SO_x from the emissions. Currently, the primary technology for FGD is to use limestone or chalk, which, when mixed with the SO_x in the exhaust gas, creates gypsum. This requires the limestone or chalk to be mined, transported and processed, and the gypsum to be recovered, processed and transported. For many purposes, the resulting gypsum is of higher quality than mined gypsum, and it is used in building materials and cement manufacture. There are also FGD processes which can recover elemental sulphur or sulphuric acid for further industrial use. However large quantities of gypsum are disposed of in landfill. Several power stations, including Battersea Power Station in Central London, have used sea water scrubbing for FGD. In comparison to ships, the volumes of SO_x created are huge, so depending upon how much the sea has been diluted by fresh river water, the scrubbing water is supplemented with limestone or chalk.

To decide whether land based FGD or sea water scrubbing deals most environmentally efficiently with the problem of sulphur in fossil fuel would require a full life cycle analysis of the two routes. It seems probable that removing sulphur in ships, which are floating in the neutralising material, would compare favourably with removal by land-based sources.

- The fuel is sequestered or stored so that it is beyond use. From a climate change perspective, this is attractive, as it implies that we use the lighter fractions of the oil, high in hydrogen (which burns to water), but reduce our use of carbon (which burns to the GreenHouse Gas CO₂). The sulphur can remain associated with carbon. It may be feasible to use depleted oil fields as a permanent store for the material. In practice, there are environmental risks, as we would have to transport more of the difficult and unpleasant heavy oils around the globe, and reinsertion would be hard and messy. Unless carbon costs or taxes are much larger than now, however, this is unlikely to be economically attractive.
- The sulphur is removed from the fuel, which we discuss next.

Are there other better ways of returning the sulphur to the sea?

Fuel oil can be desulphurised. The process generally involves forming hydrogen (H₂) and reacting this with the oil. The sulphur in the fuel reacts to form Hydrogen Sulphide, which is then further processed. The further processing may create Sulphuric Acid, a useful industrial chemical, or elemental sulphur, which is also of value in chemical industries. It may also be processed into gypsum for use in building materials.

The potential environmental attraction of this is that the sulphur recovered could replace sulphur that is otherwise mined as a feedstock to the chemical industry, and the gypsum could replace the gypsum that is mined.

There are disadvantages:

- Forming Hydrogen is an energy intensive process. Indeed, hydrogen by itself is very attractive, clean fuel.
- Hydrogen Sulphide is a dangerous gas. It is lethal at concentrations of 50 ppm, and at levels far below this will anaesthetise our sense of smell, which otherwise finds it pungent and unpleasant. At higher concentrations it is explosive.
- Concentrated Sulphuric Acid is a dangerous chemical to transport, and the environmental risks and energy cost of doing so may outweigh any benefit from reduced mining.

For many fuel uses, where no other means of removing SO_x are available, the environmental benefits of desulphurisation can clearly outweigh these disadvantages, and continued investment and regulation to achieve lower sulphur levels is well directed. This is certainly the case for road transport fuels where even small quantities of sulphur reduce the effectiveness of catalysts used in exhaust gas treatment. When directed at desulphurisation of shipping fuels, the overall environmental benefit is less clear. This is particularly so when we consider the added CO₂ burden from using energy intensive processes to remove the sulphur from fuel for shipping.

Once removed from fuels, the sulphur, mostly as sulphuric acid, is used in a rich variety of industrial and chemical processes. Indeed, sulphuric acid production is a key indicator of industrial activity. Some is also used in to manufacture fertiliser. However, almost all uses are dissipative. These uses neutralise it to form various sulphates. If soluble, these are eventually washed to the sea. If insoluble, they may be disposed of in landfill as well as carried to the sea as silt. Our efforts to reduce sulphur in fuels may still result in the sulphur making its way to our oceans.

New processes may be found that give other ways of using the sulphur, and if we reduced our dependence on fossil fuels, less would be released. But, at present, seawater scrubbing looks like a benign way to return the sulphur that comes from extraction of fossil oils to the ocean from which it once came.

What about Soot?

All combustion processes, including ships engines, produce PMs, many of them very small and therefore carried a long way. Much depends upon the design and operation of the engine.

If the fuel used is low in sulphur, its PM emissions will generally be less. However, scrubbing reduces the emitted PMs much more than is currently possible using clean fuels and operating with well-tuned and well-designed engines.

It is only in the last decade or so that the scale of the health harm of PMs has become apparent, and the numbers are disturbingly large. In Denmark, which suffers particularly from PMs as well as from shipping emissions (it is nearly surrounded by shipping lanes), there are estimated to be some 5000 excess deaths per year, as well as many other morbidity effects. Other countries suffer similar effects. While the shipping contribution is not easily quantified, it is significant and the benefit of reductions in airborne PMs from shipping is substantial.

Such reductions are achieved as an additional (and arguable zero cost) environmental benefit of seawater scrubbing by shipping.

A key perceived disadvantage of scrubbing the PMs from exhaust is that the PMs (as well as the SO_x) end up in the scrubbing water. If this water is not further treated, then its discharge would put this waste into the sea in a more concentrated form than it would be if it was first dispersed through air emissions. It does not add to the volumes of pollutants being put to the sea, just shortens the route by which it reaches the sea.

What about the discharge water?

It is this discharge that is the focus of the main environmental objections to seawater scrubbing, and is quoted as a reason not to encourage (or even permit) seawater scrubbing.

Even without further treatment, the balance of environmental and health benefits will, in most ecosystems, outweigh any harm from these discharges. However, there are many ways of removing oily and solid wastes from water. Current shipping regulations have encouraged the installation and use of water cleaning technologies, and they are well

understood by the industry. At sea, as well as in refineries, seawater that has been used for scrubbing can readily be treated before discharge, and the technical standards for such equipment will undoubtedly require that this is done. Sea-water scrubbing will require an on-going commitment to the complete safety of all discharges.

The Environmental Case

Seawater scrubbing of shipping exhausts is an environmentally benign way of reducing sulphurous and particulate emissions from ships, and provides a safe way of reducing the overall environmental sulphur burden our use of fossil fuels creates. There are substantial health and environmental benefits from the technology. The risks from this technology can be safely mitigated, resulting in a win-win opportunity that enables growth of the energy efficient shipping sector while substantially reducing its environmental burden.

It is for other papers to show that this is also minimises the economic burden on shipping, its passengers and its users.

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David Hirst (www.davidhirst.com) is a Management Consultant in Sustainability, and a core team member of SEAaT.

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