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EFFICIENT DUAL WATER HYBRID SCRUBBER DESIGN PARAMETERS

– for merchant ships

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EFFICIENT DUAL WATER HYBRID SCRUBBER DESIGN PARAMETERS

A compact Dual Water hybrid scrubber is an optimized solution for removing sulphur emissions from ship's exhaust gases, which is dimensioned according to installation specific features along with more operational environment related design parameters. Ongoing Dual Water hybrid scrubber projects are focusing on Cruise ship segment and the studied and designed solutions are highly customer tailored and customer specific. The objective of this study was to analyze design parameters, their influence to dimensioning and their functionality to the scrubber dimensioning and efficiency. Furthermore, the aim was to generate design parameter values for merchant fleet, possibly enabling more efficient design for a Hybrid scrubber with standardized design setpoint.

Design parameters have a great effect on scrubber unit's size and the total system's efficiency. Open loop stage is the most energy consuming as large sea water volumes are pumped high up to the scrubber unit. Therefore, when optimizing the sea water flow the most efficient system operation could be achieved. The material for this thesis work has been obtained by an extensive literature research. The focus has been on merchant fleet but the results are also valid for other ship types. The results have been tested in a case study by the process simulation calculations from real ship projects with Wärtsilä's 2-stroke engines.

The variation in values of the design parameters, such as in heavy fuel oil quality, in fuel oil consumption, in exhaust gas flow, in sea water temperature and alkalinity questions the possibility to standardize the design setpoint and the performance of the Dual Water hybrid scrubbers. However, with optimized design parameters for Open loop scrubbing, the needed sulphur content reductions could be achieved with the sea water flow of 30 l/kWh, which is 15 l/kWh less than the quantity used at present with the Dual Water hybrid scrubbers and the Open loop scrubbers. In order to achieve a more economical scrubber operation, the sea water pumping should be executed so that the pumping capacities follow the scrubber load.

KEYWORDS:

Hybrid scrubber, Exhaust gas scrubber, exhaust gas, ship emissions, SOx, sulphur oxides, HFO, ECA, EGS, IMO, MARPOL, PM

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TEHOKKAAN DUAL WATER -HYBRIDIPESURIN SUUNNITTELUOHJEARVOT

Kompakti Dual Water -hybridipesuri on optimoitu ratkaisu laivojen pakokaasujen rikinpuhdistukseen, mikä mitoitetaan installaatiokohtaisten ominaisuuksien mukaan huomioiden myös toimintaympäristösidonnaiset suunnitteluparametrit. Käynnissä olevat Dual Water -hybridipesurihankkeet keskittyvät risteilyalussegmenttiin ja suunnitellut ratkaisut ovat pitkälle räätälöityjä ja asiakasspesifejä. Tämän tutkimuksen tavoitteena oli analysoida hybridipesurien suunnitteluparametreja, niiden vaikutusta mitoitukseen, sekä niiden toiminallisuutta pesurinmitoituksessa ja tehokkuudessa. Lisäksi tavoitteena oli tuottaa suunnitteluparametriarvoja kauppalaivastolle, mahdollisesti mahdollistaen tehokkaamman suunnittelun Hybridipesurille standardoitujen suunnitteluohjearvojen myötä.

Tutkimuksessa havaittiin, että suunnitteluparametreilla on suuri vaikutus pesuriyksikön kokoon sekä koko järjestelmän tehokkuuteen. Eniten energiaa kuluttava osio koko järjestelmässä on avoimenkierron (merivesi) -vaihe, jossa suuria merivesimääriä pumpataan korkealle pesuriyksikköön. Näin ollen erityisesti merivedenvirtauksen optimoinnin myötä voidaan saavuttaa tehokkain järjestelmän toiminta-aste. Aineistoa tähän opinnäytetyöhön on hankittu laajalla kirjallisuustutkimuksella. Tutkimuksen pääpaino on ollut kauppalaivastossa, mutta tulokset ovat sovellettavissa myös muihin alustyyppeihin. Kirjallisuusosuuden tietoa on testattu tapaustutkimusosiossa käyttämällä prosessisimulointilaskelmia todellisissa laivanhankkeissa, joissa on Wärtsilän 2-tahtimoottorit.

Suunnitteluparametrien standardoinnin haasteena ovat taustamuuttujien vaihtelut, kuten vaihtelut raskaan polttoöljyn laadussa, polttoaineenkulutuksessa, pakokaasun virtauksessa, sekä meriveden lämpötilassa ja emäksisyydessä. Optimoiduilla avoimenkierron suunnitteluparametreilla voitaisiin kuitenkin saavuttaa tarvittava rikinvähennys 30 l/kWh merivedenvirtauksella, joka on 15 l/kWh pienempi vesimäärä, mitä nykyään käytetään Dual Water -hybridipesureissa sekä avoimenkierronpesureissa. Jotta voitaisiin saavuttaa vielä tehokkaampi pesurin toiminta, tulisi merivedenpumppaus toteuttaa niin, että pumppauskapasiteetit seuraisivat pesurin kuormitusta.

ASIASANAT:

Hybridipesuri, pakokaasupesuri, pakokaasu, laivojen päästöt, SOx, rikkioksidit, HFO, ECA, EGS, IMO, MARPOL, PM

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LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
AWP	Advanced Wastewater Purification
BC	Black carbon
BBP	Bunkerworld Benchmark Prices
BOTU	Bleed-off treatment units
BSEF	Brake specific exhaust gas flow
BSFC	Brake specific fuel consumption
$CaCO_3$	Solid calcium carbonate
CAPEX	Capital expenditures
CFCs	Chlorofluorocarbons
CH_4	Methane
CIMAC	International Council on Combustion engines
CO_2	Carbon dioxide
CO	Carbon monoxide
CSS	Compact Silencer System
DWT	Dead weight tonnes
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EGC	Exhaust gas cleaning
EGCS	Exhaust gas cleaning systems
EGR	Exhaust gas recirculation
EIA	U.S. Energy Information Administration
EIAPP	Engine International Air Pollution Prevention

EMM	Effluent monitoring module
EP	Environmental Passport
E.G.	Exhaust gas
FNU	Formazin nephlometric unit
GDP	Gross domestic product
GHG	Green house gas
GRP	Glass-reinforced plastic
HC	Hydrocarbons
HFO	Heavy fuel oil
H_2O_2	Hydrogen peroxide
HSFO	High sulphur fuel oil
IACS	International Association of Classification Societies
IF	Inorganic fraction
IFO	Intermediate fuel oils
ISO	International Organization for Standardization
LNG	Liquefied natural gas
LSFO	Low sulphur fuel oil
L/G	Liquid-to-Gas ratio
MARPOL 73/78	International Convention on the Prevention of Pollution from Ships
MCP	Main control panel
MCR	Maximum Continuous Revolution
MECL	Marine and Energy Consulting Limited
MEPC	Marine Environmental Protection Committee
MFO	Marine fuel oil
MGO	Marine gas oil
NaOH	Sodium hydroxide
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_X	Nitrogen oxides

NTU	Nephlometric turbidity units
O_3	Ozone
OA	Oceanic acidification
OPEX	Operational excellence
POM	Particulate organic matter
PAH	Polycyclic Aromatic Hydrocarbons
PAH_{phe}	Phenanthrene equivalence
PM	Particulate matter
PSU	Practical salinity unit
SCR	Selective catalytic reactor
SEAF	Ship Emissions Allocation Factors
SEEMP	Ship Energy Efficiency Management Plan
SFOC	Specific fuel oil consumption
SOF	Soluble Organic Fraction
SECAs	SO_X Emission Control Areas
SMS	Safety Management System
SO_2	Sulphur dioxide
SO_3	Sulphur trioxide
SO_X	Sulphur oxides
SST	Sea surface temperature
SWS	Sea water scrubber
TA	Total Alkalinity
tEaT	Temperature of exhaust gas after turbine
TEU	Twenty-foot equivalent unit containers
UNCLOS	United Nations Convention on the Law of the Sea
UNFCCC	United Nations Framework Convention on Climate Change
VOC	Volatile organic compounds
WinGTD 3.0	General Technical Data -calculation tool for Wärtsilä two-stroke engines.

1 INTRODUCTION

1.1 Background

Upcoming emission regulations define strict limits for emission levels in ship exhaust gases: stricter nitrogen oxides (NO_X) emission levels are regulated according to IMO Tier III (2016) and sulphur oxides (SO_X) emissions are regulated by global limits and specified limits in regional Emission Control Areas (ECAs). In engine power generation sulphur oxides are formed when sulphur containing fossil-fuels are combusted. According to the latest studies in the field of Diesel engine technology, the primary methods by means of developing engine performance and structure, cannot achieve the emission reduction levels set for the future. If so, when operating with heavy fuel oil (HFO), the secondary flue gas cleaning methods are needed. In many cases this would mean that if the ship's engine is operating with HFO especially on ECA, the ship's exhaust gas system may need a selective catalytic reactor (SCR) or exhaust gas recirculation (EGR) for NO_X removal, and an exhaust gas scrubber for SO_X removal.

During the past 20 years Flue Gas Desulfurization (FGD) technology, which is called scrubbing technology in Marine sector, has received considerable attention over the years. Various FGD processes have been developed for the removal of SO_2 from various industrial sources: lime-based dry and semi-dry FGD, sea water FGD, limestone/gypsum wet FGD and fresh water & caustic soda or ammonia wet FGD. The wet Flue Gas Desulfurization in the coal-fired and oil power plants has been the most widely used because of its high SO_2 removal efficiency, reliability and low utility consumption (Dou & all, 1).

Since 2005, Wärtsilä has been developing and testing scrubbing technologies for removing SO_X from the exhaust gases of marine diesel engines. The first commercial marine scrubber project agreement for a main engine was signed in 2010. Since 2010, there has also been a development project for a Hybrid scrubber combining the sea water scrubbing and fresh water scrubbing processes in so called “Dual Water” scrubber unit and Wärtsilä has also applied for a patent for this technology. On 31st January 2012 Wärtsilä acquired Hamworthy PLC, which has successfully developed sea water scrubber applications and later on also Hybrid scrubber applications for Marine installation. By this acquisition Wärtsilä became the world's leading marine scrubbing technology manufacturer and supplier with three marine scrubber applications: Wärtsilä Closed loop scrubber (Fresh water scrubber), Wärtsilä Open loop scrubber (Sea water scrubber) and Wärtsilä Hybrid scrubber systems. All these applications are available as a main stream scrubber for an individual diesel engine and an integrated scrubber for several main and auxiliary engines and oil-fired boilers onboard.

1.2 Objectives and Scope of the Study

An efficient and compact Dual Water hybrid scrubber is an optimized solution dimensioned according to installation specific data along with more operational environment related design parameters. Ongoing Dual Water hybrid scrubber projects are focusing on Cruise ship segment and the studied and designed solutions are highly customer tailored and specific.

Depending on the selected design parameters, the sea water stage (1) of the scrubber can be designed to reduce the exhaust gas emissions to selected level (% by mass) of sulphur in fuel. This level can be designed up to ECAs' sulphur level of 0.1 m-% in fuel when steaming in defined conditions. These design parameters and conditions should be selected so that they prevail at oceans, where most of the ship's sea traffic occurs. When operating on water areas with less alkalinity in water, some alkali may be consumed in the fresh water stage (2). However, this consumption can be minimized by utilizing the alkalinity potential of the ship surrounding water (scrubber sea water stage is running).

In the situation where higher emission reduction is required, such as in ports, fresh water stage alone should be capable to remove sulphur to the level of 0.1

m-% in fuel. In this mode alkali consumption will be higher. As it is crucial that the scrubber fulfils requirements for sulphur level of 0.1 m-% in fuel, the fresh water stage is to be dimensioned according to most demanding conditions that may occur on the target ship. Also the design and the effectiveness of the fresh water stage (2) affect the fresh water/ alkali consumption and plume visibility. This means that in order to reach the minimized and compact size with a more economical total system operation, the sea water stage should be utilized.

The objective of this study is to analyze design parameters, their influence on dimensioning and their functionality in Dual Water hybrid scrubber efficiency and dimensioning. Furthermore, the aim is to generate design parameter values, study their effects on scrubber dimensioning, possibly enabling more efficient design with standardized design. The following design parameters are analysed in this study:

- Ship specific criteria
- Sulphur content (m-%) in fuel oil, max
- Sea water alkalinity (µmol/l), min.
- Sea water temperature (°C), max.
- Sea water inflow to scrubber (litres/kWh), max.
- Electric power consumption (% of MCR), max.

The design aspects which are also considered are:

- Scrubber configurations
- Product modularization

This study also includes background information of utilizing the HFO in future shipping and its challenges, a review of conventional scrubbing technologies, the function of Wärtsilä's scrubbing technologies and solutions. The different design parameters are also tested in a case study from a couple of real merchant ship projects equipped with Wärtsilä 2-stroke engines.

2 HEAVY FUEL OIL IN MARINE POWER GENERATION

In shipping all stands and falls follow worldwide macroeconomic conditions. Also developments in the world economy and merchandise trade are driving developments in seaborne trade (UNCTAD 2011, 7). The rapid growth in global trade during the past few decades was powered by easily available and affordable oil. The shipping, handling over 80 % of the volume of world trade, is heavily reliant on oil for power generation and is not yet in a position to widely adopt alternative energy sources. However, as evidenced by the recent surges in oil prices and as highlighted by many interest groups, the era of easy produced and cheap oil is drawing to an end with the prospect of a looming peak in global oil production (UNCTAD 2011, 24).

The main fuel powering the international shipping is HFO, which is a mix of residues from refinery processes to produce lighter and cleaner high-quality products from crude oil. A term residual fuel is thus often used. It is characterized by high viscosity and requires heating for storage and combustion. In general, the sulphur content is high, although the sulphur content of HFO is dependent on the sulphur content of the crude oil (Svensson 2011, 1).

The environmental record of maritime shipping is mixed. One can say that sea shipping is relatively climate friendly as the emissions of greenhouse gases per amount of transport work are low compared to other modes (see Figure 11). Shipping is also a relatively small contributor to the total volume of atmospheric emissions compared to road vehicles and public utilities, such as power stations. But in absolute terms the greenhouse emissions from shipping are significant and rising due to the increase in the global trading of goods. Sea shipping is also an important source of air pollutants where, especially in coastal areas and harbours with heavy traffic, the contribution of shipping emissions to air pollution is substantial (CE Delft & all 2006, 2; IMO 2012b, 36).

Upcoming emission legislations, such as the IMO Marpol Annex VI, are major drivers for engine performance development of current marine engines and marine power solutions. In the past the focus was on developing engine efficiency, which has also reduced atmospheric pollution from the ships. As more stringent legislations have and will come into force, the focus has been shifted towards emission reduction. This is affecting on engine internal technologies, after-treatment solutions as well as fuel quality options. With the presence of IMO Marpol Annex VI and by the effect of local emission limits like the EU Sulphur Directive, there are three options available for ship operators, which will continue operating with conventional fuel oils:

1. Use High Sulphur Fuel Oil (HSFO) and add Low Sulphur Fuel Oil (LSFO) in appropriate quantities in order to dilute the sulphur content to the correct level (Dual Fuel Operation). However, this option would only be feasible until 2015 within Emission Control Areas.
2. Use marine distillate fuels meaning using Marine gas oil (MGO) by single fuel operation.
3. Use HFO oil combined with the use of abatement equipment like exhaust gas scrubbers (IMO 2012b, 36; Skema 2010, 9; Wärtsilä 2010a, 1).

2.1 Heavy Fuel Oil

Fuel oils are comprised of mixtures of petroleum distillate in long hydrocarbons chains, particularly alkanes, cycloalkanes and aromatics. When producing oil products in distillation processing (boiling off) of crude oil, four broad product fractions or categories are generated: refinery gases (primarily methane, ethane and hydrogen), liquefied petroleum gases (primarily propane and butane), gasoline and distillate fuels. Each of these fuel categories have different boiling temperature ranges so starting from the lowest they vaporize from the crude oil until the oil will not boil without thermally decomposing. This non-boiling fraction is called residuum or residual oil. Consequently the fuel oil may be a distillate fraction of crude oil, a residuum from refinery operations or a blend of these (EPA 1999, 3; Irwin 1997, 5).

The selection of operating fuel oil for marine applications used to depend on three elements: the engine in use, the cost of the fuel and the availability of the fuel. At present, a fourth element needs to be added: legislation for sulphur emissions in operating water ways. Commercial shipping companies and engine manufacturers have the higher volume and low-cost interests to arrange deals with refiners to produce tailored marine fuels oils that are most cost effective for their engines. Therefore, there is also an interest to produce fuels that involve less refining leaving more sulphur in the fuel and therefore lowering production costs and the fuel price (EPA 1999, 5).

Heavy fuel oil is petroleum -based fuel, which contains the un-distilled residue obtained during the distillation process of crude oil. HFO is a thick, syrupy, black, tar-like liquid and is often called bunker fuel oil (bunker C), marine fuel oil or No. 6 fuel oil (Vaezi & all 2010, 1). Because of the proven engine technology, good availability and low production costs the HFO is the most popular fuel oil in marine sector and there is a great interest to keep that position even though more stricter legislations for sulphur emission are coming into force.

2.1.1 Fuel Oil Classifications

Since the time of industrialization, there have been several classifications for fuel oil. The American Society for Testing and Materials (ASTM) has published specifications for fuel oils, in where those are classified to six grades numbered from one (1) to six (6) according to fuel's boiling point, composition and purpose. In addition Bunker fuel classification contains different type of fuel oil used on ships. The name originates from the containers, i.e. bunker fuel tanks, on ships and in ports where the fuel oil is stored in. Since the 1980s, a standard set by International Organization for Standardization (ISO) has been the accepted as the main standard for marine fuels (bunkers). The standard is ISO 8217, which was updated in 2010 as fourth edition, which classifies fuel oils to Residual and Distillate fuels. The ISO standard describes four qualities of distillate fuels and 10 qualities of residual fuels. These different fuel oil classifications are listed in Table 1 (Perry & Green 2008, chapter 9: 2; WLSA 2011, 7-9).

Table 1. Fuel oil classifications (WLSA 2011, 8).

ASTM	Bunker fuel	ISO 8217	Name
Number 1 fuel oil	-	Distillate	Kerosene (Volatile distillate oil)
Number 2 fuel oil	Bunker A	Distillate	Home heating oil
Number 3 fuel oil	-	Distillate	Low-viscosity burner oil
Number 4 fuel oil	Bunker B	Distillate/ Residual	Low-viscosity heating oil
Number 5 fuel oil	Bunker B	Residual	Residual-type industrial heating oil
Number 6 fuel oil	Bunker C	Residual	High-viscosity residual oil

Generally marine fuels are divided into two categories: residual HFO and light marine distillates. The light marine distillates are further divided into MDO and MGO, which often has the lowest sulphur content when HFO has high sulphur content (Wahlström & all 2006, 17). HFO is pure or nearly pure residual oil and roughly equivalent to No. 6 fuel oil. In some cases, the name Marine fuel oil (MFO) is used for HFO. Commercial heavy fuel oils are often sold as Intermediate fuel oils (IFO), which are a blend of distillate oil and heavy fuel oils. MDO is a blend of heavy gasoil that may contain small amounts of black refinery feed stocks having low viscosity up to 12 cSt at temperature of 40 °C. MGO is roughly equivalent to No. 2 fuel oil and made only from distillates. Different marine fuel types and classifications with most important fuel oil characteristics, viscosity and sulphur content, can be found in Table 2 (WLSA 2011, 8-9).

Table 2. Marine fuel classifications (WLSA 2011, 9).

Fuel type	Fuel grades	Commercial name	Common industry name	Viscosity (cSt)	Sulphur content (%)
Residual	RMA - RMK	MFO	Marine fuel oil, residual fuel oil, heavy fuel oil	30-700 [1]	3.5-4.5
Intermediate	IFO180	MDF	Marine diesel oil, Intermediate fuel oil	180 [1]	3.5
	IFO380			380 [1]	3.5
Distillate	DMB	MDO	Marine diesel oil	11 [2]	2
	DMA	MGO	Marine gas oil, Gas oil	1.5-6.0 [2]	0.1-1.5

1) At temperature of 50 °C
2) At temperature of 40 °C

2.1.2 Characteristics of Heavy Fuel Oil

Fuel properties are the physical and chemical measures of fuel qualities that are related to fuel performance and handling characteristics. Fuel oil properties can be analyzed from three perspectives: specifications, actual properties and regional variations of properties. Sulphur content is usually the primary regulatory interest. Other properties often compared include viscosity, which is an important determinant of fuel performance, and cetane as well as ash contents, which are indications of the amount of heavy components in a fuel (EPA 1999, 6; WLSA 2011, 17).

According to Platts (2012a), there are four main fuel oil trade areas with specified fuel oil products: European products, Asian products (including Middle-East), Chinese products and products from the area of US, Caribbean and Latin America. The worldwide market generally assesses four grades of marine fuel in all bunkering locations: IFO180 cSt, IFO380 cSt, MDO and MGO. The specifications most commonly followed are defined by the International Organization for Standardization in document ISO 8217:2005 (E) - Petroleum products - Fuels (class F) - Specifications of marine fuels. According to Platts (2012a), the new ISO standards issued in 2010 have not yet become commonly reflected in most bunker supplies around the world (Platts 2012a, 24). ISO 8217 Fuel standard 4th edition from 2010 can be found as Appendix 1.

There are still several residual fuels on the market with different national and international specifications. According to ISO 8217, individual grades are designated by the letters A, B, D, E, G and K, and a number signifying the viscosity limit. As an example, RMA-10 is Residual Marine fuel A with a maximum viscosity (at 50 °C) of 10 centistokes (ISO 8217). Heavy fuel oils are mainly traded with their product names IFO180 and IFO380 (intermediate fuel oils), where the numbers are viscosity limits at the common fuel handling temperature of 50 °C, which are equivalent to 25 and 35 centistokes at 100 °C. Therefore, the official specifications for IFO180 are RME-25 and RMF-25 and for IFO380 those are RMG-35 and RMH-35. These intermediate marine fuels can be manufactured by blending residual oil with heavy distillates or from straight run residual oil, where the temperature and pressures are controlled to leave some heavy distillate in the residuum. At least on the European markets, generally the IFO380 is a mix of 98 % of residual oil and 2 % of distillate oil and with the IFO180 has a share of 88 % and 12 % with similar fuel oils. A wide variety of properties of residuum originates from different crude oils and design specifications of engine manufacturers create a wide variety of intermediate and residual marine fuels to the markets (EPA 1999, 9; Rozmarynowska & Ołdakowski 2012, 7). The most common marine fuel oils on global fuel oil markets are summarized in Table 3.

Table 3. Most common marine fuel oils on the global fuel oil markets.

Fuel type	Commer-cial name	ISO 8217 range	Product name	ISO 8217	Viscosity (cSt)	Sulphur content (%)
HFO	MFO	RMA - RMK	IFO380	RMG380	380 [1]	3.5
			IFO180	RME180	180 [1]	3.5
			LS 380	RMG380	380 [1]	1.0
			LS 180	RME180	180 [1]	1.0
MDO*	MDO	DMB	MDO	DMB	11 [2]	2
MGO	MGO	DMA	MGO	DMA	1.5-6.0 [2]	1.5
	lsMGO	DMA	lsMGO	DMA 0.1 %	1.5-4.5 [2]	0.1

*) Limited availability
1) At temperature of 50 °C
2) At temperature of 40 °C

2.1.3 Availability

As the whole bunker fuel supply chain includes traders, suppliers, brokers, bunkering-service providers or facility operators, and bunkering ports, the information on different segments in the bunker fuel supply chain varies dramatically. There are approximately 400 major bunkering ports around the world. Production, logistics and transport cost factors as well as local environmental regulations influence the location of these bunker ports. Ships need to bunker fuel at bunkering stations near or onto their trading routes. As the ports are usually located close to supply sources i.e. petroleum refineries and end consumers, strategic locations of the bunkering ports are often along high-density shipping routes near major population centres. Different stakeholders in marine bunker fuel sector nominate Singapore, Rotterdam, Fujairah and Houston as major ports in the world. Still there are big differences in bunkering volumes even with the biggest ports. As an example Singapore handles more than twice the bunker fuel volume of Rotterdam, which is the next largest port (EPA 2008, 39-40; UNCTAD 2011, 163).

According to World bunkering (2012), there are over 100 bunker suppliers and many times more bunker traders in the world from which some are acting globally and some only locally. The biggest global oil companies and refinery operators are strongly represented in most of the biggest and busiest ports. On Asian bunker markets the major players are British Petroleum, Shell, ExxonMobil, Consort Bunkers, Singapore Petroleum Company, Chevron Singapore, OW Bunker and Chemoil. The European markets are dominated by companies like Shell Marine Products, Lukoil and Statoil. In the Middle-East the bunker market is serviced by companies like FAL Energy Company, GAC Bunkers Co. and FAMM Middle East Ltd. In the USA the major suppliers are Shell Marine Products, Valero Marketing and Supply Co., Chemoil Corp., BP Marine Fuels and Bominflot Atlantic LLC dominate (EPA 2008, 39-48).

OPEC states that the expansion in world trade inevitably means increasing shipping activity but at the same time, oil use efficiency improvements in the marine bunkers sector will limit the scope for oil demand growth. In 2008, they estimated that approximately 4 % of global oil demand is accounted by marine bunkers. According to Table 4, the oil demand will increase in marine bunkers more than 2.8 mboe/d (thousand barrels of oil equivalent per day) over the period between 2008-2035, where 78 % of demand growth will originate from China and Southeast Asia (OPEC 2011, 97).

Table 4. World's oil demands as mboe/d in marine bunkers (OPEC 2011, 97).

Area	Levels				Growth
	2008	2010	2020	2035	2008-2035
North America	0.5	0.5	0.5	0.4	-0.1
Western Europe	1.1	1.0	1.1	1.1	0.0
OECD Pacific	0.3	0.2	0.1	0.1	-0.2
OECD	**1.9**	**1.7**	**1.7**	**1.6**	**-0.3**
Latin America	0.2	0.2	0.2	0.3	0.1
Middle East & Africa	0.1	0.1	0.1	0.1	0.0
South Asia	0.0	0.0	0.0	0.0	0.0
Southeast Asia	0.8	0.7	1.0	1.5	0.7
China	0.2	0.2	0.6	2.1	1.9
OPEC	0.5	0.4	0.5	0.7	0.3
Developing countries	**1.7**	**1.7**	**2.4**	**4.7**	**2.9**
Russia	0.0	0.0	0.1	0.1	0.1
Other transition economies	0.1	0.1	0.1	0.2	0.0
Transition economies	**0.1**	**0.1**	**0.1**	**0.2**	**0.1**
WORLD	**3.7**	**3.5**	**4.3**	**6.5**	**2.8**

Det Norske Veritas (2012b) has issued that current annual demand for distillate fuels is around 30 million tonnes, which will rise to 45 million tonnes in 2012, when the 0,1 % sulphur limit comes into force in ECAs and will be around 200-250 million tonnes by 2020 when the global limit drops to 0.5 %. This would affect HFO production in a way that it will plummet from around 290 million tonnes in 2019 to 100 million tonnes once the expected global emissions regulations enter into force in 2020. Also Purvin & Gertz (2010) has highlighted that the sulphur limits set for regional and global shipping will affect bunker fuel qualities and indeed the type of fuel consumed by global shipping. At the same time new technologies in exhaust gas cleaning could mitigate the fuel quality impact in some degree and especially the scrubber adoption would have a direct effect on refiners. Thus the degree in which the exhaust gas scrubbers are adopted will determine the balance between the use of residual and distillate fuels over the next 25 years. Further impact on demand of crude-oil based bunkers will be the use of alternative fuels like the LNG (Det Norske Veritas 2012b, 4-5; MECL 2011, 27; Purvin & Gertz. 2010).

During the past several years, the bunker industry has been notorious for the lack of formal statistics. The received data of bunker fuels has been official or less official with quite large variations. However, several studies are still carried out and of them is “Outlook for Marine Bunkers and Fuel Oil to 2030 from 2011” published by Marine and Energy Consulting Limited (MECL). It gives following estimation of bunker fuel demand in upcoming years. According to the outlook, even in year 2030 the residual fuel oil with the sulphur content of 3.5 % have quite remarkable share as can be seen from Figure 1. Residual fuel demand may start to increase under the assumption that most of the new building ships have scrubbers installed but the overall demand for conventional bunkers may decrease as more alternative forms of energy are utilized in the marine sector (MECL 2011, 61).

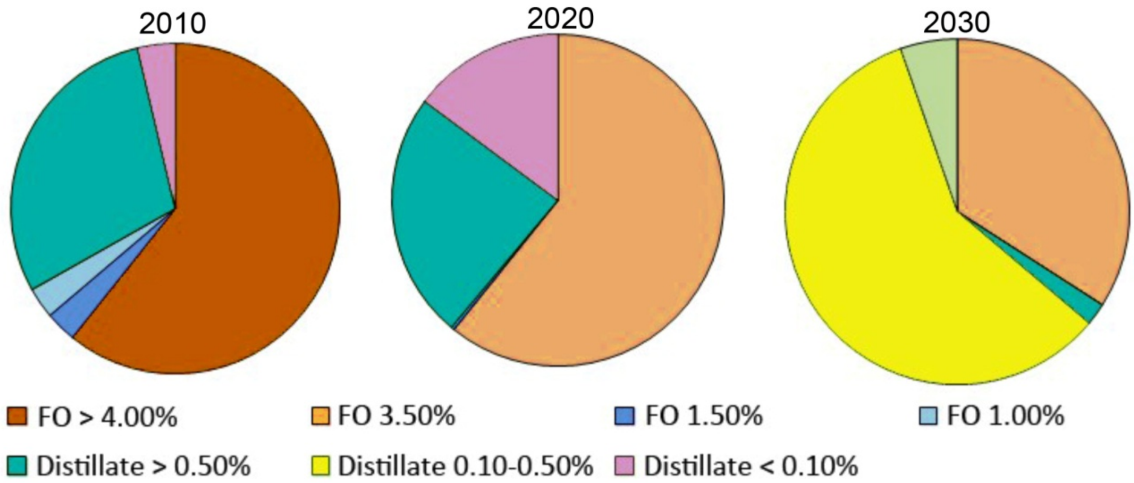


Figure 1. Demand by bunker fuel type in 2010-2030 (MECL 2011, 27).

2.1.4 Sulphur Content

According to new bunker fuel specifications, set out by the MARPOL under amendments to Annex VI of the convention, since 2012 high sulphur bunker fuel, supplied at major global bunkering locations, may contain a maximum of 3.5 % sulphur. The first level of IMO’s sulphur content control is the actual sulphur content of the fuel oils as bunkered. The sulphur value has to be stated by the fuel oil supplier on the bunker delivery note (IMO 2012; Platts 2012a, 24). The sulphur content of bunker fuel (IFO380) is typically around 0.3-3.9 %. Figures 2 and 3 summarize IFO180 and IFO380 global sulphur content development in 2007-2012. The sulphur data is provided by Lloyd's Register

FOBAS and Guardian Marine Ltd and it is charted on Bunkerworld's online publication pages (Bunkerworld 2012b).

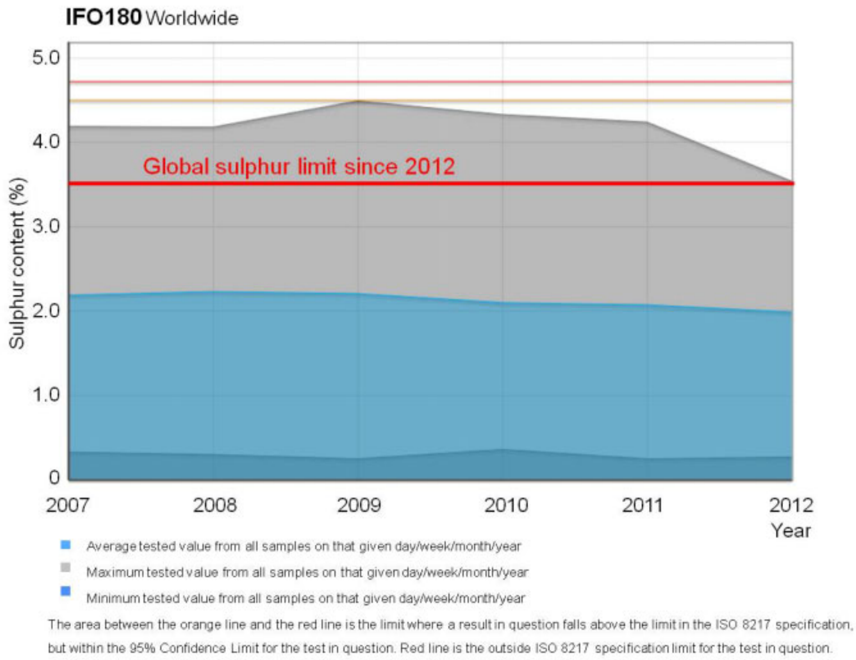


Figure 2. Global sulphur content development for IFO180 in 2007-2012 (Bunkerworld 2012b).

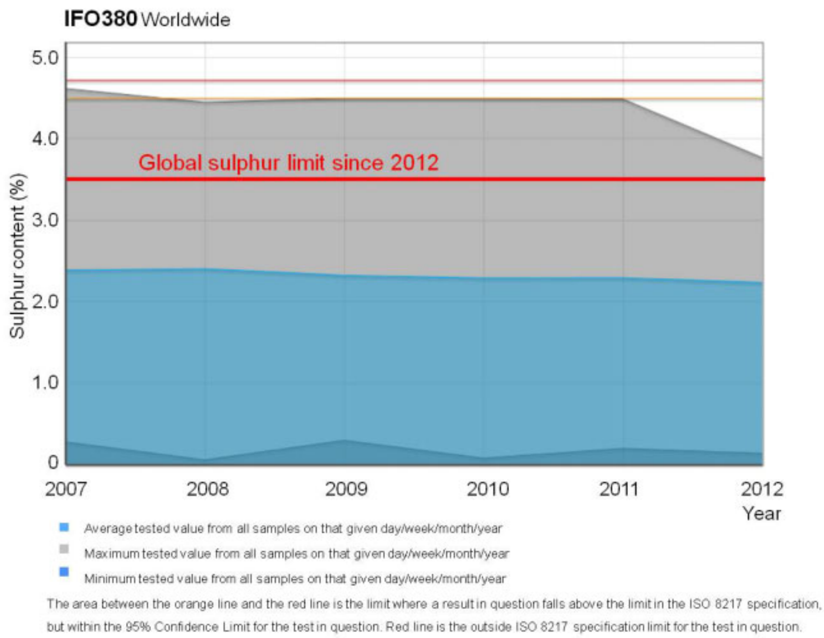


Figure 3. Global sulphur content development for IFO380 in 2007-2012 (Bunkerworld 2012b).

According to Figures 2 and 3, the maximum tested sulphur value is decreasing on both IFOs and also the average sulphur content is slowly decreasing. However in 2011, IMO's sulphur monitoring reported a slight increase in the global average sulphur content for HFO. According to a report presented to IMO's 64th session of the Marine Environment Protection Committee (MEPC), MEPC 64, in 2011 the sulphur average for HFO was 2.65 %, which had increased from 2.61 % in 2010 and from 2.60 % in 2009. This average was based on 97,137 samples from HFO deliveries, equalling 87,730,775 metric tonnes (mt) of HFO (Bunkerworld 2012c). However, there are some variations in the average global sulphur contents since for example in 2011 DNV Petroleum Services (DNVPS) gave only 2.32 % as the average global sulphur content (Juoperi 2013).

As an example, Table 5 contains RME180 (IFO180) and RMG380 (IFO380) sulphur content values based on Bunker quality report dated 14.9.2012. The data is based on samples as analysed by DNV Petroleum Services and is an abstract from their more detailed fuel quality statistics. In Table 5, the key bunker ports have been grouped in geographical regions for brevity and comparison has been made according to international fuel oil standard ISO 8217 (IMarEST 2012, 14).

Table 5. RME180 and RMG380 sulphur content by geographical regions in November 2012 (IMarEST 2012a, 14; IMarEST 2012b, 31).

ISO fuel specifi-cation	**Sulphur (m-%)**							
	North-Europe	West-Mediter-ranean	Central-Mediter-ranean	Middle-East	East-USA	USA Gulf	West-USA	Far East
RME180 average	1.15	2.41 *	2.11	3.27	0.98	0.93	1.68	2.50
RME180 maximum	3.01	2.88 *	3.36	3.40	0.98	1.00	2.42	2.84
RMG380 average	1.41	2.48	2.56	3.35	1.54	2.65	2.95	2.74
RMG380 maximum	3.44	3.37	3.41	3.46	2.83	3.42	3.27	3.60
*) Values from September 2012								

As can be seen in Table 5, the average sulphur content with RME180/RMG380 in most of the regions is lower than the IMO's global maximum sulphur content limit 3.5 % but the value from Far East is exceeding (marked with red colour) the maximum sulphur content value. Also the data in Table 5 shows that the highest sulphur contents have been measured in Middle-East and Far East areas, which can also be noticed from Appendix 2 in where the regional sulphur content developments for IFO180 and IFO380 in 2007-2012 are presented as figures collected from Bunkerworld's Bunker quality database.

2.1.5 Fuel Oil Prices

Intermediate and distilled fuel oil prices follow peaks and downs set by the world economical situation so supply and demand fundamentals are the major drivers also for the fuel oil price. One can say that HFO's price correlates positively with crude oil price and negatively with global temperature. Extremely warm winters globally in past years, like in year 2003, have had significant impact to decreasing residual oil prices. Unlike prices of distilled fuels, the HFO price is not related to Gross domestic product (GDP) growth and the demand for HFO is much more price elastic than demand for distilled fuels because there are several substitutes available for heating purposes. However, one should always exercise caution when predicting future prices for fuels since there are so many variables involved. Besides bunker fuel price trends are not always based on facts nether all various expectations and beliefs concerning the future (Kalli & all 2009, 10-11; UNCTAD 2011, 26; Wärtsilä 2009b, 23).

According to the International Energy Agency's (IEA) New Policies Scenario, worldwide oil demand increases slowly to 2035 reaching 99.7 million barrels per year (mb/d) from 87.4 mb/d in 2011. Then China alone may account for 50 % of the net increase worldwide. U.S. Energy Information Administration (EIA) and British petroleum estimates that petroleum and other liquid fuels are the world's slowest growing source of energy with expectations that the world oil prices will remain relatively high. They also estimates that the consumption of liquid fuels increases at an average annual rate of 1.0 % from 2008 to 2035, whereas total energy demand increases by 1.6 %/year. However, the fuel oil demand is predicted to decrease, as in the future, less world power will be generated with oil, and the share of middle distillates and bio fuels are constantly increasing (BP 2012, 23; IEA 2012, 4; EIA 2012, 10; UNCTAD 2011, 26). This trend can be seen from Figure 4 in where the shares of future world power generation by fuel type, transport fuel demand by energy type and liquids demand by product group are presented.

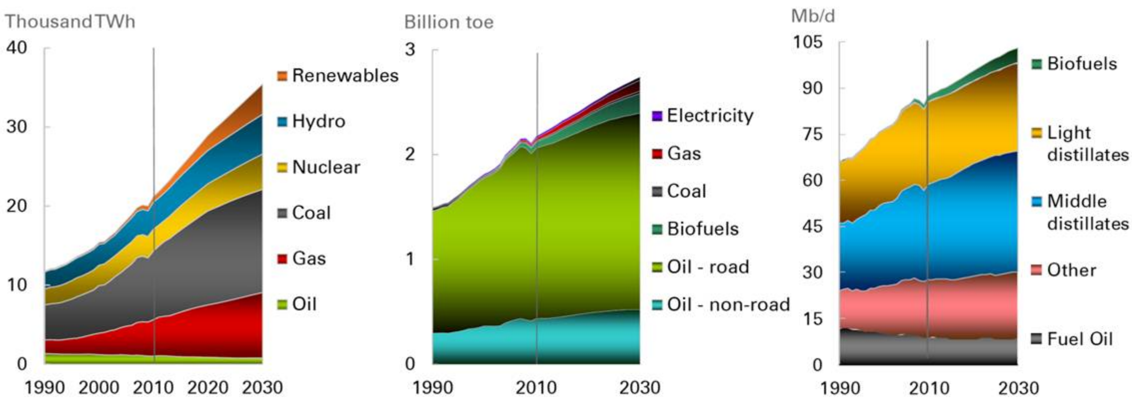


Figure 4. Predicted world power generation by fuel type (right), transport fuel demand by energy type (middle) and liquids demand (left) by product group in 1990-2030 (BP 2012).

Higher oil prices may also impact on shipping and trade through both their dampening effect on economical growth. According to IEA (2012), it is estimated that $10 per barrel rise in the price of oil, if sustained for a year, can cut about 0.2 percentage points from GDP growth and the upward pressure on the cost of fuel oils used in shipping, as higher oil prices drive up ship bunker fuel prices. As much as 60 % of a ship’s operating costs can accumulate from fuel costs, a rise in oil prices will undoubtedly increase the operating costs for the shippers and therefore potentially undermine trade (UNCTAD 2011, 26).

Fuel oil prices can vary from port to port and from bunker supplier/ trader to another. Figure 5 visualizes Bunkerworld Benchmark Prices (BBP), which are daily benchmark prices of 380 centistokes intermediate fuel oil (IFO380) with maximum sulphur content of 4.5 % from last three years in four major ports: in Singapore representing South East Asia, in Rotterdam representing North &

West Europe, in Fujairah representing Middle East and in Houston representing US Gulf & Caribbean. Prices are quoted in US$ per mt as delivered on board basis so those include barge transport and/or ex-pipe fees (Bunkerworld 2012a). For comparison Figure 6 visualizes price differences between IFO380 BBP as above and Rotterdam's MGO BBP with maximum 1.5 % sulphur in fuel.

Figure 5. Bunkerworld Benchmark Prices for IFO380 in $/mt from Singapore, Rotterdam, Fujairah and Houston between 1.10.2009-1.10.2012 (Bunkerworld 2012a).

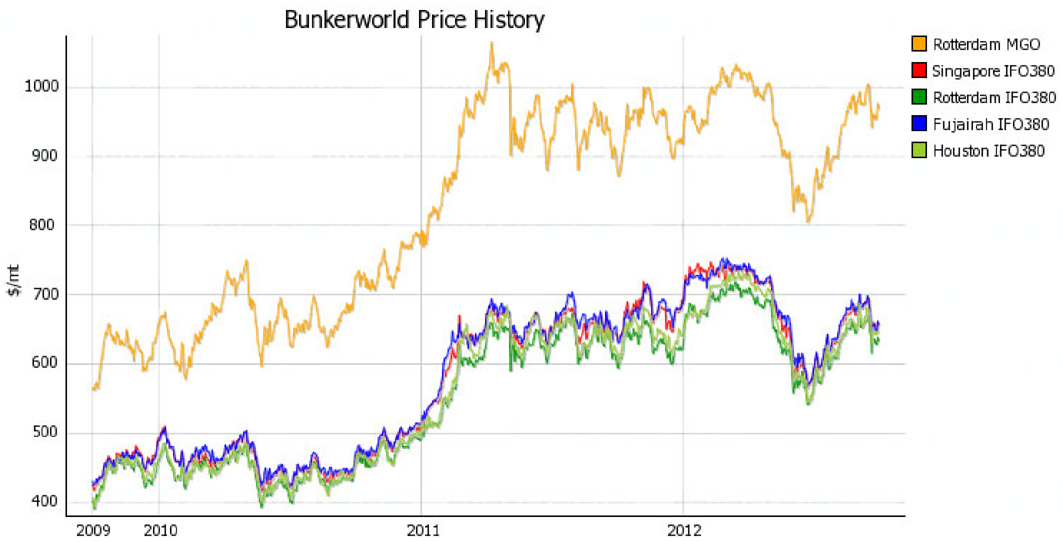


Figure 6. Bunkerworld Benchmark Prices for IFO380 in $/mt from Singapore, Rotterdam, Fujairah and Houston and MGO from Rotterdam between 1.10.2009-1.10.2012 (Bunkerworld 2012a).

As can seen in Figures 5 and 6, the prices follows peak and curves quite simultaneously but according to Bunkerworld data the IFO 380 prices are higher in the East than in the Western parts of the world. The premium for low sulphur distillate (MGO) price has globally been 40-50 % over residual fuel and is likely to remain that way. This can be noticed also from Table 6. Therefore, the difference in price between MDO/MGO and HFO makes the scrubber choice more price competitive in certain circumstances and not economically viable in others. The sulphur limits set out in Annex VI can have far-reaching implications for the shipping and oil industry as they will affect on bunker fuel costs and quality, to the future of residual fuel, to oil refineries, as well as to technologies such as exhaust cleaning systems and alternative fuels. Even the low sulphur content levels in MDO and MGO are relatively low and the upcoming ECA sulphur limits can be fulfilled, depending on the technology used for the diesel engines and the areas where the ship is operating, they might still need some NO_X abatement by using SCRs (SOCP 2011,16; UNCTAD 2011, 26). For comparison, more Bunkerworld Benchmark Prices for different fuel oils in ports listed above can be found from Appendix 3.

2.2 Marine Exhaust Gas Emissions

Public opinion and media’s assertion about air pollution might lead to think that the term air pollution has been adopted and indentified in the second half of the 20th century. However, the fact is that the air pollution has been known in larger cities at least from the 14th century when the use of the coal became a general method for heating houses. Although, the kind of air pollution which human beings have been exposed has changed with time (Schenelle & Brown 2002, chapter 1: 1). Since the industrialization period, pollutions became more popular topic after World War II when aftermath of atomic warfare and testing made evident the perils of radioactive fallout. After that a conventional catastrophic event The Great Smog of 1952 in London caused premature death of an estimated 12,000 people and illness to many others. This massive event prompted some of the first modern environmental legislation the Clean Air Act in 1956 (Surhone & all 2010, 6).

Sources of air pollution can be either man-made or natural. Man-made sources are the ones which should be focused on as there is a possibility to achieve some control to these sources. Both gaseous and particulate sources are troublesome (Schenelle & Brown 2002, chapter 1: 8). Air pollution can be a local, regional and transboundary problem caused by the emission of specific pollutants, which either directly or through chemical reactions lead to negative impacts (European Environment Agency 2011, 11-12).

The emissions in a term of air pollution can affect the following subjects by the following means:

1. Effects on human health which can be caused by exposure of air pollutants or intake of pollutants transported through the air, deposited and accumulated in the food chain.
2. Eutrophication in ecosystems on land and in water, which can lead to yield losses and damage affecting agricultural crops, forests and other plants due to exposure to ground-level ozone as well as to changes in species diversity.
3. Acidification of ecosystems by means of both aquatic and terrestrial, which can lead to loss of fauna and flora.
4. Impacts of persistent organic pollutants and heavy metals on ecosystems, due to bioaccumulation and due to their environmental toxicity.
5. Decreasing of atmospheric visibility.
6. Increasing effects and phenomenon on climate forcing.
7. Damage to materials and cultural heritage due exposure to acidifying pollutants, ozone and soiling (European Environment Agency 2011, 11-12).

The exhaust gas from the ship's diesel engine(s) mainly consist of nitrogen, oxygen and combustion products like carbon dioxide (CO_2), water vapour and minor quantities of carbon monoxide (CO), nitrogen oxides (NO_X), sulphur oxides (SO_X), partially reacted and non-combusted hydrocarbons (HC), chlorofluorocarbons (CFCs), volatile organic compounds (VOC) and particulate matter (PM). In some contexts the PM emissions are divided to particulate organic matter (POM) and black carbon (BC) emissions. Most of these combustion product emissions are categorized as air pollutions, released as chemicals and particles into the atmosphere. Some of these shipping related emissions and their impacts are presented in Figure 7. Once emitted these airborne emissions can travel considerable distances so the shipping emissions also affects on land air quality. In addition, the emissions released during ship's port stays can be substantial contributor to the local land air quality (Surhone & all 2010, 7; Wahlström & all 2006, 7; Wärtsilä Ship power technology 2011, 113).

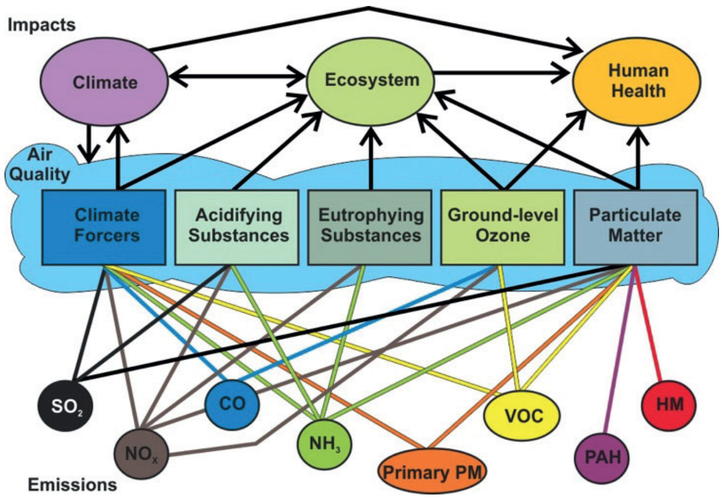


Figure 7. Major air pollutants clustered according to impacts on human health, ecosystems and the climate (European Environment Agency 2011).

The exhaust gas emissions and particles from shipping contribute significantly to the total emissions from the transportation sector and thereby the shipping is affecting the chemical composition of the atmosphere, climate and regional air quality and health. Some impacts are dependent upon latitude and upon whether emissions occur in coastal areas or in the open oceans (Eyring & all 2009, 1-30). Nearly 70 % of ship emissions occur within 400 km of land and therefore ships have the potential to contribute significant pollution in coastal communities especially with SO_X emissions (Corbett & all 2007, 1). Some shipping related air pollution effects to the health, environmental and climate have been summarized in Table 6.

Table 6. Typical effects of air pollutants from marine exhaust gas on human health, environment and climate (European Environment Agency 2011, 3).

	Health effects	Environmental effects	Climate effects
Nitrogen oxides (NO_X)	NO_2 can affect the liver, lung, spleen and blood. It can aggravate lung diseases leading to respiratory symptoms and increased susceptibility to respiratory infection.	NO_X contributes to the acidification and eutrophication of soil and water, leading to changes in species diversity. Those enhance sensitivity to secondary stress (such as drought) on vegetation. Acts as a precursor of ozone and, particulate matter, with associated environmental effects. Those may form nitric acid and damage buildings by surface recession.	NO_X contributes to the formation of ozone and particulate matter, with associated climate effects.
Sulphur oxides (SO_X)	SO_X aggravates asthma and can reduce lung function and inflame the respiratory tract. Those can cause headache, general discomfort and anxiety.	SO_X contribute to the acidification of soil and surface water. Those contribute indirectly to the transformation of mercury to the bioaccumulative methyl-mercury, which is toxic. SO_X causes injury to vegetation and local species losses in aquatic and terrestrial systems. Those also contribute to the formation of inorganic particulate matter with associated environmental effects and those can Damage building materials.	SO_X contribute to the formation of sulphate particles, cooling the atmosphere.
Particulate matter (PM)	PM can cause or aggravate cardiovascular and lung diseases (e.g. reduced lung function, asthma attacks, chronic bronchitis, susceptibility to respiratory infections), heart attacks and arrhythmias. PM can also affect the central nervous system, the reproductive system and cause cancer. The outcome may be premature death.	PM can affect animals in the same way as humans. Those also affects plant growth and ecosystem processes. PM can cause damages and soiling of buildings, including monuments and objects of cultural heritage. PM can also reduce visibility.	PM originated climate effects varies depending on particle size and composition: some are reflective and lead to net cooling, while others absorb solar radiation leading to warming. PM emissions can lead to changed rainfall patterns. PM deposition can lead to changes in surface albedo.

2.2.1 Exhaust Gas Composition

In diesel engines, chemical energy of the fuel oil is converted into mechanical power in process, where it is injected under high pressure into the cylinder, where it evaporates and mixes with air and combustion process occurs. This process produces mechanical power, heat and exhaust gases. Diesel exhaust constitutes of gases, vapours, aerosols and particles and properties depend on the combustion conditions process itself and the fuel oil in use (Wahlström & all 2006, 27; Wärtsilä Ship power technology 2011, 113).

HFO, like other fuel oils, contains different impurities, which convert into air pollutants as a result of the combustion process. The major pollutants in exhaust gases are a direct result of the diesel combustion process itself produced by the ship's main and auxiliary engines. The gases consist of fully and partly combusted fuel elements and side products from the combustion process and components are either gaseous, particle or liquid type of substances and compounds. The distribution of the components changes when pressure and especially combustion temperature decreases (Wärtsilä Ship power technology 2011, 113).

In the diesel exhaust gas, the nitrogen and the oxygen are the main components, because those are present also intake air, from which only the oxygen takes a part in the combustion process. The main combustion products are CO_2 and water. Secondary combustion products are CO, hydrocarbons, NO_X, SO_X, soot and PM. Emissions of CO and hydrocarbons are low in a diesel engine compared to other internal combustion engines because of the high air/fuel ratio in the combustion process. The air excess allows an almost complete combustion of the HC and oxidation of the CO to CO_2 so therefore their quantities in the exhaust gas stream are very low (Wärtsilä Ship power technology 2011, 113). Major combustion related the components and the emissions in marine diesel engines are shown in Table 7. From those, only NO_X, SO_X, PM, smoke, BC and CO_2 emissions are studied further in this paper. The nitrogen oxides and the sulphur oxides are emissions with effect on the human health and with standing or upcoming emission regulations. NO_X regulations will have also a great impact to ship's engine technologies and also to the exhaust gas treatment systems as the SCR might be needed in order to meet upcoming NO_X regulations. The carbon dioxide is most crucial greenhouse gas and it is also facing upcoming regulations. Particulate matter emissions are also health risks but not yet regulated by any rules in shipping. Those are still very crucial to shipping segment and diesel engine industry along with smoke and black carbon emissions, as these might face upcoming regulation in the future. The scrubbers are designed to SO_X reduction but those can have effect on PM, smoke and BC emissions as well.

Table 7. Typical diesel engine's exhaust gas composition (CIMAC 2008, 2).

Component		**Typical component concentration range in diesel exhaust gas (vol-%)**	**Component concentration in natural dry ambient air (vol-%)**
Nitrogen	N_2	75-77	78.08
Oxygen	O_2	11.5-15.5	20.95
Carbon dioxide	CO_2	4.0-6.5	0.039 [1]
Water	H_2O	4.0-6.0	
Argon	Ar	0.8	0.934
Totally		> 99.7	
Additional components found in diesel exhaust typical concentration range (steady state, high load, residual and distillate fuel oils)			
Nitrogen oxides	NO_X	0.10-0.15	
Sulphur oxides	SO_X	0.003-0.09	
Carbon monoxide	CO	0.002-0.015	
Total Hydrocarbons	THC (as CH_4)	0.002-0.010	
Volatile org.comp.	VOC (as CH_4)	0,.002-0.010	
Particulates [2]	PM	0.002-0.010 mg/Nm3, dry, 15 % O_2: Fuel composition related	
Smoke	Related to low load (< 50 % load), start-up and fast load increase		
1) Earth System Research Laboratory 2013 2) Measurement method: ISO 9096 or other principally similar method			

2.2.2 Nitrogen Oxides, NO_X

The combustion process gives secondary products as Nitrogen oxides (NO, NO_2, N_2O_2, etc.). At high combustion temperature the nitrogen, usually inert, reacts with oxygen to form Nitric oxide (NO) and Nitrogen dioxide (NO_2), which are usually grouped together as NO_X emissions. Their amount is strictly related to the combustion temperature, especially when the combustion process contains high peak temperatures, which exists especially in the diesel process.

The main nitrogen source is the combustion air but the NO_X formation process is extremely complex including hundreds of different chemical reactions. Some NO can also be formed through oxidation of the nitrogen in fuel and through chemical reactions with fuel radicals. The NO in the exhaust gas flow is in a high temperature and in high oxygen concentration environment so it can rapidly oxidize to NO_2. Total NO_X emissions contain approximately 5 % NO_2 emissions (European Environment Agency 2011, 39; CIMAC 2008, 2; Patterson & Springer 1973, 6; Wärtsilä Ship power technology 2011, 113).

The NO_X emission effects on the health, environmental and climate can be found from Table 6. The NO is a colourless gas and it oxidizes fast to toxic NO_2, which is a reddish-brown gas (gas form) and yellow-brown when it starts to condensate. NO_X-mass emissions are usually represented in mg/Nm^3, g/kWh, etc. and those are calculated as NO_2 (i.e. 100 % of NO_X is calculated as NO_2) (CIMAC 2008, 2).

It should be noticed that some exhaust gas after-treatment systems might have negative impact to the NO_X emissions. According to European Environment Agency, there are clear indications that for traffic emissions the direct NO_2 fraction are increasing significantly due to increased penetration of diesel vehicles, especially with newer diesel vehicles fulfilling European Emission Standards Euro 4 and 5. Such vehicles can emit up to 50 % of their NO_X as NO_2 because their exhaust after-treatment systems for the carbon monoxide, hydrocarbons and particulate matter increases the direct NO_2 emissions (European Environment Agency 2011, 9, 40-44).

2.2.3 Sulphur Oxides, SO_X

Sulphur dioxide (SO_2) is emitted when fuels containing sulphur are burned as the sulphur oxides are direct result of the sulphur content of the fuel oil. It is a colourless, non-combustible and toxic gas. Its emission effects on the health, environmental and climate are explained in Table 6. Gaseous sulphur dioxide is readily soluble in water and its solubility increases as the partial pressure increases and the temperature drops (European Environment Agency 2011, 48; Hasenberg 2008, 6-7).

Sulphur dioxide emissions are released into the atmosphere by motor vehicles' (car, trucks, ships, locomotives and other non-road equipment) exhaust gases (from all combustion engines), by burning fossil fuels, by smelting and roasting ores, by refining crude oil, by bleaching processes, during papermaking and glass production, by fumigation of ships with sulphur, during extermination of insects and by many other processes. Also volcanic gases contain sulphur dioxide as well as many other components. The annual amount of sulphur dioxide from all the active volcanoes is estimated to be about 10^7 t. This amount introduced into the environment by volcanoes is still estimated to be lower than that origin from air pollution (EPA 2012c; Hasenberg 2008, 10).

During the combustion process, the fuel bound sulphur is rapidly oxidized to SO_2. Also a small fraction of SO_2 may be further oxidized to sulphur trioxide (SO_3) (Wärtsilä Italia S.p.A. 2010, 119). The SO_2 emissions introduced by shipping are oxidized to sulphate primarily in the aqueous phase, meaning in cloud droplets and sea-salt particles, by hydrogen peroxide (H_2O_2) and ozone (R29-R34), and in the gas phase by the OH radical (R28). Still the largest impact of shipping on sulphate chemistry is through the direct emissions of SO_2 (Eyring & all 2009, 12). The processes from SO_2 emissions to acidic depositions are illustrated in Figure 8.

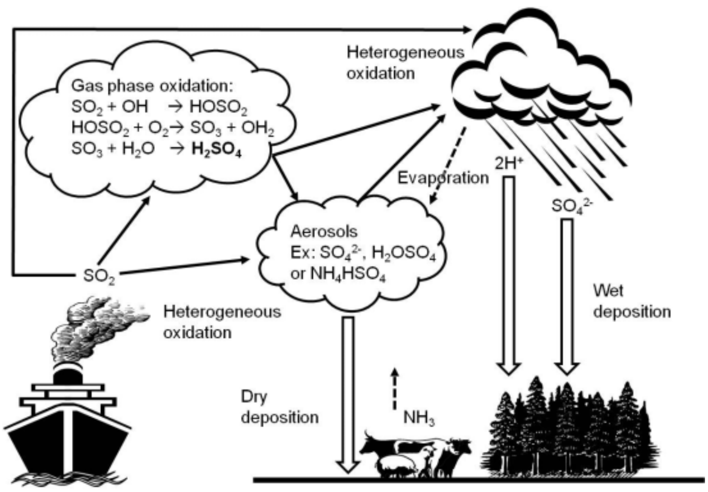


Figure 8. Illustration of sulphur emission, transportation and deposition.

It is stated that SO_2 has a dual impact as it forms aerosols, which reflect sunlight and have a direct cooling effect. These aerosols may serve as nuclei for the condensation of water vapour, which can cause the formation of so called “ship tracks”, which are low clouds that can be observed in busy sea routes. These low clouds also reflect sunlight and thus reduces global warming (CE Delft & all 2006, 187).

2.2.4 Particulate Matter, PM

Particulate matter is the general term used for a mixture of aerosol particles with a wide range in size and chemical composition. The particulate matter can occur in either a liquid or solid form (European Environment Agency 2011, 18; Patterson & Springer 1973, 6). Particles are frequently described by their diameter. Large or coarse particles are well above 10 microns. For comparison the diameter of a human hair is approximately 50 to 110 microns. Fine particles are less than one 2.5 micron, or submicron. Marking $PM_{2.5}$ refers to fine particles with a diameter of 2.5 micrometres or less. Smoke and fumes are included to this size range. “Lung damaging dust” ranges are considered to be those between 0.7 to 7.0 microns. The other PM effects on the health, environmental and climate are explained in Table 6 and later in this chapter (European Environment Agency 2011, 18; Schenelle & Brown 2002, chapter 19: 1).

The amount of the particulates in a given diameter is very informative but one should pay attention to the number distribution and the mass distribution. Table 8 illustrates the particle distinction. In Table 8, first 100,000 particles have one (1) micron diameter and as each particle have a unit mass of one (1) it gives a total mass of 10^5 (100,000). When adding 1,000 particles with a diameter of 10 microns plus 10 particles with a diameter (d_j) of 100 microns, a size distribution can be calculated for one (1), 10, and 100 micron particles. Thus there are 101,010 particles of which 99 % are one (1) micron in diameter. Since the mass of each particle varies with the cube of the diameter and because of the volume, the mass of one-micron particles is only 9 % of the total mass of all particles.

This is why size distributions are commonly expressed in terms of the mass distribution (Schenelle & Brown 2002, chapter 19: 1).

Table 8. Number fraction vs. mass fraction (Schenelle & Brown 2002, chapter 19: 1).

d_j (µm)	Number	Number fraction	Mass of particle	Total mass	Mass fraction
1	100 000	0.990000	1	10^5	0.009
10	1 000	0.009900	1000	10^6	0.090
100	10	0.000099	10^6	10^7	0.900
TOTAL	**101 010**	**1.0**		**1.11 x 10^7**	**1.0**

There are also different terms used to describe particulate matter according to its size:

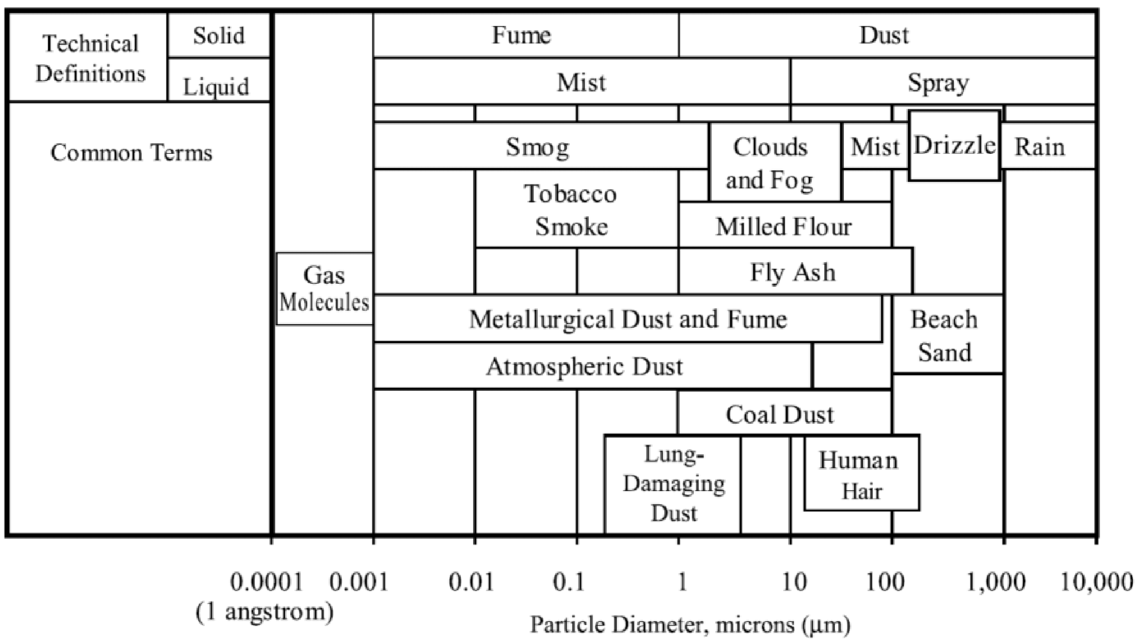


Figure 9. Common particulate terms and size ranges (Schenelle & Brown 2002, chapter 19: 2).

The amount of formed particulate matter depends on measurement method and fuel quality with presents of current cooling conditions: temperature, cooling rate, residence time in the conditioning, etc. There are two fundamentally different standard procedures used for the particulate matter measurement.

One is ISO 8178 in where the particles are collected after dilution in air, which promotes particle growth by condensation. Second is ISO 9096 where the particles are collected on a hot filter in order to avoid condensed matter. Exhaust gas particulate matter composition of residual fuel operation can be summarized as simplified by following fractions:

$$PM = Soot + SOF + IF \tag{1}$$

In the Equation (1) Soluble Organic Fraction (SOF) refers to organic material and IF (Inorganic Fraction) to volatile, semi-volatile and non-volatile compounds like water, metals, sulphates and nitrates (CIMAC 2008, 17; IMO 2007, 12).

PM is either directly emitted as primary particles or formed in the atmosphere from transformation and oxidation of primary gaseous emissions. Particles which are formed from condensed material are called as secondary particles. The most important originator for secondary particles are for example nitrogen oxides, sulphur dioxide, ammonia and VOC. PM is either of natural origin (e.g. sea salt, naturally suspended dust, pollen, volcanic ash) or from anthropogenic sources, mainly from fuel combustion in e.g. thermal power generation, incineration, households for domestic heating and vehicles. In cities vehicle exhaust, road dust re-suspension, and burning of wood, fuel or coal for domestic heating are important local sources (European Environment Agency 2011, 18).

In diesel process, the liquid particles are formed mainly at low load where the ignition in very lean mixtures has failed to occur. In the diesel engine's exhaust gas, the particulate fraction represents a complex mixture of inorganic and organic substances, which are mainly fuel oil ash (together with sulphates and associated water), comprising soot (elemental carbon), nitrates, carbonates and varieties of non- or partially combusted hydrocarbon components of the fuel oil and lubricating oil (Patterson & Springer 1973, 6; Wärtsilä Ship power technology 2011, 113).

In Figure 10 there are shown two examples of typical exhaust particulate composition at high engine loads presented originally by CIMAC (2010) and measured with ISO 8178 measurement method. As can be noticed from Figure 10, also with distillate fuel, the formation of ash is at same level than with residual fuel. With distillate fuel, the soot formation (60 %) is six times higher than with residual fuel (10 %). According to CIMAC, also NO_X -reducing techniques, like SCRs, tend to increase particle formation (CIMAC 2010, 3).

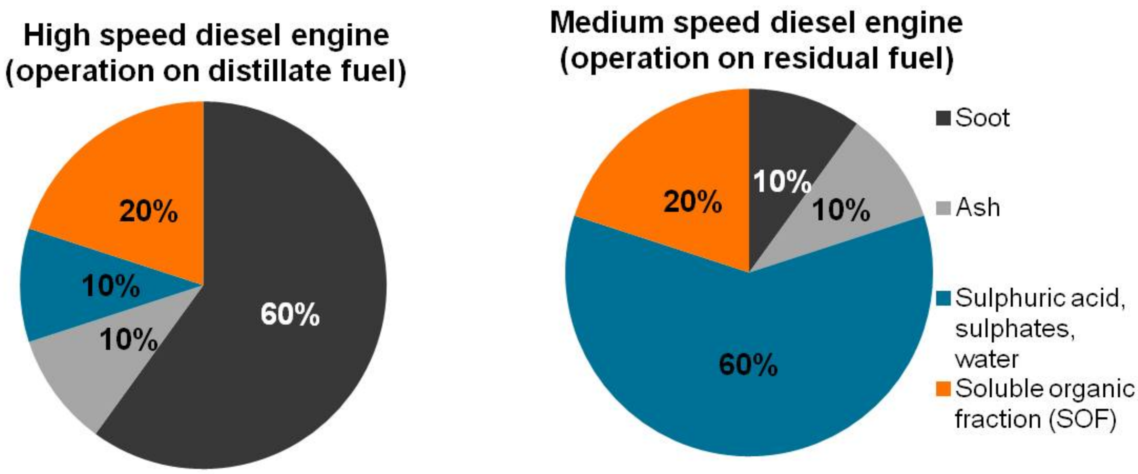


Figure 10. Example of typical exhaust particulate composition at high engine loads with ISO 8178 measurement method (CIMAC 2008, 29).

In 2007, Corbett & all studied the health effects from shipping-related PM emissions and their results indicated that those contributes approximately 60,000 deaths annually at a global scale, with impacts concentrated especially on major trade routes in coastal regions. Most of these mortality effects were seen in Asia and Europe where high populations and high shipping-related PM concentrations occurs. Their work also suggested that health and mortality benefits in multiple regions globally could be realized from policy action to mitigate ship emissions of primary $PM_{2.5}$ formed by engine combustion and secondary $PM_{2.5}$ aerosols formed from gaseous exhaust pollutants (Corbett & all 2007, 6).

2.2.5 Smoke

The correlations between particulate emissions and smoke is not fixed even the smoke is usually the visible indication of particulates in the exhaust gas. The lighter and more volatile hydrocarbons are not visible nor will the particulates emitted from a well maintained and operated diesel engine (Wärtsilä Ship power technology 2011, 113).

Smoke is always visible and it can be black, blue, white, yellow or brown in appearance. Black smoke mainly originates from comprised of carbon particulates (soot). Blue smoke indicates the presence of the incomplete combustion of the fuel oil or lubricating oil in fuel oil. White smoke originates usually condensed water vapour. Yellow smoke originates from NO_X emissions. Brown appearance may occur because of the condensed NO_2 component when the exhaust gas is cooled significantly before discharging to the atmosphere (CIMAC 2008, 17; Wärtsilä Ship power technology 2011, 113).

2.2.6 Black Carbon, BC

In addition to PM emissions, large diesel engines also emit black carbons and aerosols into the atmosphere. This black carbon originates from incomplete combustion and sources include both natural and anthropogenic sources. In combustion engines, BC is usually formed in conditions were insufficient amount of oxygen is present for complete oxidation of carbonaceous fuel to CO_2 (fuel-rich). These fuel-rich zones may exist when flame reactions are limited by mixing of fuel and air, so that all diffusion flames offer the possibility of soot formation (Bond & all, 12; CIMAC 2012, 19).

Atmospheric BC and surface deposition is considered to contribute positively to global warming and also causing accelerated melting of ice and snow especially in the Arctic regions. IMO (2011a) has predicted that the BC emissions in the Arctic regions may increase from 0.88 kilo tones (kt) per year in 2004 to between 2.7-4.7 kt per year by 2050 depending on World trade development and future use of Arctic sea routes. However, it is also predicted that aerosols and BC emitted in the exhaust of large HFO burning engines may offset atmospheric heating effect on some degree (CIMAC 2012, 2; IMO 2011a, 3).

It is estimated that approximately 40 % of the BC emissions originates from open biomass burning and a similar proportion (~40 %) is from fossil fuel burning when the remaining 20 % may originate from bio fuels (CIMAC 2012, 19). Estimations of BC emissions origin from the international commercial shipping industry are about 1-2 % of global total BC emissions. However, ships still emit more BC, as well as PM per unit of fuel consumed than other fossil fuel combustion sources due to the quality of fuel used i.e. HFO (Lack & all 2012, 6). According to IMO (2011a), there have been a multitude of recent submissions that refer to BC emissions from ships and their impacts on the environment and public health. Norway, Sweden and USA discussed in Submission MEPC 60/4/24 about impacts of BC emissions from shipping on the Arctic climate, its significance and different approaches to reduce those emissions. In addition, the European Parliament passed a resolution on 20th January 2011 where was stated that “the rapid warming of the Arctic makes it necessary, in addition, to work on possible further short-term measures to limit Arctic warming” (IMO 2011a, 2-3).

2.2.7 Carbon Dioxide, CO_2

Even shipping emits various greenhouse gases, it is commonly stated the most important is CO_2. Different estimates that CO_2 emissions from maritime transport account for 1.8 % to 3.5 % of global emissions, depending on the method of calculating emissions. In 2009, IMO estimated in Second IMO GHG Study that in 2007 international shipping emitted 870 million tonnes or about 2.7 % of the global man-made emissions of CO_2. Furthermore, greenhouse gas emissions from sea shipping are constantly rising (CE Delft & all 2006, 181; IMO 2012a). Future scenarios indicate that CO_2 emissions from ships will more than double by 2050 (Det Norske Veritas 2010, 4). As can be seen from Figure 11 when transporting goods shipping has the lowest emitted grams of CO_2 per 1 ton goods per 1 km but the as the volumes are large and the global world trade is heavily relying to shipping it still rises the CO_2 emissions to current level.

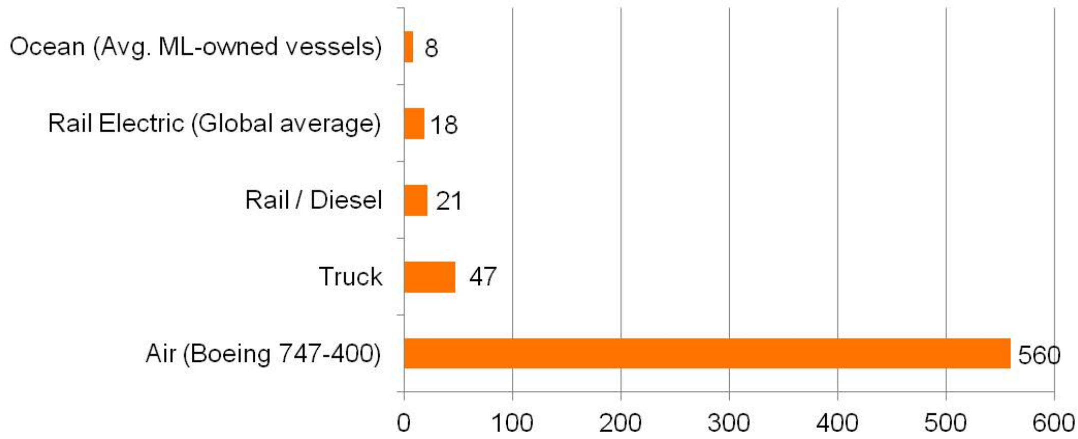


Figure 11. Grams of CO_2 emitted per 1 ton goods per 1 km (Based on data from the Network for Transport and Environment, Sweden).

IMO is currently working to establish GHG regulations for international shipping, with a coordination of stakeholders such as the European Union (EU) and United Nations Framework Convention on Climate Change (UNFCCC), to implement regulations for reduction of GHG emissions through technical and operational measures. The Second IMO GHG Study 2009 estimate that, if implemented, these measures could increase efficiency and reduce the emissions rate by 25 % to 75 % below the current level.

2.3 Environmental Regulations

International shipping along with other Marine activities is regulated by a mixture of the international law of the sea and the law of a particular State. The United Nations Convention on the Law of the Sea (UNCLOS) is the cornerstone of international maritime law and it endorses the right of any sovereign State to have a ship register and thus become a flag State, and it provides ships with the right to innocent passage through territorial waters and economic zones (IMO 2009c, 18).

However, the increasing concern over the air pollution has resulted in the introduction of exhaust emission control and regulation to the Marine activities and industry. Emissions from international shipping are increasingly considered in proposed regulation in local, national, and international sectors. In order to avoid the growth of uncoordinated regulations, different societies like IMO, EU, governments and national stakeholders have implemented rules and regulations of different emission reduction in marine sector. Still in many areas regulatory deliberations have not been fully informed, as the extent of shipping emissions health impacts has been unknown (Corbett & all 2007, 1; Wärtsilä Ship power technology 2011, 114).

In this thesis the focus is on SO_X regulations but also regulations for NO_X are discussed because the future engines have to fulfil also their requirements and some NO_X-related exhaust gas treatment equipment might be needed if operating with fuel oils. Also some other regulations are discussed as they can have affect on scrubber installations.

2.3.1 International Convention on the Prevention of Pollution from Ships

The International Maritime Organization is an agency of the United Nations, which has been formed to promote maritime safety. The agency was originally established to provide machinery for cooperation among Governments in the field of governmental practices relating and regulation to technical matters of all kinds affecting shipping engaged in international trade; to facilitate and encourage the general adoption of the highest practicable standards in matters concerning maritime safety, efficiency of navigation as well as prevention and control of marine pollution from ships (IMO 2009c, 18; Wärtsilä Ship power technology 2010, 1).

IMO ship pollution rules are contained in the International Convention on the Prevention of Pollution from Ships, which represents the first set of regulations on marine exhaust emissions. This is known as MARPOL 73/78 and it is the most important international marine environmental convention. The convention is designed to minimise pollution of the seas, including dumping, and oil and exhaust pollution. On 17th February 1973, the original MARPOL Convention was signed but did not come into force. The current Convention is a combination of 1973 Convention and the 1978 Protocol and it entered into force on 2nd October 1983. The MARPOL contains six (6) annexes from of which

Annex VI concerns the Air Pollution. The MARPOL 73/78 Annex VI entered into force on 19th May 2005 setting limits on Nitrogen Oxides, Sulphur Oxides and Volatile Organic Compounds emissions from ship exhausts and prohibits deliberate emissions of ozone depleting substances (Eyring & all 2009, 2; Wärtsilä Ship power technology 2010, 1; Wärtsilä Ship power technology 2011, 114).

2.3.2 IMO NO_X Regulation 13

In MARPOL Annex VI the emissions of NO_X are addressed in regulation 13 with IMO Tier standards I-III. IMO has declared the goal of a 30 % NO_X reduction from internationally operating ships. Since the 1st January 2000, all new marine diesel engines for new ships had to comply with Tier I regulation introducing a NO_X limiting curve in Annex VI, which depends on engine speed (Eyring & all 2009, 2; IMO 2009c, 39).

IMO Tier II standard for new marine engine applications came into force in January 2011. The NO_X limit reduction from IMO Tier I level is in the range of 15 % for low speed engines (2-stroke) and up to 20 % for medium speed engines (4-stroke). This reduction was reached mainly by engine optimization. Future IMO Tier III standard for new engines will come into force in 2016 but it will be applied only in designated Emission Control Areas, see Figures 12-14. The areas where IMO Tier III will be applied are for instance the Baltic Sea, the North Sea, as well as the US and Canada coastal waters. IMO Tier II NO_X level will apply outside the designated ECAs. IMO Tier III standard will introduce a remarkable reduction on the cycle average NO_X emission limit equal to 80 % from the IMO Tier I level. This reduction can be reached by applying a secondary exhaust gas emission control system. At moment SCR and EGR are the only efficient ways to reach the NO_X reduction of needed 80 % with marine diesel engines (IMO 2009c, 39; Lloyd's Register 2012, 32-37; Wärtsilä 2010a, 1; Wärtsilä Ship power technology 2010, 3).

2.3.3 IMO's SO_X Regulation 14

SO_X emissions of are addressed in regulation 14 of MARPOL Annex VI, which have been limiting sulphur emissions globally at 3.5 % m/m and less in ECAs, which are in some extend discussed as SO_X Emission Control Areas (SECAs). In ECA areas, the sulphur content of fuel oil used on board ships must not exceed 1.0 % m/m. At the moment there are three ECAs in operation. These are:

1. The Baltic Sea ECA, in force since 19.5.2006
2. The North Sea ECA, in force since 22.10.2007
3. North-America ECA, in force since 1.8.2012

Also English Channel is listed as an ECA as can seen from Figure 12.

Figure 12. European ECA areas.

As an alternative, an exhaust gas cleaning system, like the scrubber(s) can be applied to reduce the total emission of sulphur oxides from ships, including both auxiliary and main propulsion engines, to 6.0 g/kWh or less calculated as the total weight of sulphur dioxide emissions (IMO 2008, 19-20; IMO 2009c, 41; Wärtsilä Ship power technology 2011, 116).

When the Annex VI entered into force in May 2005, it set global sulphur limit to 4.5 % m/m. The limit in ECA areas was originally 1.5 % m/m. In IMO MEPC 12 meeting in April 2008 proposals for new sulphur limits were agreed. Proposals for global limits were 3.5 % m/m on and after 1st January 2012 and 0.5 % m/m on and after 1st January 2020. Proposals for ECA limits were 1.0 % m/m on and after 1st July 2010 and 0.1 % m/m on and after 1 January 2015 along with the global sulphur limit of 0.5 % m/m. In October 2008, the final adoption of these proposed sulphur limits was taken by IMO/MEPC 58 although a review of the 0.5 % S global limit will be performed in 2018. The introduction of the limit will be postponed to 2025 in case readiness is not deemed to be sufficient by 2020 (Eyring & all 2009, 2; IMO 2008, 19-20, Wärtsilä Ship power technology 2011, 116).

On 26th March 2010, the IMO amended the MARPOL designating specific portions of U.S., Canadian and French waters as an ECA. France joined as a co-proposer in July 2009 on behalf of its island territories of Saint-Pierre and Miquelon, which form an archipelago off the coast of Newfoundland. Allowing for the lead time associated with the IMO process, the North American ECA became enforceable on 1st of August 2012. The area of the North American ECA includes waters adjacent to the Pacific coast, the Atlantic/Gulf coast and the eight main Hawaiian Islands including. It extends up to 200 nautical miles from coasts of the United States, Canada and the French territories as can seen from Figure 13. As an exception, this ECA does not extend into marine areas subject to the sovereignty or jurisdiction of other States (IMO 2012c).

In July 2011, a fourth area, the United States Caribbean Sea ECA, was adopted designated under MARPOL amendments. It will come in force on 1st January 2014 covering certain waters adjacent to the coasts of Puerto Rico and the United States Virgin Islands (IMO 2012c). The area is presented in Figure 14.

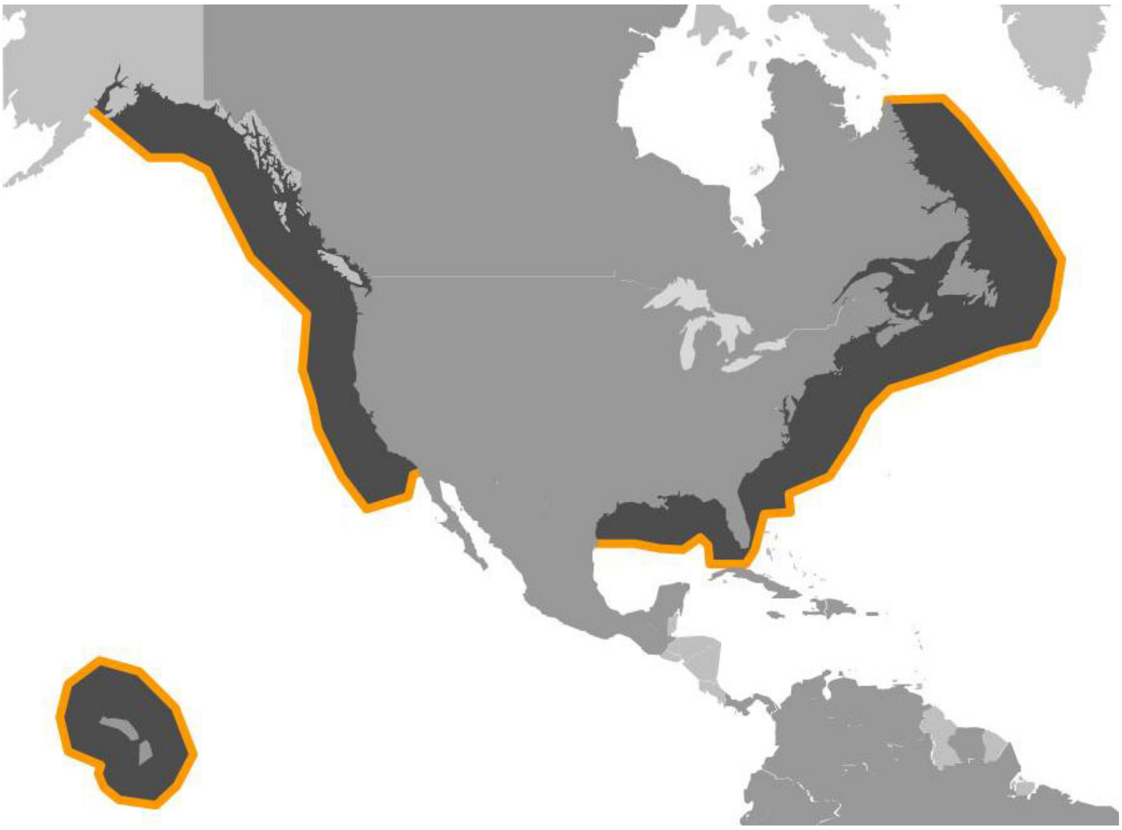


Figure 13. North-America ECA areas.

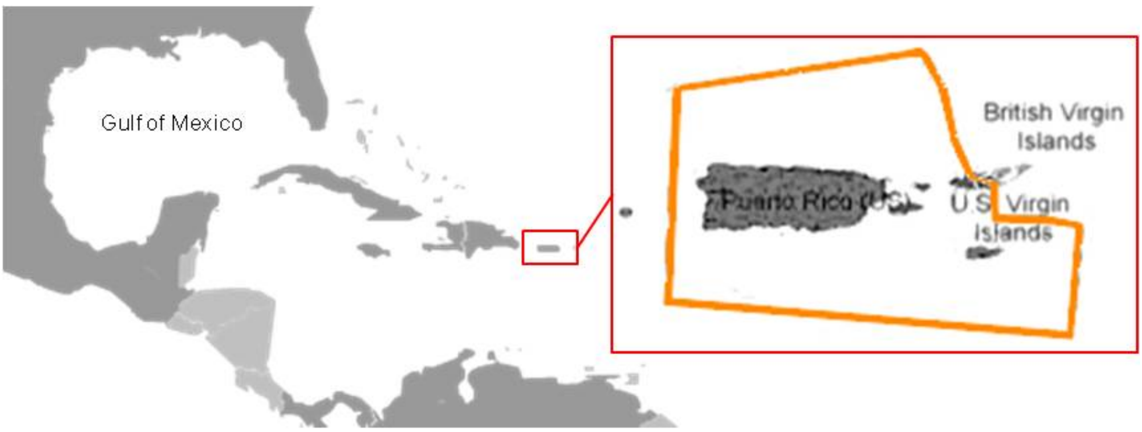


Figure 14. United States Caribbean Sea ECA areas.

2.3.4 EU SO_X Regulation

As the pollution has increased in harbour cities, also the EU has set directives currently regulating ambient air concentrations of main pollutants, which are designed to avoid, prevent or reduce harmful effects of air pollutants on human health and the environment. Directives 1999/32/EC and 2005/33/EC sets reductions to sulphur dioxide emissions when HFO and MGO are used in seagoing ships (European Environment Agency 2011, 16; Eyring & all 2009, 2).

Since 1st January 2010, the sulphur content has been limited to 0.1 % m/m in marine fuels used by ships on inland waterways and around EU ports. Also sulphur content of MDO sold in the European Union has been set to 1.5 % m/m and the limit for MGOs sold in the European Union is 0.1 % m/m. Because of these directives, the sulphur emissions cannot exceed the level of 0.1 % for ships berthed in EU ports for more than two hours or ships moving in its inland waterways. However, ships are still allowed to use an approved emission abatement technology, like the exhaust gas scrubbers, if those continuously achieve emission reductions, which are at least equivalent and possible waste streams discharged into enclosed ports and estuaries have no impact on ecosystems (European Union 2007; Lloyd's Register 2012, 48).

2.3.5 EPA Emission Standards

United States Environmental Protection Agency (EPA) has set specific emission standards for Marine diesel engines installed on ships flagged or registered in the United States. The main focuses in these are the certification and compliance with the standards, emission limits and technology involved. EPA Tier 2 and 3 emission standards are for Category 3 Marine engines covering engines with cylinder displacement exceeding 30 litres/ cylinder in US Flagged Ships. For those, the final rulemaking text published in December 2009. Standards sets limits on NO_X and fuel sulphur content including implementation dates, which are consistent with those adopted by IMO meaning that NO_X limits are similar to IMO Tier II (since 2011) and Tier III (since 2016), and the fuel sulphur limits of 1.0 % (since August 2012) and 0.1 % (since 2015) are also set by EPA. It also designates coastal areas of USA and Canada as an ECA since August 2012. Limits are also set for HC (2 g/kWh) and CO (5 g/kWh). According to standards, PM measurement is required at certification but without any limit although reporting to EPA is required (EPA 2012a).

There are also specified EPA Tier standards for Category 2 engines with cylinder displacement below 30 litres/ cylinder in US Flagged Ships. These are:

- Tier 2 with implementation date in 2004-2007, which set limits for combined HC + NO_X, PM and CO in g/kWh.
- Tier 3 with implementation date in 2013-2014, which sets limits for combined NO_X + THC and particles.
- Tier 4 with implementation date in 2014-2017, which will limit NO_X, THC and PM.

All the standards for all marine engines nominate FGD (exhaust gas scrubbers) as an alternative to low sulphur fuel (EPA 2012a; Lloyd's Register 2012, 49).

In Alaska USA there are smoke limits set by United States Environmental Protection Agency within three miles of the coastline in where visible emissions, excluding condensed water vapour, may not reduce the visibility through the exhaust effluent of a marine ship by more than 20 % but with few exceptions (EPA 2012b).

2.3.6 Differentiated Fairway and Harbour Fees

In Sweden there is a sulphur tax, which is an excise duty paid on the sulphur content of many fuels. It is administered by the Swedish Tax Agency covering petrol, oil, LPG, natural gas, coal and coke. However, the sulphur tax is not charged for fuels containing 0.05 % or less by weight of sulphur. If the ship is limiting sulphur emissions by purifying exhaust gases or binding the sulphur, those pay reduced tax. In 2012 the rate of tax was around SEK 30 per kg sulphur (Naturvårdsverket 2012).

In addition to US federal emission controls based on Annex VI, the state of California has its own regulation, Title 13 California Code of Regulations, CCR section 2299.2, on fuel oil sulphur content for ocean-going ships within California waters and 24 nautical miles of the California baseline. California specifies the use of distillate fuels with their own implementation timeline that differs in part to the federal legislation enacting Annex VI. Since 2012, the maximum sulphur content in MGO has been set to 1.0 % m/m and MDO to 0.5 % m/m. From 1st of January 2014 on the sulphur content limit for MGO/ MDO will be set to 0.1 % by mass (CIMAC 2008, 13; Lloyd's Register, 49).

In 2007, the Ministry of Finance in Norway implemented the differentiated NO_X fee, which aimed to reduction of the annual NO_X emissions in Norway. In 2012, the NO_X fee was a surcharge of 16.43 NOK / emitted kilo NO_X emissions to air from all types of marine and offshore installations with engines bigger than 750 kW operating in Norway and NO_X emissions from industry and the petroleum industry. Ships which are operating between Norwegian and foreign harbours and Norwegian fishing ships when operating outside Norwegian waters, may get reduced fee or they are set completely free from the NO_X surcharge (CIMAC 2008, 13; Næringslivets Hovedorganisasjon 2012).

2.3.7 Voluntary Emission Control Programs

There are several emission control programs which are voluntary and usually set by Classification Society or some other authority. Following examples are voluntary programs set by different authorities:

- American Bureau of Shipping: Environmental Safety
- Bureau Veritas: Cleanship and Cleanship Super
- Det Norske Veritas: Clean and Clean Design
- Germanischer Lloyd’s: Environmental Passport
- Lloyd´s Register: Supplementary “N” and “S” Character
- RINA: Clean Air
- US-EPA: Blue Sky (CIMAC 2008, 13)

As an example, the Germanischer Lloyd’s Environmental Passport (EP) is a voluntary class-notation for ships where all mandatory and voluntary environmental features of the ship are compiled in a single document. This includes the Environmental Passport certificate, flag state certificates, compliance certificates and NO_X emission diagrams. Along with emissions into the sea, the EP covers emissions into air such as NO_X and SO_X emissions (GL 2010).

2.3.8 Scrubber Guidelines

The International Maritime Organization has implemented MEPC resolution MEPC.184(59), adopted on 17th July 2009, specific guidelines for marine exhaust gas cleaning (EGC) systems including exhaust gas scrubbers. These guidelines specifies the requirements for the testing, survey certification and verification of exhaust gas cleaning systems to ensure that they provide effective equivalence to requirements of regulations set in Annex VI of MARPOL 73/78. Two schemes are permitted in these guidelines: Scheme A containing Unit Certification with Parameter and Emission Checks, and Scheme B containing Continuous Emission Monitoring with Parameter Checks (IMO 2009a, 2-3).

An EGC unit should be certified for the emission level the unit is capable of achieving on a continuous basis specified by the manufacturer with fuel oils of the manufacturer's specified maximum % m/m sulphur content. As discussed above, IMO has set two optional methods for statutory approval: Scheme A and Scheme B. In both cases, along with the identification of the unit and other unit specific data, the EGC unit's Technical manual should contain following operating limits or range of operating values:

- Maximum and minimum (if possible) exhaust gas mass flow rates.
- The power, type and other relevant parameters of the combustion unit connected to EGC unit. If boilers are connected, also the maximum air/fuel ratios at 100 % load. If diesel (2- or 4-stroke) engines are connected:
- Maximum and minimum scrubbing water flow rate(s), inlet pressures and minimum inlet water alkalinity (ISO 9963-1-2).
- Exhaust gas inlet temperature ranges along with maximum and minimum exhaust gas outlet temperature when the EGC unit is in operation.

- Exhaust gas differential pressure range and the maximum exhaust gas inlet pressure when the connected combustion unit operating at MCR or 80% of power rating whichever is appropriate.
- Fresh water elements or salinity levels needed to provide adequate neutralizing agents.
- Other factors which affect on design and operation of the EGC unit relevant to achieving a maximum emission value no higher than the Certified Value (IMO 2009a, 3-11).

Diesel engines which supply power for both main propulsion and auxiliary purposes, should meet the emission reduction requirements at all loads between 25-100 % of the engines' load range, to which they are fitted. Load range for auxiliary diesel engines and boilers is 10-100 % of the engines' load range, to which they are fitted. For loads below these (idling conditions), the EGC unit should continue in operation with maximum SO_2 emission concentration of 50 ppm at standardized O_2 concentration (15.0 % diesel engines and 3.0 % boilers) (IMO 2009a, 7-8).

IMO has set criteria also for washwater discharge. When the EGC system is operated in harbours, in ports, or in estuaries, monitoring and recording should be continuous. Monitored items include pH, Polycyclic Aromatic Hydrocarbons (PAH), turbidity and temperature with set limits. Minimum pH of the washwater is 6.5 and measured at the ship's overboard discharge. However, when commissioning of the unit(s) after installation, the discharged washwater plume should be measured externally at 4 metres from the discharge point. Maximum continuous PAH concentration is 50 µg/L PAH_{phe} (phenanthrene equivalence) above the inlet water PAH concentration and turbidity in washwater should not be greater than 25 FNU (formazin nephlometric units) or 25 NTU (nephlometric turbidity units) or equivalent units. However, for a 15-minute period in any 12-hour period, the continuous turbidity discharge limit may be exceeded by 20 %. The washwater treatment system should also prevent the discharge of nitrates with limits associated with a 12 % removal of NO_X from the exhaust, or beyond 60 mg/l normalized for washwater discharge rate of 45 tons/MWh whichever is greater. There is also an assessment of the washwater for EGC technologies, which uses chemicals, additives, preparations or create relevant chemicals in order to fulfil possibly needed requirements for washwater additives and other substances (IMO 2009a, 14-16). Also EPA has similar criteria in their Exhaust Gas Scrubber Washwater Discharge limits and requirements but for example the minimum pH of the washwater is set 6.0 measured only at the ship's overboard discharge (EPA 2013, 54-58).

2.3.9 EEDI and SEEMP

Although international shipping is only a modest contributor to overall carbon dioxide CO_2 emissions and the most energy efficient mode of mass transport, IMO states that a global approach to further improve its energy efficiency and effective emission control is needed as sea transport will continue growing apace with world trade (IMO 2012a).

IMO's mandatory measures to reduce emissions of GHGs from international shipping were adopted on 15th July 2011 by Parties to MARPOL Annex VI represented in the Marine Environment Protection Committee. This act implemented a new chapter 4 Regulations on energy efficiency to MARPOL Annex VI Regulations for the prevention of air pollution from ships, designating the Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for all ships, which entered into force on 1 January 2013 (IMO 2011b).

The EEDI is a non-prescriptive, performance-based mechanism, which aims to use of more energy efficient and therefore less polluting equipment and engines leaving the choice of technologies to use in a specific ship design to the industry. It requires a minimum energy efficiency level per capacity mile (tonne mile) for different ship type and size segments. EEDI will come into force in 4 phases in 2013-2025, and it is developed for the largest and most energy intensive segments of the world merchant fleet, thus embracing 72 % of emissions from new ships. In EEDI calculation there are size (DWT) related reduction factors and reference values for the different ship types (IMO 2011, 10-12; IMO 2012b, 37; IMO 2012d). Following formula is simplified from the real a complex mathematical EEDI calculation formula:

$$EEDI = \frac{CO_2\ from\ propulsion + \ CO_2\ fom\ auxilires - efficient\ use\ of\ energy}{f_i \times Capasity\ \times\ V_{ref} \times f_W} \quad (2)$$

In where f_j corresponds is a correction factor to account for ship specific design elements; V_{ref} is the ship speed, measured in nautical miles per hour (knot), on deep water with maximum design load condition (Capacity) at the shaft power of the engine(s) and assuming the weather is calm with no wind and no waves; and f_w is a non-dimensional coefficient indicating the decrease of speed in representative sea conditions of wave height, wave frequency and wind speed (IMO 2009b, 2-6).

The SEEMP is an operational measure and a mechanism to improve the energy efficiency of a ship in a cost-effective manner providing an approach for shipping companies to manage ship and fleet efficiency performance over time. It encourages the ship owner and operator at each stage of the plan to consider new technologies and practices when seeking to optimise the performance of a ship. Monitoring tools, like Energy Efficiency Operational Indicator (EEOI), have been developed for SEEMP measurement. The EEOI enables operators to measure the fuel efficiency of a ship in operation and to gauge the effect of any changes in operation, e.g. improved voyage planning or more frequent propeller cleaning, or introduction of technical measures. This may also form part of the ship's Safety Management System (SMS) (IMO 2011b, 13; IMO 2012d).

As the exhaust gas cleaning systems doesn’t increase the ship efficiency or create significant GHG reduction, they do not have any direct effect on EEDI as a reduction technology. Either with almost all conventional cargo ships, the energy consumption associated with scrubbers, does not adversely impact a ship’s EEDI value as the auxiliary power consumption will be calculated as a fixed proportion of the installed main engine power and is unrelated to the actual auxiliary power consumption. However, if the installation exhaust gas cleaning systems reduces cargo carrying capacity then the EEDI will be directly affected (Lloyd's Register 2012, 28).

2.3.10 Adopted and Future Sulphur Emission Limits

On 11th of September 2012 the European Parliament adopted new revised EU legislation aimed at reducing sulphur pollution from ships. The proposed EU legislation implements internationally-agreed IMO standards tightening limit values for sulphur emissions from ships by ensuring they can be properly enforced at EU level. The proposed maximum limits for sulphur content of marine fuels will be lowered in the designated European ECAs to 0.1 % from 2015, affecting EU's territorial water in the Baltic Sea, the North Sea and the English Channel. In the rest of EU waters, the limits will be reduced to 0.5 % from 2020. Also the provisions for delaying the limit value to 2025 based on IMO decisions were removed (European Parliament 2012).

It is predicted by different maritime stakeholders that adaption of regulation for sulphur content limits will increase in near future. However, it is also predicted that the upcoming global sulphur level of 0.5 % will, to some extent, remove the need for specified Emission Control Areas. Here are listed few potential and discussed future ECA areas with their earliest ECA introduction years: Norwegian and Barents Seas (2020), Antarctic Ocean (in place but not as ECA), Arctic Ocean (2015), North-East Atlantic (2020/2025), Japan (2015), Mediterranean Sea (2020 but probably by Global limit), Mexico and Panama (2020), Malacca Straits (2020), Singapore (2015), Australia and New Zealand (2018) and Hong Kong (2018). As a conclusion, no significant new ECAs are expected to come in force before 2020, which would impact the most busiest shipping routes except the arctic routes if the traffic there increases greatly (MECL 2011, 22-24). Figure 15 summarizes past, present and upcoming adopted fuel oil sulphur content related emission limits.

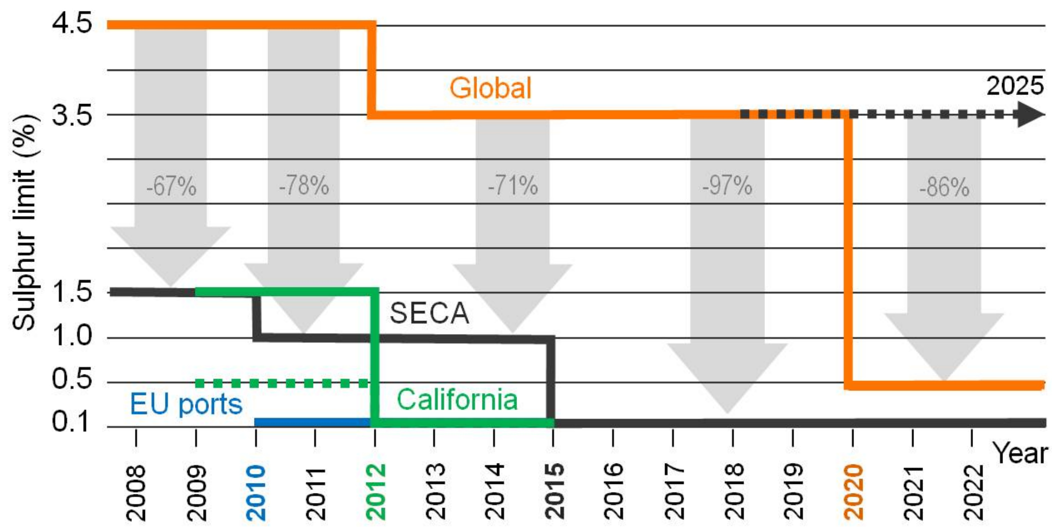


Figure 15. Adopted fuel oil sulphur content limits (Wärtsilä).

As the shipping industry is now focusing to its CO_2 emissions reduction, it is important to recognise that CO_2 is not the only emission of relevance from a climate change perspective. Emissions like NO_X and SO_X, are mainly discussed as health and environmental issues, but they also have an effect on the climate. While CO_2 emissions result in climate warming, emissions of SO_2 causes cooling by the effects on atmospheric particles and clouds, while NO_X reduce methane (CH_4) levels and increase the levels of the GHG ozone (O_3), causing cooling and warming, respectively. Still at present, the result of a net global mean radiative forcing from the shipping sector is strongly negative, which is leading to a global cooling effect. However, with upcoming NO_X and SO_X regulations this is about to change as they come with unintended side-effect, which reduce the cooling effects from the shipping sector (Det Norske Veritas 2010, 22).

2.3.11 Emissions on Global Shipping Routes

The global merchant shipping sails on a most-time-efficient route available between designated ports. Even if all the merchant shipping actions are taken into account, there is relatively small number of principal transport routes and those pass through only few areas of the oceans. One key factor is also the size of the ship when determining the optimal route. As an example, a ship designed to fit through the Suez Canal in Africa with a maximum of cargo will not fit through the Panama Canal in Central America, and a cargo ship designed for maximum capacity of the Panama Canal will not fit through the Welland Canal between Lake Ontario and Lake Erie (IMO 2012b, 7). Figure 16 presents a map of global shipping routes, tracked with ships' VHF receiver and GPS, as well as the main strategic passages forcing a convergence of shipping routes at specific locations.

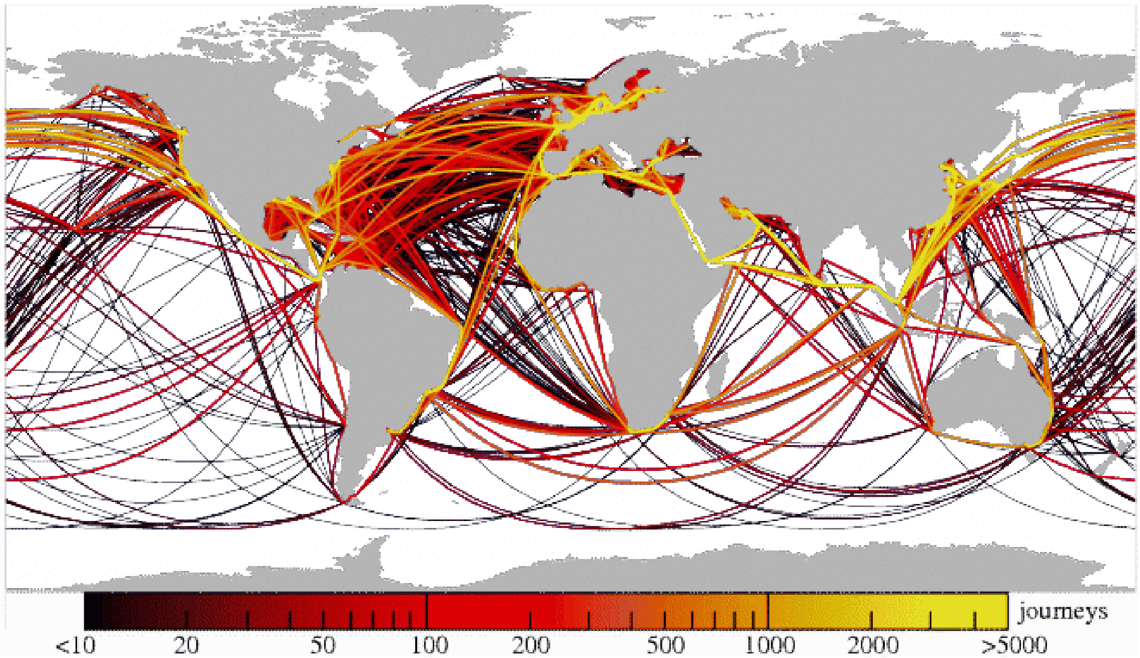


Figure 16. Global shipping routes (IHS Fairplay).

As can be seen from the map, the busiest routes are the sea routes to the ports of Europe and East Asia, particularly Japan, Shanghai, Singapore and Hong Kong, and also the United States especially the East Coast as it is a major sender and receiver of cargo. Maritime traffic to South America is also increasing and Arctic ship traffic is rising. Because of the global warming, the climate models predict a significant decrease in Arctic summer ice cover over the next ten years. Less ice provides new opportunities for Arctic ship traffic (Schäfer & all 2010, 171). Many of global routes have present or possibly upcoming Emission Controlled Areas on their route and this also applies with most of the traffic bottlenecks like Panama Canal, Gibraltar, Suez Canal, Singapore and Soya strait, which are also presented in Figure 17 (Eyring & all 2009, 7; Schäfer & all 2010, 171).

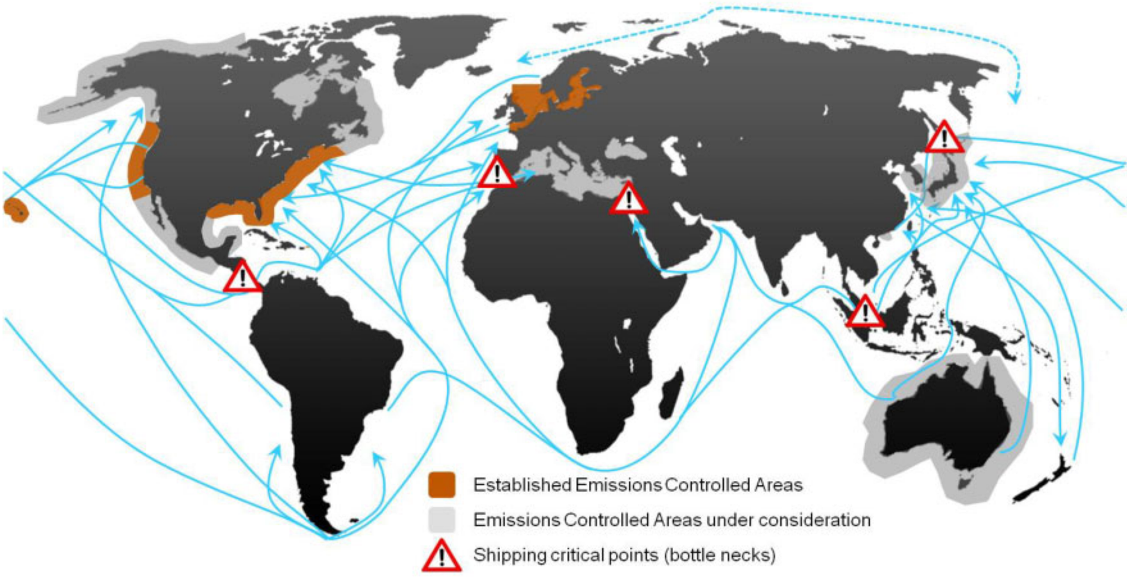


Figure 17. Global shipping routes with critical point and ECAs (Wärtsilä).

According to most of the studies made from shipping emissions, the majority of the ship emissions occur in the Northern Hemisphere within a fairly well defined system of international sea routes. They estimated that 80 % of the traffic occurred in the Northern Hemisphere with distribution of 32 % in the Atlantic, 29 % in the Pacific, 14 % in the Indian Ocean and 5 % in the Mediterranean. Consequently remaining 20 % of the traffic in the Southern Hemisphere had approximately equally distributed between the Atlantic, the Pacific, and the Indian Ocean. They have also estimated that near 70 % of ship emissions occurred within 400 km of coastlines conforming to major trade routes. However, the significant growth in ship activity in Asian waters over recent years, will change the above distribution (Eyring & all 2009, 7). In Appendix 4 are given Global Ship Emissions Allocation Factors (SEAF) from EDGAR (2006), AMVER (2003) and ICOAD (2007), which also highlight the busiest shipping routes and their emission distribution.

2.4 Exhaust Gas Scrubber Market Potentials

According to IMO (IMO 2012b), ships like are sailing on modern-day, have never been as technically advanced, never been so sophisticated, never carried so much cargo, never been so environmentally-friendly and never been safer as they are at present. These have been achieved because of the IMO's continuously act as a focal point and a driving force to regulate oil pollution, preparedness, response and co-operation in tackling pollution, developing Maritime technologies and the safety at the sea. Through past years the MARPOL Convention has remained the most important international treaty instrument covering the prevention of pollution by ships (IMO 2012b, 8, 24). Still there will be request for emission abatement technologies such as the exhaust gas scrubbers, which will generate future markets for different solutions.

2.4.1 Exhaust Gas Scrubber Installation Potentials

The cost advantage for exhaust gas scrubber is a combination of quantity of fuel oil burned in ECA and the cost differential between the high- and low-sulphur fuels. One of the key break points is in fuel cost differentials when sulphur limits become so low that it cannot be practically or cost-effectively achieved by just removing sulphur from residual fuel oil. These limits, generally meaning 0.5 % sulphur or lower, requires high-cost distillate fuel oil (MGO) or alternative technologies such as scrubbers or natural gas engine applications. The cost advantage becomes widespread in 2015 when, by the ECAs as they require the 0.1 % sulphur emissions and when worldwide sulphur limits reach 0.5 % in either 2020 or 2025, the cost savings opportunity extends to ships regardless of their operating area. Savings by the scrubber installation are generated by two factors, the price difference between low sulphur fuel and heavy fuel oil, and consumption of fuel in ECA, so in general more time the ship spends in an ECA and the higher its fuel consumption, the greater are the savings (SOCP 2011, 36; UNCTAD 2011, 26; Wärtsilä Corporation 2013b).

Calculations made for Ship Operations Cooperative Program in 2011, indicates that ships, burning at least 4000 metric tons of fuel oil annually within the ECA starting in 2015, should consider the exhaust gas scrubber installation. In general, this reflects to ocean-going ships with slow or medium speed diesel engines. According to multitude of studies made by Wärtsilä along with other industry key stakeholders, ships that spend over 90 % of its time within ECAs would have payback time of less than two years for the scrubber investment. However, there are also classes of marine ships that burn residual fuel oil in medium speed diesel engines like anchor handling tugs, special vessels, larger ferries and cruise ships. Also with these cases, there can be a high fuel cost differential but the fuel oil consumption may not be in significant quantity to justify the equipment expenses. The installation of the exhaust gas scrubber to smaller marine ships or non-ocean-going ships may face also other several challenges: machinery, funnel or deck spaces may be too restricted to fit the relatively large scrubber systems; many of those already operates with high cost MDO or MGO eliminating much of the potential fuel cost savings; and as discussed, those which operates with residual fuel oil, may not use enough to gain adequate pay-back on the capital investment (SOCP 2011, 36; Wärtsilä Corporation 2013b).

Because of the machinery concepts, operating profiles and areas as well as relatively high fuel oil consumptions and therefore also operating costs, the merchant fleet would be the most reasonable target group for scrubber installation. Most of these ocean-going ships require high autonomy as well as they sail great distances thus as a result, the LNG may not be feasible solution for these ships. Wärtsilä categorizes its scrubber applications according to the customers' needs in terms of:

- Closed loop scrubbers for customers sailing on low-alkalinity waters and/ or with a need for zero discharge.
- Open loop scrubbers for customers sailing with ocean-going ships.
- Hybrid scrubbers for customers with ships operating in both types of waters or requiring full flexibility of operations (Wärtsilä 2012e, 42).

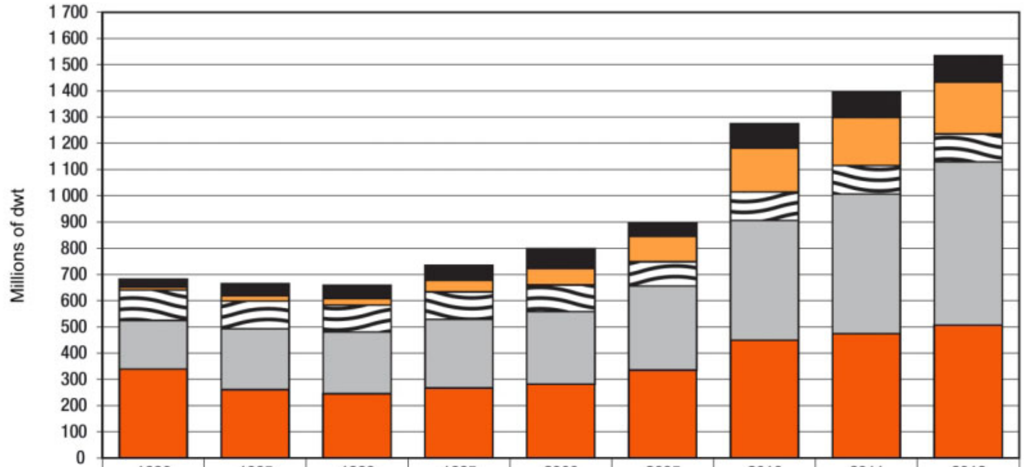
2.4.2 World Merchant Fleet

The composition of the world fleet reflects the demands for seaborne trade of different merchandises, including liquid, dry bulk and manufactured goods. Even the in-order fleet has been cut downed and ship demolition is accelerated, the global fleet has grown at unprecedented rate over the past four years and the population of merchant fleet will be some 25 % larger in capacity by 2015. Table 9 contains statistics from most of the world's merchant ships in 2011 collected from the commercial database of IHS Fairplay. The database uses over 100 descriptions of ship type but those have been aggregated into 12 main types (EMSA 2012, 3; MECL 2011, 27; UNCTAD 2011, 36).

Table 9. World fleet by total number of ships according to type and size (EMSA 2012, 6).

Ship type	Small [1]		Medium [2]		Large [3]		Very large [4]		Total	
	No.	(%)	No.	(%)	No.	(%)	No.	(%)	No.	(%)
General cargo ships	4627	16.4	12210	33.1	197	2.1	-	-	17034	21.5
Specialized cargo ships	14	0.0	188	0.5	48	0.5	-	-	250	0.3
Container ships	16	0.1	2411	6.5	1679	17.6	868	20.1	4974	6.3
Ro-Ro ships	32	0.1	774	2.1	587	6.2	144	3.3	1537	1.9
Bulk carriers	362	1.3	3647	9.9	4215	44.2	1373	31.8	9597	12.1
Oil and chemical tankers	1852	6.5	6373	17.3	2255	23.6	1348	31.2	11828	15.0
Gas tankers	44	0.2	1014	2.7	187	2.0	329	7.6	1574	2.0
Other tankers	259	0.9	402	1.1	5	0.1	-	-	666	0.8
Passenger ships	3461	12.2	2505	6.8	269	2.8	135	3.1	6370	8.1
Offshore vessels	2185	7.7	4312	11.7	75	0.8	120	2.8	6692	8.5
Service ships	2196	7.8	2219	6.0	23	0.2	4	0.1	4442	5.6
Tugs	13238	46.8	872	2.4	-	-	-	-	14110	17.9
Total	**28286**	**100**	**36927**	**100**	**9540**	**100**	**4321**	**100**	**79074**	**100**
1) GT < 500 2) 500 ≤ GT< 25000 3) 25000 ≤ GT< 60000 4) GT ≥ 60000										

As manufactured goods are increasingly containerized, the share of the containership fleet has increased from 1.6 % of the world fleet in 1980 to over 12.9 % in January 2012. Since 1980, the general cargo fleet has decreased by 7 % while the rest of the world fleet has increased by 150 %. The largest growth of tonnage with plus 17 % reasserts dry bulk carriers in the position as largest ship type with a share of 40.6 % of world's total capacity. Also refrigerated cargo is increasingly containerized and only very few new specialized reefer ships are being built at present. It is forecasted that the 85 % of the refrigerated cargo will be containerized in 2015 as the share is now near to 65 %. Since 1980, the share of oil tankers has also decreased from almost 50 % to 33.1 %. The recent growth in merchant fleet is also illustrated in Figure 18 (UNCTAD 2011, 36).



	1980	1985	1990	1995	2000	2005	2010	2011	2012
Other	31	45	49	58	75	49	92	96	100
Container	11	20	26	44	64	98	169	184	198
General cargo	116	106	103	104	101	92	108	109	106
Dry bulk	186	232	235	262	276	321	457	532	623
Oil Tanker	339	261	246	268	282	336	450	475	507

Seagoing propelled merchant ships of 100 gross tonnage (GT) and above

Figure 18. World merchant fleet by principal ship types in selected years (UNCTAD 2012, 34).

The average age of the world fleet of seagoing propelled merchant ships of 100 GT and above is 21.9 years. Figure 19 shows a detailed age structure of the merchant fleet. From new-buildings, almost 39 % of GT delivered in 2011 was built on Chinese shipyards followed by other Asian countries Republic of Korea (35.2 %), Japan (19 %) and the Philippines (UNCTAD 2012, 46, 54-56). The exceptional ordering over the past several years will continue to enlarge the fleet and the ordering process is slowing down but the huge over-capacity will be hitting freight income in all sectors. At present, shippers are cutting costs of fuel and absorbing capacity with slow-steaming as well as moving to fulfil other strategic objectives such as energy and operational efficiency together with environmental sustainability, including cutting carbon emissions. Yet, the slow-steaming has only partially lessened the over-capacity (MECL 2011, 32; UNCTAD 2011, 22).

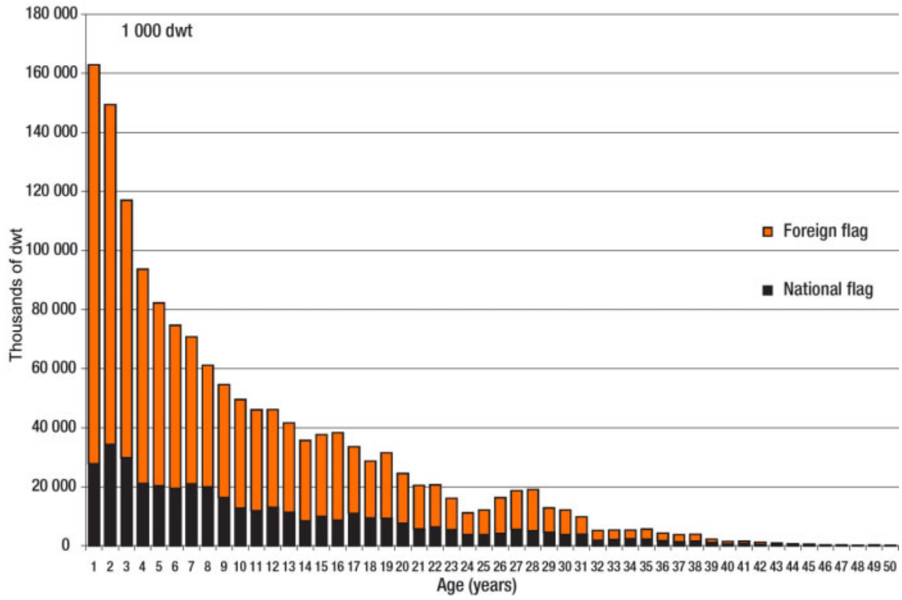


Figure 19. Age structure of world merchant fleet by national and foreign flags in 2011 (UNCTAD 2012, 39).

The rapid growth in global trade recorded over the past few decades has been powered by affordable and easily available oil. Shipping, handling over 80 % of the volume of world trade, is heavily reliant on oil for propulsion power production. Now the era of easy and cheap oil is coming to an end, with the prospect of a looming peak in global oil production. The fuel costs can account for as much as 60 % of a ship's operating costs thus rising oil prices will certainly increase the transport cost bill for the shippers and therefore potentially destabilize the global trade. However, the size and nature of the global fleet is at present much less reflected by the bunker fuel demand. The shipping, along with all industrial sectors, is not immune to economic downturns. In 2009 the world economy witnessed the worst global recession in over seven decades and the sharpest turn down in the volume of global merchandise trade. Before that event, the size and the nature of the fleet provided a predictor of bunker fuel demand with the faster merchant fleet having significant impact to fuel needs (IMO 2012b, 7; MECL 2011, 32; UNCTAD 2011, 26).

Study made by UNCTAD has shown that 10 % increasing in oil prices would raise the cost of shipping for a container by around 1.9 % to 3.6 % and the cost of shipping for one ton of iron ore and one ton of crude oil would increase by up to 10.5 % and 2.8 % respectively. Another issue arising is regulatory driven and relates to the transition to low sulphur fuel, which will have same kind of effect as with increasing oil price. Therefore, it is predicted that by 2030 some 60 % of the world fleet may have exhaust gas scrubbers installed and by the year 2035 probably most of the HFO operated will have scrubbers on board in daily use (MECL 2011, 62; UNCTAD 2011, 26).

2.5 Future of Heavy Fuel Oil in Marine Sector

Even when stricter environmental legislations come in force in the near future, the HFO will still power ships many years to come. In the future, ships operating in ECA will have the obvious advantage when operating with the HFO instead of MDO with 1.0 m-% S maximum until 2015 and then MGO 0.1 m-% S thereafter. Therefore, the price and availability of distilled fuel oils will give advantage to the HFO operation and the HFO will most likely be available on markets for years to come. Along with present and upcoming emission reduction limits set by the IMO, in the future other ship emission related reduction limits might come in to force especially related to the PM and BC emission. At the IMO, discussion about the reduction of the PM origin from ships, with specific or implied reference to the BC, arose several years ago. Since the 10^{th} session of the Bulk Liquids and Gases sub-committee, several studies of the PM and BC emissions, with their measurement and abatement methods, have been carried out. The main concern has been pointed to the climate and impacts of the ship originating the BC on the Arctic. The discussion is still ongoing without any regulations appointed directly to the PM and/or the BC emissions but the wet exhaust gas scrubber technology has already been recognized as an optimal abatement method (Lack & all 2012, 6). Obviously, in case where the wet exhaust gas scrubbers would be installed for other reasons, like the utilization of HFO in the future, the PM and BC reduction would come as a collateral benefit (Det Norske Veritas 2012b; Lack & all 2012, 45).

The merchant fleet is the largest fleet by number of ships. They have also the largest ships with the biggest installed power on board and big fuel oil consumptions. Their operating costs originate in a great extent from fuel oil costs so they will have enormous interests to utilize the cheapest fuel oil available on the markets. Their ship design is also more flexible for bigger exhaust gas scrubber installations but still one should pay attention to scrubber location and power consumption by the means of EEDI. If the scrubber increases the ship's total power consumption, by requiring more installed power and thus increasing the CO_2 emissions, and/or the installation decreases the cargo space, the EEDI would be negatively affected. This could set the exhaust gas scrubbers into bad light in the eyes of ship operators and ship yards. However, the merchant fleet will still need cheap fuel to power their journeys across the oceans and that might be the biggest segment for scrubber markets in the future.

DNV has predicted in their Shipping 2020 -project, that the scrubbers will have limited uptake, with approximately 200 installations per year only, until the global sulphur limit is enforced in 2020. They have estimated that the main reason for this would be a low LNG price compared to HFO, which would favour to invest in gas engines and LNG storing systems rather than in scrubbers, and that there is a limited proportion of the global fleet which spends enough time in ECAs to justify scrubber system to be installed. After 2020, or 2025, all ships operating with liquid fuel oil are required to run on low sulphur fuel or clean the exhaust all the time. Then scrubbers are more potential to be fitted to several thousand ships. As over half of the merchant fleet is less than 10 years old so the scrubbers should be feasible also for retro-fit installations. However, it is unlikely that the retro-fit scrubber installation will be economical to a ship of more than 20 years old. After 2015 operating for more than 80 days or 90 % in ECA will recover the capital investment of the scrubber installation in 2 to 4 years (Det Norske Veritas 2012b; MECL 2011, 46; Skema 2010, 49; Wärtsilä Corporation 2013b).

3 WET SCRUBBER SOLUTIONS

Wet scrubber is a term used to describe a variety of devices that uses liquid to remove particulates and/or pollutants from flue gas stream by spraying it with the liquid, by forcing it through a pool of liquid, or by some other contact methods (Surhone & all 2010, 1). These scrubbers have been used for a long time in the industrial world. A packed tower absorber scrubber was patented in 1836 and in 1935 the English were removing 98 % of SO_2 from the flue gases with the scrubber. In 1901, a particulate control scrubber was patented extending the recognize use of both particulate and sulphur reduction (Hesketh & Schifftner 1996, 1).

Functional principles of wet scrubbers are related to absorption and adsorption phenomenons, which are both diffusional separation processes that can be used to collect hazardous air pollutants. In absorption, the pollutant is transferred to the solvent which then, in most of the cases, needs further treatment. Recovery of the solvent can be undertaken by separation, by distillation or by stripping the absorbed material from the solvent. Most of the gaseous contaminants such as sulphur oxides, some of nitrogen oxides or hydrochloric acids, with present along with the particulates, can be collected simultaneously by absorption. If the pollutant material has a value as a localized object, the adsorption may provide the means for the material to be more readily recovered. In the wet scrubbing, the particles can be collected through the mechanism of inertial impaction (Schenelle & Brown 2002, chapter 10: 1-2).

At present, available commercial wet scrubbing systems used as exhaust gas cleaning systems (EGCS), also known as the exhaust gas scrubbers, are divided into three categories according to their operating principles:

- Open loop scrubber systems, which uses sea water as scrubbing medium.
- Closed loop scrubber systems, which uses fresh water with the addition of an alkaline chemical as scrubbing medium.

- Hybrid scrubber systems, which can operate in both Open loop and Closed loop -modes (EPA 2008, 20; Lloyd's Register, 14).

3.1 Conventional Scrubbing Technologies

There are several ways to categorise wet scrubbers. The scrubbers can be divided into two major categories: the particulate collectors and gaseous emission control devices (Hesketh & Schifftner 1996, 4). Scrubbers can also be categorized by its structural design or scrubbing method, which are usually interlinked together (Lee 2005, 859). Since wet scrubbers vary greatly in complexity and method of operation, devising them into categories covering all the varieties is extremely difficult. Scrubbers designed for particle collection are usually categorized by the gas-side pressure drop of the system. In here, gas-side pressure drop refers to the pressure difference, or pressure drop, that occurs as the exhaust gas is pushed or pulled through the scrubber. The pressure that would be used for pumping or spraying the liquid into the scrubber is disregarded (Joseph & Beachler 1998, chapter 1: 6-7).

Another way to classify wet scrubbers is by the use for primarily collect either particles or gaseous pollutants. Again with this classification, the distinction is not always clear since scrubbers can often be used for removal of both types of pollutants. In commonly used categorization, wet scrubbers are categorized by the manner in which the gas and liquid phases are brought into contact. All the wet scrubbers are designed to use power, or energy, from the gas stream or the liquid stream, or by some other method to bring the pollutant gas stream into contact with the liquid (Joseph & Beachler 1998, chapter 1: 6-7; Lee 2005, 859). These categories are listed in Table 10.

Table 10. Categories of wet scrubbers by energy source (Joseph & Beachler 1998, chapter 1: 6-7; Lee 2005, 859).

Wet scrubber	Energy source used for gas-liquid contact
Gas-phase contacting	Gas stream
Liquid-phase contacting	Liquid stream
Wet film	Liquid and gas streams
Combination of above: • Liquid phase and gas phase • Mechanically aided	 Liquid and gas streams Mechanically driven rotor

During the history of scrubbing, a number of wet scrubber designs have been introduced for gaseous pollutants removal with the packed tower (Wet film scrubber) and the plate tower (Gas-phase contacting scrubber) being the most common ones (Joseph & Beachler 1998, chapter 1: 3). This study covers only spray tower (Liquid-phase contacting scrubber) and packed tower scrubbers as those are the technologies selected to Wärtsilä Dual Water hybrid scrubber but also Venturi scrubbers are briefly covered as the technology is used in Open loop scrubbers and those are a possible solution in order to achieve more efficient particle removal capability.

3.1.1 Wet Scrubbers in General

Wet scrubbers, which are designed to remove gaseous pollutants, are referred to as absorbers (Joseph & Beachler 1998, chapter 1: 3). Scrubbers utilizing liquids for gas absorption rely on the creation of large liquid surface areas by the means of different operational principles or mechanical structures (Hesketh & Schifftner 1996, 7). Because of the operational environment, the wet scrubbers have the ability to handle high temperatures and moisture. In wet scrubbers, the flue gases are cooled resulting smaller overall size of equipment. Wet scrubbers can also neutralize corrosive gases. Some disadvantages of wet scrubbers include a possible corrosion risk, a need for water mist removal to obtain high efficiencies, a need for treatment or reuse of spent liquid, and reduced plume buoyancy (Joseph & Beachler 1998, chapter 1: 4).

The absorption is one of the most commonly used methods for removal of water-soluble gases. It requires intimate contact between a gas and a liquid, which is usually provided by breaking the liquid up into small droplets or by providing thin films. These are constantly renewed through turbulence in order to provide high liquid surface area for mass transfer and/or a fresh, unsaturated surface film for high driving force. The most commonly used industrial scrubbing technique is a two-step flue gas desulfurization process, where the absorbing solution containing alkaline (dissolved soda ash, sodium bicarbonate, or NaOH) is used inside the absorption tower and then the tower effluent is treated externally. Also in some solutions, Calcium carbonate i.e. lime can be used as alkali. It is cheaper and more plentiful alkali but the direct use in the absorber may lead to plugging or coating problems, if the calcium salts produced have only limited solubility. The most commonly used industrial wet scrubbers are packed and plate columns, open spray chambers and towers, cyclonic spray chambers, and combinations of sprayed and packed chambers of type. Normally, the scrubber system is exposed to the corrosive effects of the low temperature exhaust gases and is thus entirely build of highly corrosion resistant materials withstanding the conditions (Schenelle & Brown 2002, chapter 1: 3; Schenelle & Brown 2002, chapter 11: 1-2).

3.1.2 Spray Tower Scrubbers

The spray tower scrubber is a liquid-phase contacting scrubber in where energy is applied to a scrubbing system by injecting liquid at high pressure through specially designed nozzles. These nozzles produce droplets that fan out into a spray in the scrubber chamber acting as targets for absorbing gas and/or collecting particles from the pollutant exhaust stream. In most of the liquid-phase contacting scrubbers, the liquid inlet pressure provides the major portion of the energy required for contacting the gas (exhaust stream) and liquid phases (Joseph & Beachler 1998, chapter 4: 1).

The spray tower (or chamber) itself, can be constructed very simply of empty cylindrical vessel made of steel or plastic and nozzles that spray liquid into the vessel. The exhaust gas stream usually enters from the side of the bottom part of the tower and moves upward, while liquid is sprayed downward from one or more levels. The flow of exhaust gas and liquid in opposite direction is called counter-current flow. In Figure 20 a typical counter-current flow spray tower is illustrated (Joseph & Beachler 1998, chapter 4: 1-2; Schenelle & Brown 2002, chapter 10:1).

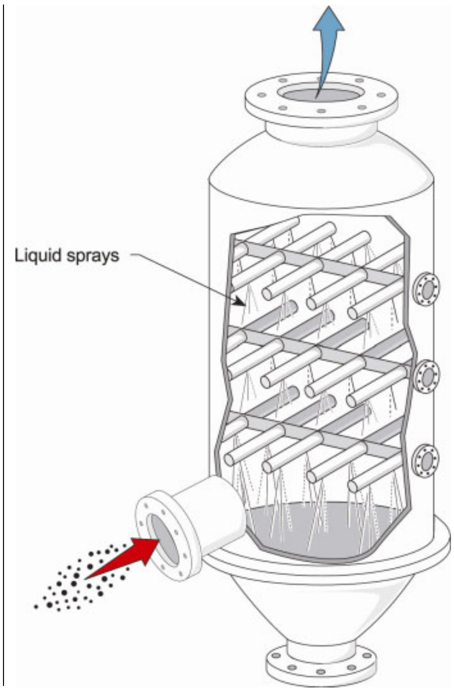


Figure 20. Spray tower scrubber.

The main purpose of using many nozzles in spray tower scrubbers is to form a tremendous amount of fine droplets for impacting particles and to provide a large surface area for absorbing gas. Theoretically speaking, smaller the formed droplets, higher the collection efficiency achieved for both gaseous and particulate pollutants. Smaller droplets can be formed by higher liquid pressure at the nozzle, i.e. with higher pumping pressure. The absorption can be increased also by increasing the liquid-to-gas ratio (L/G). However, even the spray towers are low-energy scrubbers, an increase in both power consumed and operating cost is required in order to accomplish either of these. In addition, droplets should be large enough to not be carried out of the scrubber by the exhaust stream if a droplet separator was not used. Also the physical size of the spray tower will limit the amount of liquid and the size of droplets that can be used (Joseph & Beachler 1998, chapter 4: 2-4).

Because of spray tower scrubbers' ability to handle large exhaust gas volumes in corrosive atmospheres, they can be used in a number of flue gas desulfurization systems as a first or second stage in the pollutant removal process (Joseph & Beachler 1998, chapter 4: 4).

3.1.3 Packed Tower Scrubbers

The spray towers can be used for gas absorption but they are not as effective as the packed or plate towers where the liquid is sprayed or poured over packing material contained between support trays. Since the exhaust gas stream is forced through a liquid film coated packing and the pollutants are collected as they pass through the packing, both gas and liquid phases provide energy for the gas-liquid contact. The packed towers gives an excellent gas to liquid contact and an efficient mass transfer by a large contact area between the gas and liquid phases, a turbulent mixing of the phases and a sufficient residence time for the exhaust gas to contact the liquid. These conditions are ideal for the gas absorption. Because of these features, the packed towers are capable of achieving high removal efficiencies for many different gaseous pollutants and they can generally be smaller in size than the spray tower scrubbers (Joseph & Beachler 1998, chapter 5: 1; Schenelle & Brown 2002, chapter 11: 4).

The packed towers can be designated according the flow arrangement used for the gas-liquid contact or by the material used as a packing in the bed. The most common flow configuration for the packed towers is a counter-current flow, although the design of co-current and cross-flow towers are important as well. The two first from these arrangements are illustrated in Figure 21. In the counter-current arrangement, the exhaust gas stream enters into bottom of the tower and flows upward over the packing material and the scrubbing liquid is sprayed at the top of the packing from where it flows downward over the packing material. As the exhaust gas stream moves through the packed bed, it is forced to make many winding changes in direction, thus resulting in intimate mixing of both the exhaust gas and liquid streams. Therefore, this counter-current-flow arrangement results the highest theoretically achievable scrubbing efficiency (Joseph & Beachler 1998, chapter 5- 2; Schenelle & Brown 2002, chapter 11: 5).

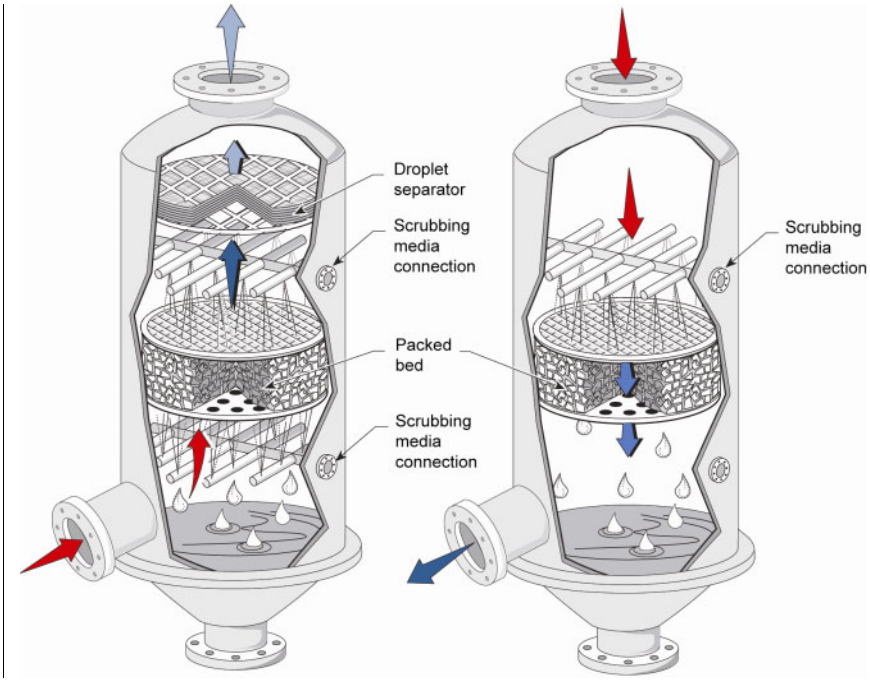


Figure 21. Counter-current (left) and co-current flow (right) packed tower scrubbers.

However, the use of the packing increases the pressure loss as the fluids moves through the column thus causes an increased demand for energy. Furthermore, the counter-current-flow packed tower does not always operate effectively if there are large variations in the liquid or gas flow rates as with too high flow rates, a condition called flooding may occur. In flooding, the liquid is held in the pockets or void spaces between the packing, and the liquid does not drain down through the packing. This phenomenon can be minimized by reducing the gas velocity through the bed or by reducing the liquid-injection rate. In co-current flow arrangement the absorber can operate with higher liquid and gas flow rates as both the exhaust gas and the liquid phases enters at the top of the tower and moves downward over the packing material. Also the pressure drop is lower than with the counter-current flow since the both streams move in the same direction and therefore the flooding is not a problem. But on the other hand, the removal efficiency is very limited due to the decreasing driving force as the streams travel down through the column and this limits the areas of application for co-current scrubbers. Still the co-current flow arrangement may be used in situations where the equipment space is limited since the tower diameter is usually smaller than with counter-current or plate towers having equivalent flow rates (Joseph & Beachler 1998, chapter 5: 3; Schenelle & Brown 2002, chapter 10:1).

3.1.4 Baffle Tower Scrubbers

Another a liquid-phase contacting scrubber for absorption is the baffle tower, which can be used especially when the plugging and scaling problems are expected to be severe. They are very similar to the spray towers in design and operation. In this arrangement, the treated gases are passing through sheets downwardly cascading liquid, providing some degree of contact and liquid atomization. Liquid sprays capture the pollutants and also remove captured particles from the baffles. The baffle construction can be made from segmental baffles or disks and doughnut plates, in where the gas alternately flows upward through central orifices and annuli, traversing through liquid curtains with each change in direction. However, the mass transfer is generally poor and adding the baffles slightly increases the pressure drop over the scrubbing system (EPA 2008, 20; Joseph & Beachler 1998, chapter 6: 9; Schenelle & Brown 2002, chapter 11: 4).

3.1.5 Venturi Scrubbers

The Venturi scrubbers effectively uses the energy from the exhaust gas stream to atomize the scrubbing liquid and they are the most commonly used scrubbers for the particle collection with the highest particle collection efficiency of any wet scrubbing system. The Venturi nomination originates from an Italian physicist Giovanni Battista Venturi who discovered the Venturi effect in 1797. In 1949, Johnstone and other researchers found that they could effectively use the Venturi configuration to remove particles from an exhaust stream. Despite the good particle removal efficiency, the Venturi scrubber has absorption limitations because in the normal Venturi design the particles and spray liquid have parallel flow. Also a short contact time limits gas absorption since the high exhaust gas velocities results a very short contact time between the liquid and gas phases (Joseph & Beachler 1998, chapter 3: 2-3 & 9-10; Schenelle & Brown 2002, chapter 22: 2).

Generally the basic Venturi scrubber consists of three sections: a converging section, a throat section, and a diverging section. Figure 22 illustrates the classic Venturi configurations. The exhaust stream enters the converging section and as the diameter decreases, the gas velocity increases. The scrubbing liquid can be introduced either at the throat or at the entrance to the converging section. The exhaust gas, which is forced to move at extremely high velocities in the small throat section, splatters the liquid from walls producing immense number of very tiny liquid droplets. The particle and gas removal occur in the Venturi's throat section as the exhaust gas stream mixes with the fog of those droplets. The exhaust stream then exits through the diverging section, where its flow is forced to slow down. In most the Venturi solutions, the particles removed from the scrubbing water by cyclonic separators (Joseph & Beachler 1998, chapter 3: 2-3 & 9-10).

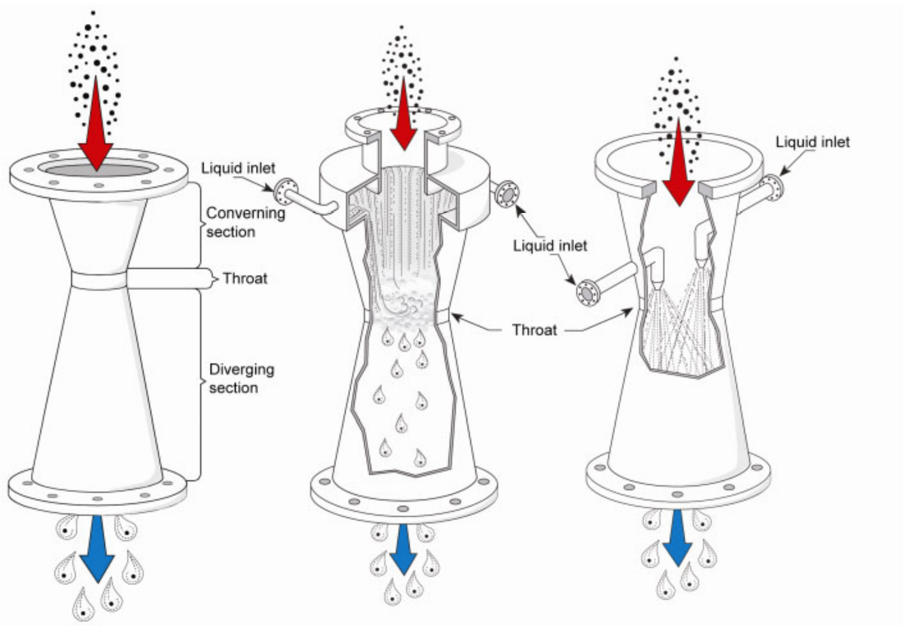


Figure 22. Venturi scrubbers: conventional Venturi (left), Venturi with wetted throat (middle) and Venturi with throat sprays (right).

As the Venturies have a relatively open design compared to other scrubber solutions, they can be used for simultaneous gaseous and particulate pollutant removal, especially when:

- The scaling can be a problem.
- A high concentration of dust or soot is in the exhaust gas stream and it is sticky or has a tendency to plug openings.
- The gaseous contaminant in exhaust gas is very soluble or chemically reactive with the liquid (Joseph & Beachler 1998, chapter 3: 10).

3.2 Closed Loop Scrubbers

The fresh water scrubber operates in Closed loop system. Closed loop -term is used because most of the scrubbing agent is re-circulated with only minimal water intake and effluent discharge. In the Closed loop scrubbing process, sulphur oxides in the exhaust gas stream are captured and neutralised by scrubbing water, which is based on fresh water boosted with alkali, typically 50 % NaOH (Sodium Hydroxide), also known as Caustic Soda or Lye. 20 % NaOH solution can also be considered in some installation due to its lower freezing point (EPA 2008, 21; Wärtsilä 2009a, 5).

3.2.1 Closed Loop Scrubber System Design

The fresh water scrubber system utilizes the fresh water and the sodium hydroxide (NaOH) based Closed loop exhaust gas scrubbing process for SO_X removal from the exhaust gas stream (Wärtsilä 2010b, 3). Main components and flows can be seen in Figure 23. The total fresh water scrubber system can be split to different systems, which are a technical fresh water system, a sea water system, a NaOH system, a scrubbing water system, a bleed-off system, a compressed air system (WLSA 2012, 120).

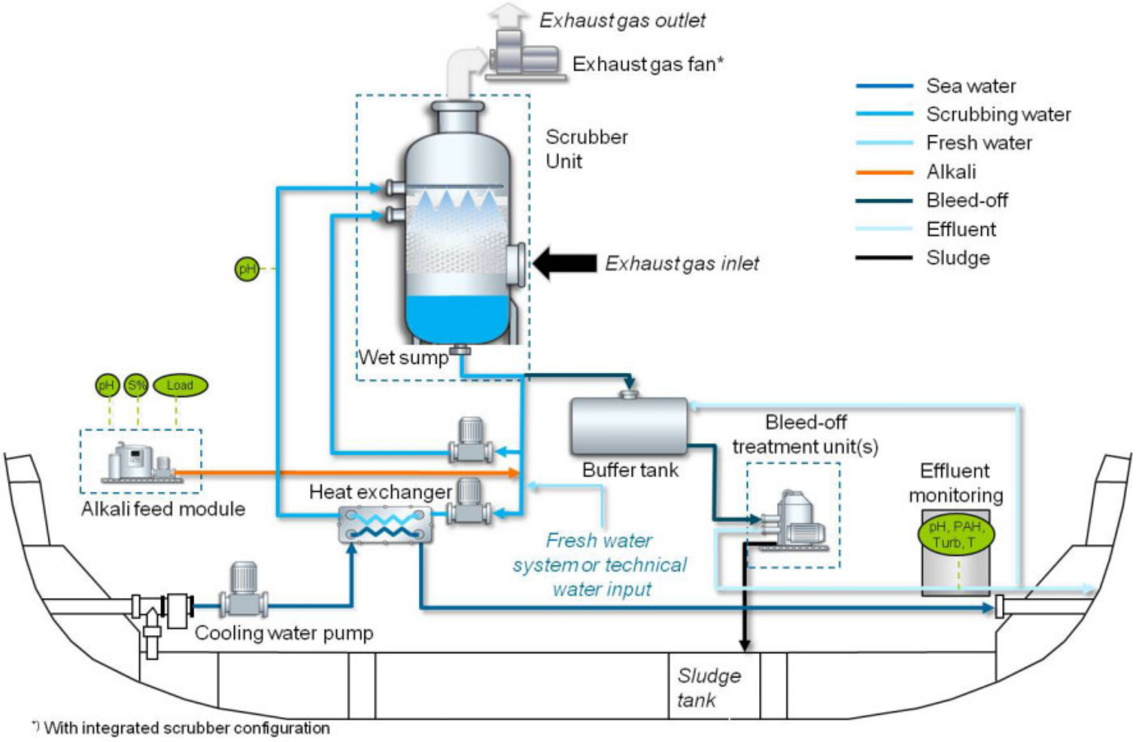


Figure 23. Closed loop scrubber system principle diagram (Wärtsilä).

A scrubber unit contains an inlet connection for exhaust gases, a vertical chamber structure with a wet sump, injection nozzles and pipes for scrubbing medium injection, a packed bed (if installed), piping and a droplet separator, which is also known as a demister. If a dry sump design is used, a process tank is needed for scrubbing water storage and circulation. The inlet connection can be installed longitudinally, transversally or in any arbitrary direction in the ship. A standard scrubber unit is made of a suitable corrosion resistant metal but also Glass-reinforced plastic (GRP) can be considered as material enabling the weight minimization. The unit is equipped with mounting brackets in the bottom part near the connection between mid shell and bottom cone and it also got mounting brackets for lateral supports in the top cone (Wärtsilä 2011d, 8; Wärtsilä 2012b, 13).

The technical fresh water system contains a scrubbing water pump unit, a technical fresh water tank and a fresh water hydrophore module. Evaporated water and a good quality tap water (bunkered from port) can be used for make-up water. On cruise ships, clean effluent from a modern Advanced Wastewater

Purification (AWP) system can also be used for water supply. Typically, the amount of processed AWP-water is much higher than the demand for scrubber make-up water, so other fresh water supply may not be needed for scrubber system at all, if the AWP-water is utilized (Wärtsilä 2011d, 22).

With the Closed loop scrubber, the sea water system supplies sea water with a sea water pump from the ship's sea chest to a heat exchanger. Typically one pump and heat exchanger per scrubber unit are needed for the system. In the alkali system some alkali is added to the scrubbing water to maintain the correct pH where typically the 50 % NaOH solution is used. The system contains, an alkali feed module, an alkali storage tank and emergency showers (SOCP 2011, 22; WLSA 2012, 138).

The scrubbing water system utilizes the scrubbing water pump unit in two circuits: upper and lower. The lower circulates the scrubbing water from sump to a lower nozzle section and the upper to an upper nozzle section via a heat exchanger in sea water system. In order remove the accumulated impurities from the scrubbing water, a small flow of bleed-off is extracted from the scrubbing water. The bleed-off system is equipped with a bleed-off distribution pipe, a bleed-off buffer tank with de-aeration equipment and connections, bleed-off treatment units (BOTU), an effluent monitoring module (EMM), an effluent holding tank and a sludge tank. Some of the equipment like the BOTUs and the buffer tank can be located to an equipment container, which can be installed to the main deck. Also the BOTU uses alkali from the alkali system. The number of installed BOTUs is project specific and depends on the bleed-off flow rate. Typically one stand-by BOTU is specified for each scrubber system for situations when one of the BOTU(s) is out of operation or under maintenance. The EMM monitors the effluent quality and controls the effluent discharge based on the effluent quality (Wärtsilä 2011d, 36-45).

Some compressed air is used as service air in the BOTUs and in the fresh water hydrophore module whereas effluent monitoring module, emission monitoring module and BOTUs uses some compressed air also as control air. As an optional arrangement, an exhaust gas re-heater can be installed for plume control. Also engine room exhaust ventilation air can be utilized to reheat the exhaust gas from the scrubber. Other exhaust gas system related arrangements and equipment are explained in chapter 3.5 Scrubber configurations (Wärtsilä 2011d, 36-45).

The Closed loop scrubber is equipped with an automation system for operation, monitoring and safety control. The system combines a dedicated scrubber control unit with display, field sensors and control valves with following functions: control and safety, monitoring and alarms, data logging with trending capability as tamper proof and in compliance with Marpol regulations, real-time process control and the control system act as interface to the bleed-off treatment system and to the emission and effluent monitoring. The scrubber interface and logging system is normally located to the ship's engine control room (Wärtsilä 2011d, 43-44).

3.2.2 Closed Loop Scrubber Process Principle

In the Closed loop scrubbing process, the scrubbing medium, in this case water mixed with alkali, is pumped from the wet sump (or process tank) through the sea water heat exchanger to the top part of the scrubber unit or directly, without cooling, to the mid part of the scrubber to further improve the SO_X removal efficiency. Circulated scrubbing water pH, and thus the cleaning efficiency, is automatically monitored and controlled by the alkali dosing in the alkali system. The water mixture is sprayed in to the exhaust gas flow from the spray nozzles. The sulphur oxides from the exhaust gas are neutralised to sulphates in the scrubbing water as a result from the chemical scrubbing process. The scrubbing water passes through the packing bed and is collected and removed through the wet sump located on bottom of the scrubbing unit. The flow rate of the scrubbing water circulation is related to the actual dimensions of the scrubber unit and the designed performance of the whole system. The water absorbs SO_X, heat and other components like traces of lubricating oil, metals, etc. from the exhaust gas stream. The heat from the scrubbing water is removed in the sea water heat exchanger(s). The reason of the cooling is to minimize the water content in the cleaned exhaust gas after the scrubber, thereby minimizing the plume opacity and the fresh water consumption. This cooling has no effect on sulphur removal efficiency from the exhaust gases (Wärtsilä 2011d, 24).

A small bleed-off is extracted from the scrubbing water circulation to remove the accumulated impurities and is led to the BOTU. In normal operation, the effluent is pumped from the BOTU to the EMM and then overboard. The effluent can be led to the holding tank for scheduled and periodical discharge if operation in Zero discharge mode is needed. The EMM monitors effluent quality and controls the effluent discharge. The effluent is measured according to IMO Resolution MEPC.184(59) where measurable parameters are pH, PAH_{phe}, turbidity and temperature. If the effluent does not fulfil the requirements, the effluent is diverted back into the buffer tank for further purification (Wärtsilä 2011d, 45).

Fresh water is added to the system for compensating scrubbing water evaporation losses and the extracted bleed-off. The water balance can be determined as following: the needed make-up water equals the humidity lost to the atmosphere plus the bleed-off minus the water content of the exhaust gas from the combustion units. The fresh water consumption depends on ambient conditions, scrubbing water and consequently also the sea water cooling temperature (Wärtsilä 2011d, 22). Effective cooling by the scrubbing water and the packed bed minimizes the humidity loss with the help of the droplet separator.

3.3 Open Loop Scrubbers

The sea water scrubber (SWS) operates in Open loop system where sea water components react with the exhaust gas components by capturing and neutralising them. The neutralisation is provided by carbonates in the sea water however, about 4.0 % of the neutralisation is provided by borates and other ions in low concentrations. The open loop -term is used as most of the water drawn in from the sea is discharged back to the sea after passing through and purified by the system (EPA 2008, 20; Hamworthy Krystallon Limited 2007, 2).

3.3.1 Open Loop Scrubber System Design

The Open loop scrubber system operates with the sea water without added chemicals or additives. The scrubber is designed to pre-treat the exhaust gas and then to intimately mix the gas with the sea water in order to remove SO_X and particulates (Hamworthy Moss AS 2011a, 3). The system's main components and flows can be seen in Figure 24.

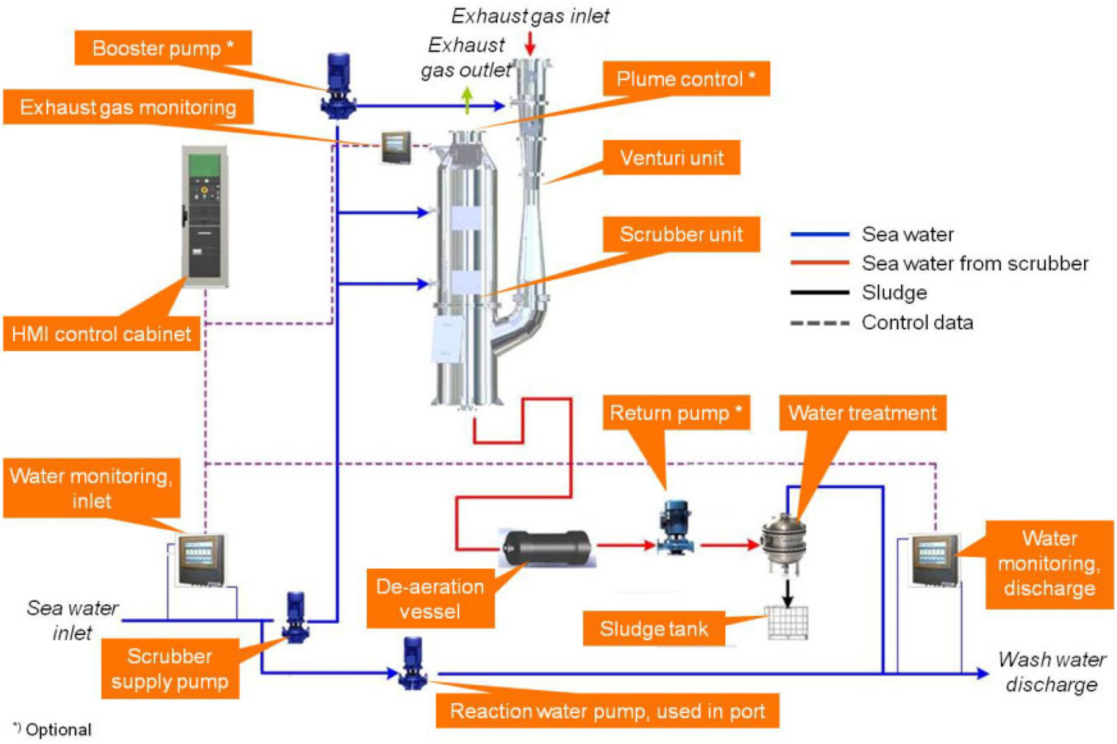


Figure 24. Open loop scrubber system principle diagram (Wärtsilä).

The system is equipped with water pumps for scrubbing water pumping and reaction water pumping. The pumps are typically in three groups. Washwater supply pumps are standard sea water pumps, which provides the sea water scrubbing medium to the scrubber. Return pumps are required if pressure in the return line is insufficient, so the pumps accommodate the pressure drop across the water treatment plant. Reaction water pumps are also standard sea water pumps and those can be used to provide sea water for neutralisation of the washwater pH before overboard discharge in port (Hamworthy Moss AS 2011a, 3; SOCP 2011, 20).

An Open loop scrubber unit contains a Venturi section with quench spray nozzles and a scrubber tower section with a bubble tray, a wet filter, droplet separator and sea water injection connections and nozzles. In the baffle scrubber tower, internal baffles divide the scrubber into several stages where the each stage causes different interactions between the gas and water. Pumped sea water is injected near the top through the special nozzles and gravitates to the bottom passing through the various baffle stages. Because of the sea water, the scrubber unit and most of the system are manufactured of the corrosion resisting steel. A de-plume facility can be provided for operation in cold climates (EPA 2008, 20; Hamworthy Moss AS 2011a, 3).

After the scrubber unit, a de-aeration tank with an overflow connection is installed for settling the scrubbing water. The scrubbing water flows from the tank to a water treatment plant via a valve controlled flow connection. The water treatment plant contains a set of large multi-cyclones. The plant is dimensioned according to the scrubber amount and capacities. After the water treatment plant, the scrubbing water can be discharged to overboard or led to a buffer tank. Sludge from the process is led to a sludge tank. The scrubbing (sea) water quality is monitored at both end of the process with a water monitoring module and an emission monitoring is enabled with a gas analyser located in the stack after the scrubber unit (Hamworthy Moss AS 2011a, 3-6).

3.3.2 Open Loop Scrubber Process Principle

In a three-stage scrubbing process the sulphur from the exhaust gas is neutralized by the carbonate/ Bi-carbonate in sea water. In the first stage, the Venturi section cools down and saturate the exhaust gas with a sea water spray, which also provides an ejector effect by reducing the total pressure drop over the system. In the second stage, the exhaust gas flow is turned upwards in bottom of the scrubber tower section and led through the bubble tray arrangement. A very turbulent mixing of the exhaust gas and the scrubbing water is created, which wets the particles and absorbs the SO_2. The arrangement also allows a higher gas velocity through the scrubber, thus leading to a smaller footprint without major increase in pressure drop. In the third stage, the wet filter polishes remaining sulphur from the exhaust gas and the droplet separator minimizes the humidity water losses (Hamworthy Krystallon Ltd 2012a, 3).

The scrubbing sea water from the scrubber unit enters to the de-aeration tank and is then pumped through the cyclones in water treatment plant, which removes the particulate matter before discharge. The cyclones are designed to separate some of the heavy particles as well as the light particles in a two-stage system (Hamworthy Moss AS 2011a, 3-4).

3.4 Dual Water Hybrid Scrubbers

There are different types of so called hybrid scrubber applications available in the markets. Generally, the hybrid scrubber is a combination of Open loop scrubber (stage 1) and Closed loop scrubber (stage 2). The Open loop stage uses sea water and in most of the applications, the Closed loop stage uses fresh water plus alkali as scrubbing medium but also sea water can be used with alkali. There are also differences in scrubber unit designs and some manufacturers have a design in where the unit can operate either in Open loop or in Closed loop mode, hence in one of these modes at the time. The other design, so called "Dual Water scrubber unit" design, enables the use of both modes with a same time in Hybrid mode. This study concentrates to this Dual Water unit design when the total system operates in Open loop with sea water and in Closed loop with fresh water and alkali. Therefore, the system components and process principles are same as with Closed loop scrubber system added with a Dual Water scrubber unit and sea water scrubbing connections and equipment.

3.4.1 Dual Water Hybrid Scrubber System Design

The Dual Water hybrid scrubber system consists of the Dual Water scrubber unit, a technical fresh water system (stage 2), an alkali feed system (stage 2), a scrubbing water system (stage 2), a sea water cooling system (stage 2), a scrubbing sea water system (stage 1), a bleed-off system (stage 2), a wash (sea) water treatment system (stage 1), an exhaust gas de-plume system, a compressed air system and an automation system. The system's simplified P&I diagram can be found in Appendix 5. Closed loop scrubbing systems (stage 2) are similar to systems in Closed loop (fresh water) scrubber and the equipment number is related to the installation specific design and system size.

The Dual Water scrubber unit, shown in Figure 25, is in one piece in where the exhaust gas inlet connection is radially from the side of the scrubber and outlet is vertically from top of the scrubber. A cross-section of the scrubber unit main body is round providing a rigid structure. The unit is a combination of Open loop (sea water) scrubbing and Closed loop (fresh water) scrubbing unit. So called "Dual Water" means that the unit can be run as in Open loop and Closed loop mode simultaneously. This is possible because of the separated scrubbing chamber (stage) structure. The lower chamber is for Open loop (sea water) scrubbing with water injection equipment and the upper chamber, separated with water mist catcher, is for Closed loop (fresh water) scrubbing containing water injection equipment, water flow trays and a packed bed (if installed). However, depending on the system's operating mode, both stages can be utilized for Open loop or for Closed loop scrubbing.

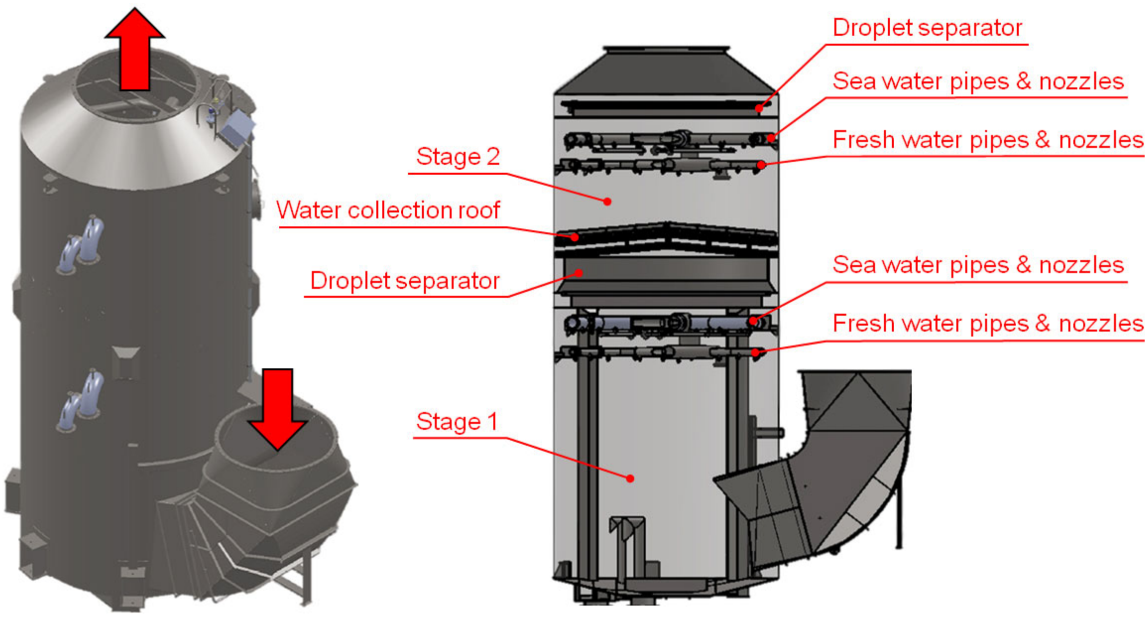


Figure 25. Integrated Dual Water hybrid scrubber unit (Wärtsilä).

Both chambers are equipped for separated water injections circuits for the sea water injection and for the fresh water with alkali injection. As there is a possibility to run both chamber with sea water, the whole unit is made of corrosion resistant metal or partly made of plastics. The unit is equipped with the demister in order to minimize the scrubbing water droplet formation in the exhaust gas after the scrubber and to minimize evaporation losses in Closed loop mode as well.

The scrubbing sea water system contains centrifugal sea water scrubbing pumps located normally below the sea level and therefore in the lowest level of the engine room. Sea water filters are after the pumps in order to prevent the scrubbing nozzles for clogging and one filter will be installed for one pump. Also common strainers can be installed on the suction side of the pumps when separated filters are not needed. The system also contains the water piping to the scrubber unit, which is normally routed through the engine casing (Wärtsilä 2012c, 11-12).

The effluent from the Open loop scrubbing process is treated in the washwater treatment system. In addition of the return piping, there is a de-aeration tank for the settling and air removal from the effluent before centrifugal washwater pumps deliver the effluent to was water treatment units, which are a hydrocyclone of type. The hydrocyclones are used for separation of solid particles from the effluent and for the separation of the contaminants. In the hydrocyclone, the effluent is caused to form a vortex flow where the denser fraction is separated to the wall due to the centrifugal forces and the lighter fraction travels to the core of the vortex (Mäenpää 2011, 42-43).

The exhaust gas de-plume system is an arrangement where the ambient air is added to the exhaust gas flow after the scrubber unit. The system consists of connection air pipes and a control damper with fail safe function in connection point. The system is also equipped with a steam heater arrangement heat-added-air is needed for the plume reduction (Wärtsilä 2012a, 9-15; Wärtsilä 2012c, 4). The automation system is based on process and safety PLCs and the scrubbing process can be monitored and controlled via an interactive main control panel (MCP). The automation system performs following functions: control and safety; monitoring and alarms; data logging with trending capability; reporting function for logged data in compliance with Marpol regulations; and real-time process control. The system is also interfaced to ship's Machinery Automation System or other external system including: group alarms (Primary alarm, Secondary alarm and Marpol alarm); engine rotation speed running signals; engine(s) fuel flow; engine(s) load; and by bus communication for alarms, indications and measurements (Wärtsilä 2012d, 9).

3.4.2 Dual Water Hybrid Scrubber Process Principles

The Dual Water hybrid scrubber can operate in different operating modes under scrubber (automation) run mode, alternating between the Closed loop operation using the fresh water and alkali and the Open loop operation using the sea water (Wärtsilä 2011b, 3). Depending on the ship's operating environment (needed sulphur reduction), the sulphur content of the fuel oil in use and the scrubber system design, the system can be operated in four (4) operating modes, which are Closed loop mode, Hybrid mode, Economy mode and Sprint mode from which the last two are operated in Open loop circuit. It is also possible to switch between different operating modes during ship's operation and the scrubber can be by-passed if needed (Wärtsilä 2012a, 6-7; Wärtsilä 2012d, 25). These operating modes and possible mode-transitions are shown in Figure 26.

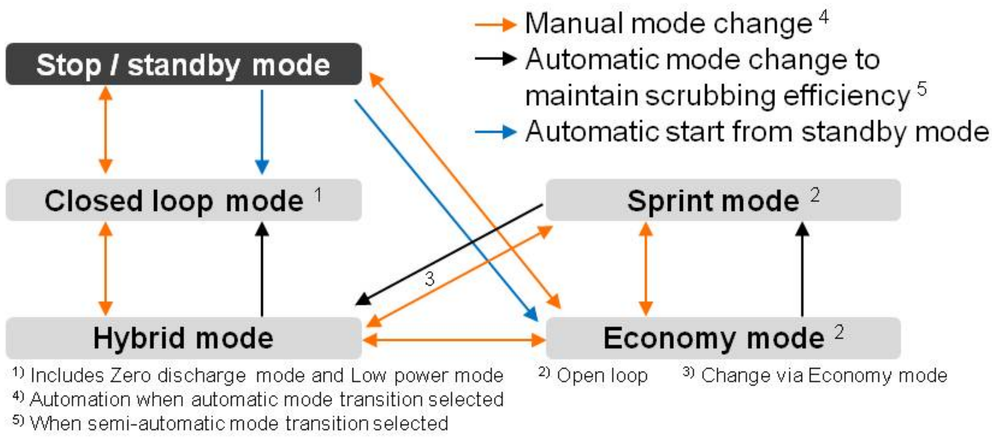


Figure 26. Dual Water hybrid scrubber operating modes and transitions.

With the “manual” mode transition, the operator initiates all mode transitions and automated mode transitions are disabled. The “Semi automatic” mode transition is the default mode for the system. In here, the scrubber automation initiates mode changes when the emission values are between certain threshold value and the actual limit values (i.e. exhaust gas or effluent/washwater) as defined in IMO resolution MEPC.184(59). These mode transitions occur only towards more efficient scrubbing modes. However, as the scrubbing efficiencies increase from the Open loop to Closed loop, the mode changes towards lower scrubbing efficiency are to be done by the operator. With “automatic” mode transition, the scrubber automation carries out automatic transitions based on the operating mode of the ship, which is obtained from the ship’s automation system (Wärtsilä 2012d, 24). Scrubber operations, by dry running of scrubber or wet running in Closed loop mode without alkali injection, are not permitted (Wärtsilä 2012a, 7).

3.4.3 Closed Loop Mode

In the Closed loop mode, both stages of the scrubber are run with the fresh scrubbing water. The scrubbing water returns from the scrubber unit to the pump module via the process tank. NaOH is added to the scrubbing water circulations to maintain the process pH and consequently the SO_X removal efficiency. Sea water is used for cooling of the second stage scrubbing water circulation, which is pumped via heat exchanger. The bleed-off purification process is same as with Close loop (fresh water) scrubber and with Close loop mode, there is also a possibility to run the scrubber with the Zero discharge mode, when all the cleaned effluent is channelled to the holding tank. Make-up (fresh) water is added to compensate scrubbing water evaporation losses and extracted bleed-off. However, if the scrubber load (the amount of fuel consumed or total engine power) connected to the scrubber is below a threshold limit, the scrubber enters automatically to Low power mode of the Closed loop. In this mode, only the upper scrubbing water circulation is maintained and the lower circuit is stopped and by that the scrubbing water pumping and circulating power demand is decreased (Wärtsilä 2012a, 6; Wärtsilä 2012d, 25-26).

3.4.4 Open Loop Modes

In the Open loop modes, the SO_X from the exhaust gas is captured and neutralized by the sea water circulated through the scrubber unit and no fresh water or alkali is needed with this mode. The system enables two possible operating modes under the Open loop mode: the Economy mode and the Sprint mode. In the Economy mode, the scrubbing sea water is circulated through the scrubber unit's stage 1 and no water flow is led to the stage 2. In the Open loop Sprint mode, the sea water is circulated through both stages 1 and 2 (Wärtsilä 2012d, 25-29).

In the Open loop mode, the sea water is taken from the ship's sea chest with the sea water scrubbing pumps. Before the water is delivered to the scrubber unit, it is passed through the sea water filter(s) or the strainer(s) on pumps' suction side. Depending on the selected mode (Economy or Sprint), the sea water is injected to the lower chamber or to both chambers. From the scrubber unit, the open-loop effluent flows by the gravity to the de-aeration tank. In these Open loop modes, there is also a possibility to by-pass the de-aeration tank. The contaminants are removed from the sea water in the washwater treatment unit before monitoring and discharge overboard. The sludge from the treatment unit is stored in the sludge tank and given to port reception facilities (Wärtsilä 2011b, 4; Wärtsilä 2012d, 27).

3.4.5 Hybrid Mode

In the Hybrid mode, both Closed loop (fresh water) and Open loop (sea water) scrubbing processes are in operation simultaneously. The SO_X from the exhaust gas is captured and neutralized by the sea water circulated through the first stage. The exhaust gas continues to the second stage, where further SO_X -reduction can be provided with the fresh water scrubbing if needed. The need for 2^{nd} stage scrubbing is depending on the ship and site dependent parameters like the fuel sulphur content, the exhaust gas flow, the sea water alkalinity, the sea water temperature and the cleaning requirements (Wärtsilä 2012a, 6-7).

3.4.6 By-passing Scrubber when Scrubber Is Not Operating

Before the scrubber unit, a 3-way by-pass damper is installed to a suction branch connection when traditional upstream exhaust pipe remains as by-pass pipe. This design is common to all the Wärtsilä's scrubber solutions. During normal scrubber operation, the by-pass pipe is closed thus preventing escape of un-cleaned gases. When the scrubber is not in operation, the by-pass connection is open. The scrubber can be by-passed, i.e. scrubber operation is not needed, when compliance with regulations is achieved by using the compliant fuel, or in the emergency situation case when the scrubber operation might damage the ship or its equipment according to Marpol Annex VI Regulation 3 (Wärtsilä 2011d, 17; Wärtsilä 2012a, 7).

3.5 Scrubber Configurations

Depending on the ship design, engine configurations, etc. technical installation specific arguments or customer's interests, the scrubber system can be designed to be a main stream or an integrated scrubber system. Both configurations should have the by-pass connection before the scrubber(s).

3.5.1 Main Stream Scrubber

The main stream scrubber is designed to be connected into the exhaust gas stream of an individual diesel engine. The main stream scrubbers are usually located to the engine casing or to the funnel, in direction of flow after the possible SCR, the exhaust gas boiler and the silencer, as illustrated in Figure 27. The configuration is advantageous with merchant ship configurations for example with a configuration of one single main engine with generator auxiliary engines and oil-fired boilers using low sulphur fuel. However, generator engines can also be equipped with the main stream scrubbers. The main stream scrubber configuration can be fitted to both new-buildings and retro-fit installations with typically 900 Pa exhaust gas pressure loss over the scrubber unit at design conditions (Wärtsilä 2010b, 3; Wärtsilä 2011d, 1-13).

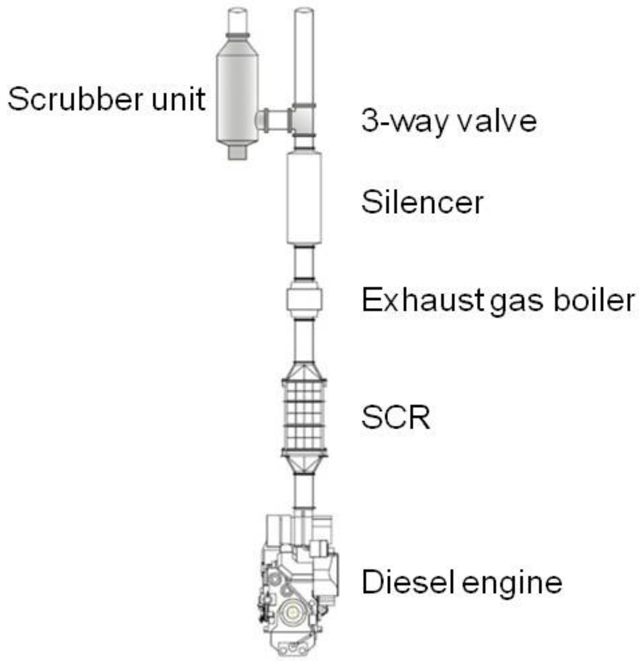


Figure 27. Main stream scrubber installation principle (Wärtsilä).

3.5.2 Integrated Scrubber

The integrated scrubber configuration can be used when the scrubber is designed to clean the exhaust gases of several main and auxiliary engines and oil-fired boilers onboard with one scrubber unit. The configuration is suitable for all ship types and especially in ships with several main engines, ships with single main engines and generator engines using heavy fuel oil and diesel-electric ships. The integrated scrubber does not increase the exhaust gas back pressure, thus making it particularly suitable for oil fired boilers, which don’t tolerate much of the back pressure. Also the integrated scrubber configuration is feasible for both new-buildings and retro-fit installations (Wärtsilä 2011d, 1; Wärtsilä 2012b, 2-1).

An ideal location for the integrated scrubber is aft of or within funnel enclosure as this enables a minimum loss of useable cargo or accommodation space with functional gas flow and access to main components. Rest of the exhaust system and engine casing are following conventional design with the possible SCR, the exhaust gas boiler and the silencer(s) installed before scrubber intake connection (Wärtsilä 2011d, 4-14). An example of the connections is illustrated in Figure 28.

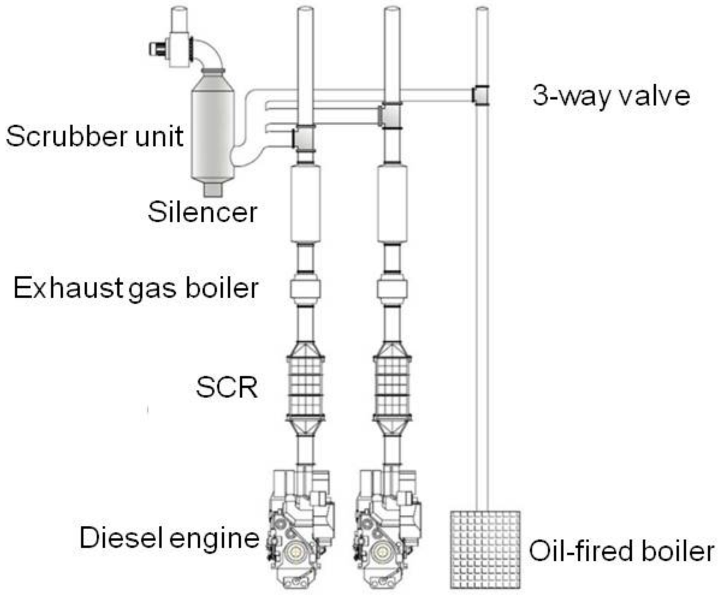


Figure 28. Integrated scrubber installation principle (Wärtsilä).

In most cases one integrated scrubber per ship is the most economical and practical solution especially with retro-fit projects when the ship is powered by HFO. However, in ships with two funnels located with a distance from each other, a configuration consisting of two integrated scrubbers may be preferred. As the high and exposed location of the integrated scrubber on upper superstructure and the ship's profile may be affected, the scrubber(s) should be considered to be part of the ships architectural design already in the project phase. This would also allow structurally continuous supporting between the scrubber and the hull. The system should also be considered in ship stability calculations due to its high vertical centre of gravity (Wärtsilä 2011d, 13-14).

3.6 General Scrubber Operational Principles

In the wet scrubbing process, SO_X diffuses through the gas phase to a liquid surface, where it dissolves and transfers by diffusion or mixes into the liquid phase. The SO_X transfer rate depends on a number of operating variables and factors such as the solubility of SO_X in the liquid and its displacement from equilibrium. Several models have been created to describe this transfer across a phase boundary and for the most popular scrubbing systems types there are empirical relationships and general "rules of thumb” that can be used to determine the possible scrubber solution if the design and operating parameters are within "normal" ranges. However, because of the complex mass and heat balance transfer occurring in the scrubber and the variety of scrubber designs, there is no collection of simple equations and models that can be used to do an in-depth evaluation of all scrubbing systems. From an economical point of view, the mole ratio of L/G is generally acknowledged as one of the most important criterions for reflecting the scrubber unit (tower) performance (Dou & all, 6; Joseph & Beachler 1998, chapter 1: 9 & chapter 5: 2).

3.6.1 Design Criteria

There are four commonly acknowledged main dimensioning criteria or factors for counter-current spray tower and packed tower scrubber dimensioning:

1. A gas velocity as the rate of exhaust gas from the combustion process determines a size of the scrubber. The scrubber needs to be designed so that the gas velocity through it will support good mixing between the gas and liquid phases. However, too fast velocity may cause flooding in the scrubber. Nevertheless, the most efficient mass transfer occurs at the flow rates just short of the flooding. Still the higher flow rates results also the higher pressure losses.
2. A liquid-injection rate as the scrubber’s removal efficiency can be increased by an increase in the liquid-injection rate to the scrubber tower. This amount of liquid is limited by the dimensions of the scrubber and increasing liquid-injection rates will also increase the operating costs by the increased pumping capacity. The optimum liquid-injection rate is also set by the exhaust gas flow rate and by the scrubber economy.
3. Scrubber tower dimensions by the height, and also packing height in packed tower scrubber, as the height increases total surface area and residence time increases, which enhance the absorption. The amount of

mass transferred is equal to the rate of mass transfer times the time of contact. However, the higher tower design and/or more packing necessitate a larger absorption system, which also increases the capital costs. Also the tower diameter influences to the flow rate of the gas that can be treated and the back pressure formation over the system.

4. A packing size in the packed tower scrubber as smaller packing sizes offer a larger surface area and therefore it is enhancing the absorption. However, the smaller packing may increase the pressure drop across the packing bed as it fits more tightly and thus decreases the open area between packing (Joseph & Beachler 1998, chapter 5: 2; Schenelle & Brown 2002, chapter 11: 5).

Other design criteria are: the pressure drop over the system; the material design, which affects on corrosion resistance; the structural strength; the weigh; the design temperature and also the installation and maintenance easiness; the operating costs; etc. (Joseph & Beachler 1998, chapter 5: 7).

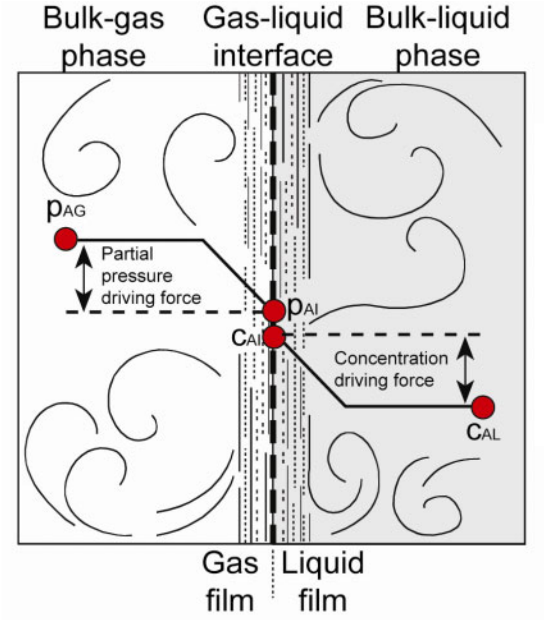
3.6.2 Absorption

The absorption is a diffusional mass-transfer operation in where a soluble gaseous component is removed from a gas stream by dissolution in a solvent liquid. The absorption phenomenon can be categorized as physical or chemical. The physical absorption may occur when the absorbed compound dissolves in the liquid and the chemical absorption may occur when the absorbed compound and the liquid (or some added reagent in the liquid) reacts. In this mass transfer, a concentration difference of the solute between the gaseous phase and the liquid phase acts as a driving force. In the absorption process, this driving force exists as there is a difference between the partial pressure of the soluble gas in the exhaust gas and the vapour pressure of the solute gas in the liquid film contacting with the gas. With the positive driving force, the gaseous pollutant and liquid are not in equilibrium with each other so the absorption process continues as long as a concentration difference exists. But if the driving force is negative, desorption or stripping may occur and the concentration of the pollutant in the exhaust gas may increase (Joseph & Beachler 1998, chapter 11: 3; Schenelle & Brown 2002, chapter 11: 1).

3.6.3 Mass-Transfer Models

The most widely used model for describing the absorption process is the two-film, also known as a double-resistance model, which indicates that the removal rate is controlled by a combination of both gas-film and liquid-film diffusions. This model was first introduced by Whitman in 1923 and it starts with the three-step mechanism of absorption, which contains: large contact area (1), good mixing (2) and sufficient residence time (3). Other variably used theories are Penetration Theory by Higbie in 1935, Surface-Renewal Theory by Danckwerts in 1951 and Film-Penetration Theory by Toor and Marchello in 1958 (Dou & all, 7; Joseph & Beachler 1998, chapter 2: 7; Slotte 2010, 29-30).

The two-film model assumes that the gas and liquid phases are in turbulent contact with each other, as they usually in the scrubber towers with horizontal inlets from the bottom, and the phases are separated by an interface area where two phases meet. This assumption can be correct but no mathematical models satisfactorily describe the transport of a molecule through both phases in turbulent motion. Therefore, the model proposes that a mass-transfer zone holds a small portion (film) of the gas and liquid phases on either side of the interface. As a result, the mass-transfer zone is composed of two films, a gas film and a liquid film on their respective sides of the interfaces like can been seen in Figure 29. These films are assumed to have a flow with a streamline or laminar motion. In this laminar flow, molecular motion occurs by diffusion, which can also be categorized by mathematical models. In the scrubbers, the absorption process requires a close contact between the gas and the liquid, so therefore the liquid is broken into small droplets or thin films, which are constantly renewed through turbulence in order to provide high liquid surface area for mass transfer as well as a fresh, unsaturated surface film for high process driving force (Joseph & Beachler 1998, chapter 11: 10-11; Schenelle & Brown 2002, chapter 11: 16).



p_{AG} = Partial pressure of solute A in the gas

p_{AI} = Partial pressure of solute A at the interface

c_{AI} = Concentration of solute A at the interface

c_{AL} = Concentration of solute A in the liquid

Figure 29. Illustration of two-film theory.

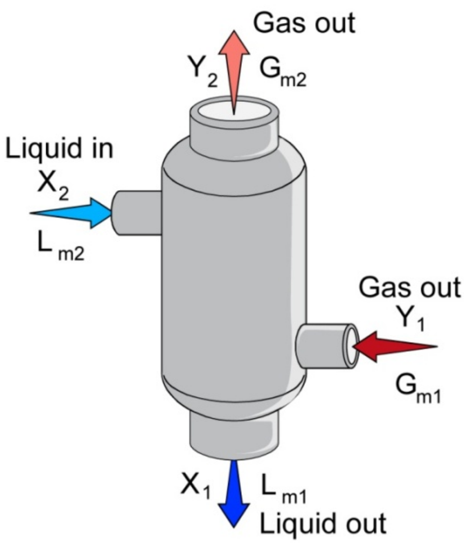
According to the two-film theory, for a molecule of substance (A in Figure 29) which is to be absorbed, it must pass through five steps. The molecule must:

1. Migrate from the bulk-gas phase to the gas film
2. Diffuse through the gas film
3. Diffuse across the interface
4. Diffuse through the liquid film
5. Mix into the bulk liquid

In the mass transfer process, the complete mixing takes place in both gas and liquid bulk phases and the interface is at equilibrium thus the pollutant molecules may transfer in or out of the interface. This leads to phenomenon where all movement's resistance occurs when the molecule is diffusing through the gas and the liquid films in order to get to the interface area. A gas concentration is expressed by its partial pressure and in the process the gas phase partial pressure changes from p_{AG} in the bulk gas to p_{AI} at the interface. Correspondingly, the liquid concentration changes from c_{AI} at the interface to c_{AL} in the bulk liquid phase as the mass transfer occurs (Joseph & Beachler 1998, chapter 11: 10-11; Schenelle & Brown 2002, chapter 11: 1).

3.6.4 Mass and Energy Balances

The basis for all process design is the mass and energy balances in where the thermodynamics serves as the scientific background for these calculations. Thus, when designing an absorption system i.e. exhaust gas scrubber, the first task is to determine the flow rates and composition of each stream entering the system. According to the law of conservation of mass, the material entering a process must either accumulate or exit meaning that what goes in to scrubber must come out. Therefore, a material balance helps determine flow rates and compositions of individual streams in the scrubbing system. The "material" refers to solute in the material balance. Energy in scrubbing process is highly related to pumping of the scrubbing fluid as well as the heat and flow energy in the exhaust gas stream hence often the flow streams of the liquid and gas are used instead. Figure 30 presents the material balance for a typical counter-current-flow exhaust gas scrubber (Joseph & Beachler 1998, chapter 11: 16-17; Schenelle & Brown 2002, chapter 8: 4).



X = Mole fraction of solute in pure liquid

Y = Mole fraction of solute in inert gas

L_m = Liquid molar flow rate

G_m = Gas molar flow rate

Figure 30. Material balance for counter-current-flow exhaust gas scrubber.

The mass balance is presented in Equation (3) and it is termed for around a cross-section through the scrubber tower assuming that the gas and liquid molar flow rates are constant.

$$Y_1 \times G_{m_1} - Y_2 \times G_{m_2} = X_2 \times L_{m_2} - X_1 \times L_{m_1} \quad (3)$$

3.6.5 Determining the Liquid Requirement

When designing the scrubber tower for exhaust gas cleaning, usually some of the variables will be known. The actual exhaust gas flow rate (G) is depending on the combustion unit(s) connected to the exhaust gas scrubber and the mole fraction of exhaust gas at scrubber inlet (Y_1) is related to the sulphur content in the fuel oil in use. The mole fraction of the cleaned exhaust gas at scrubber outlet (Y_2) is specified by IMO regulation depending on ship operating areas. The mole fraction of scrubbing liquid into the scrubbing tower (X_2) may also be known especially with Open loop scrubber, when it is usually close to zero as solvent is used only once (Joseph & Beachler 1998, chapter 11: 19-20).

The rate of liquid flow is an important parameter in wet scrubbing systems and it expresses the liquid flow as a function of the gas flow rate that is being treated. This is commonly known as the liquid-to-gas ratio. For the gas absorption, the liquid-to-gas ratio gives an indication of the difficulty of removing a pollutant while for particulate removal, the liquid-to-gas ratio is a function of the mechanical design of the system. However with Open loop scrubber, the scrubbing liquid demand is related to the sea water temperature and characteristics in means of alkalinity and salinity. Based on Equation (3) the material balance can be solved for the exit liquid concentration X_1 according to Equation (4).

$$X_1 = \left(\frac{G}{L}\right)(Y_2 - Y_1) + X_2 \qquad (4)$$

Therefore if L or G/L can be found, the entire material balance will be solved (Joseph & Beachler 1998, chapter 2: 9; Schenelle & Brown 2002, chapter 11: 26).

3.6.6 Solubility

The solubility acts as an important factor affecting the amount of a pollutant that can be absorbed in the scrubbing process. It is a function of the temperature and with minor extent the pressure of the system. High temperatures have decreasing effect on the solubility and high pressure has the opposite effect as it increases the solubility. According to the ideal gas law, as temperature increases the volume of a gas also increases. Therefore, less gas is absorbed by the liquid at the higher temperatures due its larger volume. However, by increasing the pressure of the system, the amount of gas that can be absorbed, generally increases (Joseph & Beachler 1998, chapter 11: 4).

Also in sea water scrubbing, the solubility increases with an increasing sulphur dioxide partial pressure and decreases with an increasing temperature and also by ionic strength of sulphurous compounds of the solution. However, the salinity of the sea water increases the solubility of the SO_2. In addition, the higher solubility of SO_2 in sea water can be explained by the presence of alkaline components in the sea water and it also contains an excess of base over acid with pH usually above 8. The solubility of SO_2 gases decreases when the initial neutralizing capacity of the alkalinity is consumed at the pH of 4.2 (Al-Enezi & all 2001, 1437; Karle & Turner 2007, 26; Rodríguez-Sevilla & all 2004, 1714).

3.6.7 Particle Collection

In the particle collection the exhaust gas scrubbers rely on inertial forces, also known as Newtonian forces, when collecting contaminants carried in the exhaust gas stream. The inertial forces used are an impaction, interception and diffusion, which are presented in Figure 31. Also electrostatic forces or fabric and other filters can be utilized for particle collection but those are not yet common in the wet scrubber systems. Most often the scrubbers can capture relatively small particles with the liquid droplets. These droplets can be produced by several methods but in most of the wet scrubber applications they are produced by injecting liquid at high pressure through specially designed nozzles in the scrubber tower, or more often in the Venturi -section. Other methods that can be used are aspirating the particle-laden gas stream through a liquid pool or submerging a whirling rotor in a liquid pool. The size distributions of particles, which are to be collected, are the exhaust gas source specific (Hesketh & Schifftner 1996, 5; Joseph & Beachler 1998, chapter 2: 2; Schenelle & Brown 2002, chapter 19: 4).

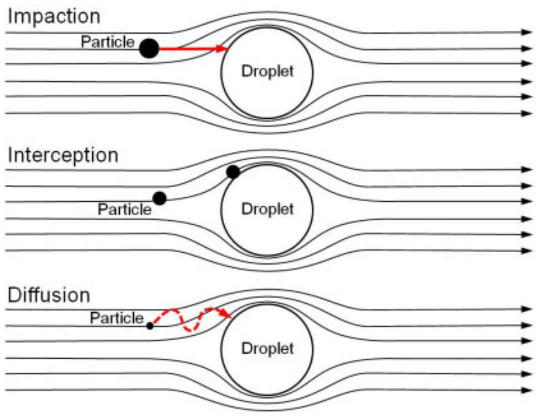


Figure 31. Basic particle collection mechanisms.

The impaction is the most common collection method of the particle removal. In the impaction, large particles moving toward to a droplet have mass and therefore momentum, which cause these large particles to travel in a straight line toward the droplet. The particle leaves the streamline when it bends to move around the target. Velocity difference between the particle and the target also affects thus as the difference increases, the particle momentum will increase and the impaction occurs more likely. Also larger the mass of the particle, more likely it will travel in the straight line. The impaction can be improved by the droplet size, when with smaller droplets the radius of curvature gets smaller, which will cause that the particle will less likely follow the streamline. Therefore, the small droplets are more likely to be impacted than the large droplets. In some scrubber applications, the particles are accelerated directly into the liquid film (Hesketh & Schifftner 1996, 5; Schenelle & Brown 2002, chapter 19: 9).

The particles which do not directly impact to droplets can be captured by the interception. The particles between 0.1 to 1.0 µm have an insufficient inertia to leave the gas streamline and are carried with the streamline. In the interception, the particles are carried by the exhaust gas streamline suitably close to the surface of the droplet, which causes a contact to the droplet. The phenomenon is droplet density related, as changes for the interception increase when the density of the droplets increases. Scrubbers, like spray tower scrubbers and high Venturi scrubbers, rely on creating high-density sprays of the very fine droplets in an effort to increase the interception (Hesketh & Schifftner 1996, 5; Schenelle & Brown 2002, chapter 19: 9).

The diffusion of extremely small particles is a result of Brownian motion. Also electrostatic forces begin to make an appearance when the particle sizes gets smaller. These submicron particles have very small mass and the number of collisions with the air molecules is low, thus random collisions with other gas molecules cause the particle to bounce around in the exhaust gas stream. This diffusion phenomenon brings the small particles into contact with the liquid droplets especially when there is little energy difference between the collecting liquid and the contaminant. The diffusion is useful in scrubbing systems where there is a high temperature difference between the exhaust gas stream and the scrubbing liquid. It also acquires a sufficient time and relative small distance between the particles and the droplets. Therefore, electrostatic precipitator and fabric filter bag houses can be more effective for collecting submicron particles than the wet scrubber application (Hesketh & Schifftner 1996, 5; Schenelle & Brown 2002, chapter 19: 9).

3.7 Efficient and Modular Dual Water Hybrid Scrubber Portfolio

As the Hybrid scrubber is a product which combines the benefit of both Open loop and Closed loop scrubbing, along with Wärtsilä’s Dual Water technology in where both loops can be in operation at the same time, it is the solution feasible for almost every bigger ship regardless of its type and or design. The Open loop scrubbing enables the usage of the ocean sea water in scrubbing process thus minimizes the need for alkali, and the Closed loop scrubbing enables the scrubber operation on crucial waters, on the low alkalinity waters and in the harbours where zero discharge may be required. Still the most important dimension factor, after selecting the feasible scrubber technology, is selecting the most optimal scrubber configuration to the ship. Other dimensioning related topics will be reviewed later in this thesis.

Along with efficient SO_X reduction, all the wet scrubber types are effective technologies for the reduction of PM when the Venturi-technology being the most effective one. Wärtsilä-Metso design based exhaust gas (Closed loop and Dual Water hybrid) scrubbers are still without the Venturi-section but in Wärtsilä's Open loop scrubbers, this feature already exists, and also other Hybrid scrubber suppliers, such as Aalborg Alfa Laval, utilizes the Venturi - technology in their designs. At the moment, Wärtsilä's design Closed loop and Dual Water hybrid exhaust gas scrubber can meet the needed sulphur reduction level but the PM removal efficiencies are not at the highest levels when comparing the products on the scrubber markets or the PM removal efficiencies have not been tested yet. As discussed earlier, IMO and other stakeholders are at the moment looking into PM emissions as well in shipping sector, so it can be easily predicted that in some point there might be some limits as well for PM emissions as well as BC emissions. Additional to this, the utilization of the Venturi-technology would be wise especially with the main stream configuration, as the scrubber unit design is at present with horizontal inlet.

In year 2016, when a new ship is operating with HFO in ECA area, most likely it will be equipped with the SCR(s) for NO_X reduction and the exhaust gas scrubber(s) for SO_X reduction. With the main stream scrubber configuration, other equipment installed to engine casing would be the silencer(s) and the exhaust gas boiler(s). Wärtsilä is a supplier for all of these equipments except for the exhaust gas boilers. Wärtsilä is marketing itself as the market leader in exhaust gas cleaning solutions for the shipping sector and its Ship Power's strategic vision is to be the leading system integrator in the marine industry. However, even this market position and strategy along with the fact that the company is the supplier for most of the ship's future exhaust gas system components; yet it doesn't have a modular solution or design for whole ship's exhaust gas system arrangements for different ship types, when all of the equipments mentioned above are needed. When the scrubber markets activate before the year 2015, this kind of design and solutions should be available for preselected ship types and designs.

4 DUAL WATER HYBRID SCRUBBER DESIGN PARAMETERS

Operating conditions have a great effect on the SO_2 removal performance. The process temperature, the reagent ratio, the SO_2 concentration and the inlet gas temperature are important factors. The scrubber unit dimensions mainly depends on the selected scrubber configuration, an exhaust gas mass flow and an inlet temperature, the permitted pressure drop in the exhaust gas system and many other parameters. The weight of the scrubber unit is affected by its material selection. In this section, the design parameters related to the Dual Water hybrid scrubber dimensioning and performance are studied and their influences to those are presented. Some of these parameters are operating environment related, so when customising these, the ship's design is not influenced apart from scrubber's side. If other project specific conditions applied, then those should be considered on a case-by-case basis (Schenelle & Brown 2002, chapter 18: 12; Wärtsilä 2011d, 7-9; Wärtsilä 2012b, 2-3, 13). Data and background information are gathered from earlier sections and also calculated data from earlier study made by Nikulainen: The Basic Theory of Seawater Scrubbing and from this thesis' case study is utilized in this section.

There are a number of different impacts that must be understood before selecting an exhaust gas scrubber for a ship. These include a technology compatibility with a current and future required equipment technology along, if possible, with future regulatory changes on sulphur, NO_X and PM as they will affect the practicality of implementing the exhaust gas scrubber (SOCP 2011, 10). Following features may affect on scrubber feasibility study:

1. A ship and cargo type, which affects on: an engine configuration and therefore also on the scrubber configuration; a space available for the scrubber system; can the cargo be used as a fuel like in LNG carriers, which can operate with dual fuel engines; is there a technical fresh water available from ship's other processes; etc. Some ship types may have the space for the scrubber installation but the system weight and the

ship's stability could be an issue with heavy scrubber units located high in the engine casing or funnel. In some other cases, the system could have a negative influence on the ship's cargo/ machinery space, thus the size would then be an issue.

2. Operating routes and regions, which affects on: the time spend in ECA as the scrubber economics is highly dependent on how many days the ship operates in the ECA area; needed scrubber utilization and SO_X reduction rate; ship autonomy requirements; sailing water type, temperatures and properties (salinity, alkalinity, etc.); alkali bunkering possibilities; bunker (fuel oil) quality; need for zero effluent discharge; etc.
3. Ship flag and classification effect on scrubber's certification and equipment classification. These originate from the IMO regulations but those can also be stricter, as the IMO sets only the minimum levels, which need to be fulfilled. As with most of the shipboard equipment installed onboard, also the exhaust gas scrubber requires both statutory certification (issued by, or on behalf of, the flag administration) to confirm that its equipment meets the required performance criteria, and a Classification Society approval (also known as class approval) to confirm that the equipment does not expose the ship for an unacceptable risk and the essential equipment are installed in order to keep the ship in continues operation. There are a number of different statutory and class approvals available by recognised organisations, like the Classification Societies, for the exhaust gas scrubbers and their ship-specific installations. In addition to these, scrubber manufacturers and operators may also wish to undertake an independent verification of the performance of either given equipment design by Type approval or the performance of a ship-specific installation by Verification of performance (EMSA 2012, 16; Lloyd's Register 2012, 12).

There are also several calculation methods for the exhaust gas scrubber dimensioning and the operational performance, from which most are focusing on the packed tower scrubbers. With this scrubber design, the flooding phenomenon may occur and the back pressure increases because of the packing material, therefore those have to be noticed in the dimensioning calculations. In addition, the packing material selection is related to that phenomenon. However, the Dual Water hybrid scrubber's Open loop (sea water) stage is normally without the packing, hence the design familiars to the spray tower scrubber when the flooding is not an issue and the back pressure formation is more related to unit's dimensions, scrubbing sea water flow and its spaying efficiency. Yet, there is no available literature about the Hybrid scrubber dimensioning and efficiency evaluation. In this thesis, the design parameters are presented in two relations: ship specific design parameters and operational environment related design parameters.

4.1 Ship Specific Design Criteria

This section focuses to design criteria, which are affected by the ship design and also by customer specific functionalities and economical interests. Designing the ship is complex process and even though the IMO and the Classification Society regulations does have an input to ship design, one cannot say that at present the ships are built to be as best as they can be. The fundamental aim of an owner of a merchant ship is, naturally, to make a profit on the investment. Characteristics of the merchant ship along with all other parts of the transportation system emerge from economics of the venture, thus those would need deeper study but some basic information is also presented in this thesis (Watson 1998, 633-635).

4.1.1 Engine Configuration

In ship design, a change of any (design) parameter may, and in most of the cases will, affect on many other factors and therefore requires changes in other parameters. Ship's machinery concept and its engine configurations are not an exception in this. One can say that it is not possible to change one parameter or dimension without a significant effect upon many dependent variables. There are many ways to carry out ship design feasibility studies and convergent processes but one of the most evocative is a design spiral, which conveys both the interactive and the iterative natures of the ship and therefore it is also highly present in machinery selection process (Watson 1998, 652). An example of the ship design spiral is presented in Figure 32 and some machinery related parameters are highlighted with colours.

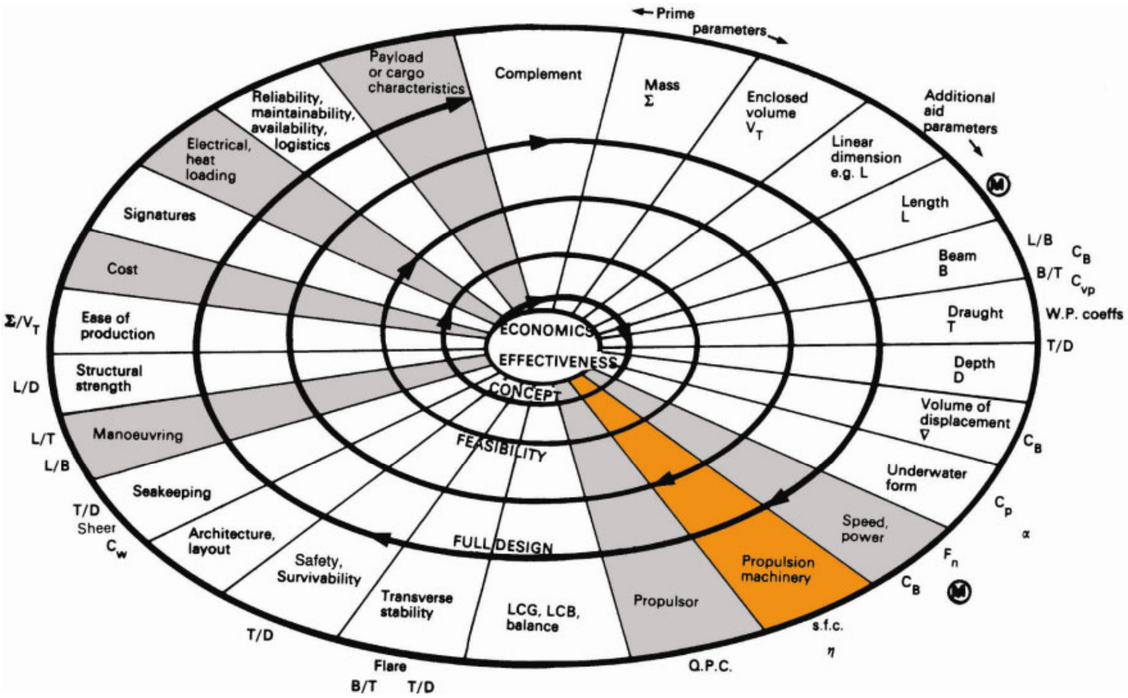


Figure 32. Ship design spiral (Watson 1998, 653).

In the design spiral, the generation of the need for the ship is represented at the centre of the spiral according to the economical or effectiveness related arguments. From there, the spiral starts first with the identification of the characteristics of the cargo or payload and the complement. When beginning, the prime parameter should be chosen and then a concept phase of the design process can be started. As can be seen in Figure 32, there are several variables that can have some affect on machinery selection as well as it has some affect on them (Watson 1998, 652).

Ships can be considered as a solution including a machinery type, engine and propulsion arrangement. The machinery solution forms most important part of the ship design. Some of the main design criteria for the machinery are:

- Mission of the ship by: ship type (passenger accommodation size and type, cargo type and its capacity, ship size, etc.) and ship’s operating profile (speed and speed limits range, power demand, duration, autonomy requirements, loading times, operating area, etc.).
- Machinery economics (initial cost, operating cost especially fuel and maintenance costs, operating revenue, etc.).
- External requirements like: rules and regulations, environmental policies, redundancy and safety requirements, public image, etc. (Wärtsilä 2003a, 18-19; Wärtsilä 2003b, 17-18).

Good total machinery efficiency is beneficial for all the ship types. It is highly reflect to the operating costs, which form a significant part of the total costs for the ship. However, it may also increase the operating range of the ship or alternatively enables to increase the payload. The total machinery efficiency has high impact on the ship’s emissions especially to SO_X and CO_2 emissions as they are directly dependent on the fuel consumption. The lubricating oil consumption is not as significant as the fuel consumption but it still have a clear affect on the operating cost of the ship especially with 2-stroge engines onboard by their cylinder lubricating oil consumptions. The good total efficiency can be reached by having low specific fuel consumption, high propulsion and auxiliary power generation efficiency with low transmission losses. The fuel consumption can be notably reduced by tailoring the machinery concept to match the ship’s operating profile (Wärtsilä 2003a, 18-19; Wärtsilä 2003b, 17-18).

Ship’s trading pattern, i.e. number of estimated harbour/ terminal visits and long haul or short haul traffic, gives a guideline to the engine and propulsion machinery alternatives/ selection. Generally, with the long haul traffic and large ships, a low speed (2-stroke) engine with fixed pitch propeller is the most preferred solution. The number of harbour visits is also affecting on the importance manoeuvring capabilities i.e. the type of main engine and the need and sizing of thrusters. Considerable number of harbour visits supports the medium speed engine alternative with controllable pitch propeller and bow thrusters (Wärtsilä 2002c, 2).

Almost 85 % of the world's merchant fleet is powered by 2-stroke engines with the remainder having 4-stroke engines. Larger 2-stroke engines usually have 10-20 g/kWh lower fuel oil consumption than with the 4-strokes engines. However, with some installations, bigger 4-stroke engines may allow lower fuel consumption than with the 2-stroke engines along with the flexibility and machinery space reduction. The traditional merchant vessel like a tanker, container ship or general cargo ship, is usually a single screw motor ship with one main diesel engine driving a FP-propeller. Ship specific amount of auxiliary diesel generator sets are installed for electric power generation. Also from one to two (1-2) emergency diesel generators may be installed outside the engine room. For heating purposes, the oil-fired boilers and exhaust gas boilers can be installed (Wärtsilä 2002b, 9: Wärtsilä Corporation 2012b, 4-10). Some of the most common engine types and machinery configurations for different ship types are presented in Appendix 6. Different ships' power ranges and main engine(s) power ranges in global fleet are given in Figures 33 and 34.

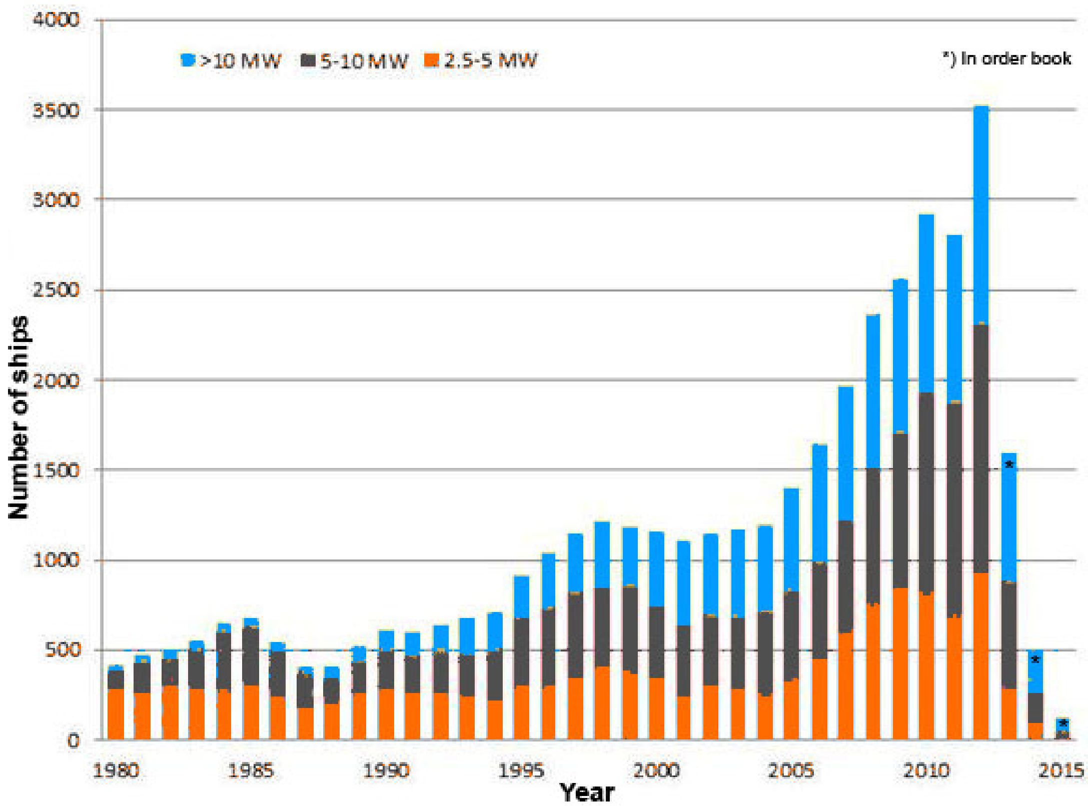


Figure 33. Global fleet in 1980-2015 with different installed power ranges (EGCSA 2012, 5).

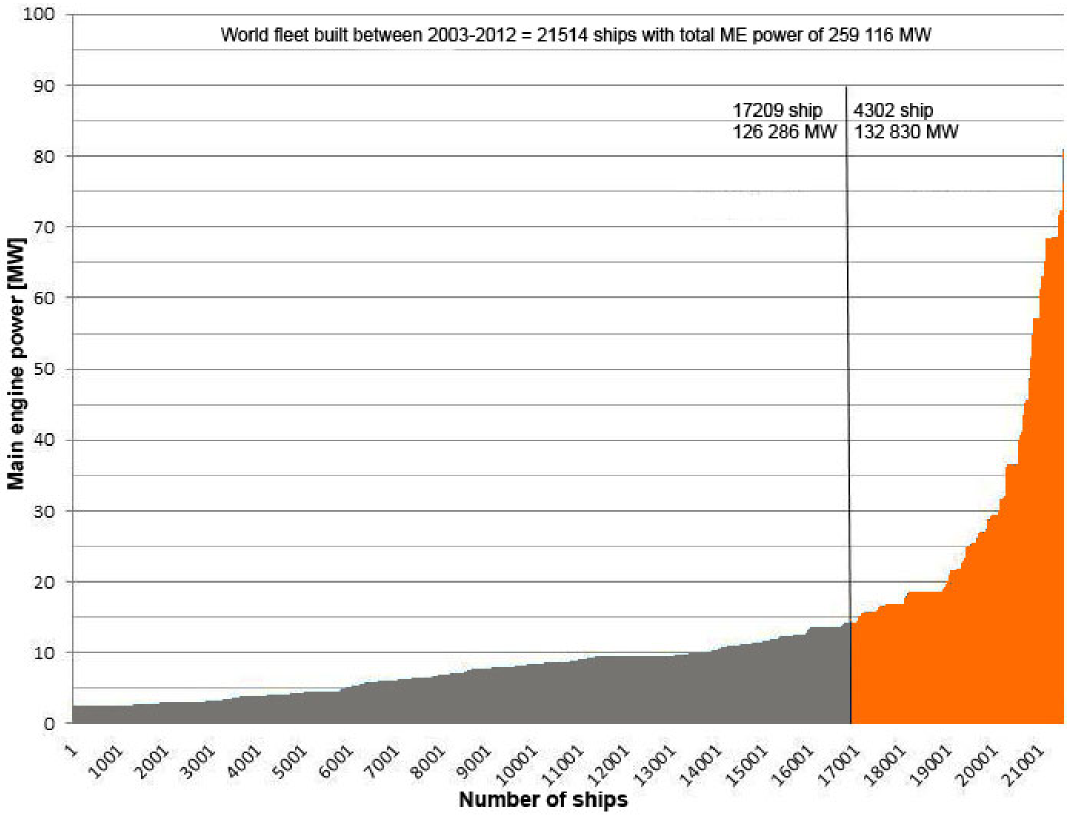


Figure 34. Global fleet according to main engine power (EGCSA 2012, 6).

Since the 1990's, there can be seen some yearly increase in the installed powers of the new ships (Figure 33). If the trend will remain this way, there will be bigger engine installations with more powerful engines also in near future when the merchant fleet would continue having the biggest share in terms of the installed power on board. As can be noticed from Figure 34, approximately 20 % of the world's fleet with main engine powers over 15 MW represents over a half of the total installed main engine power on board in whole world fleet.

Differing from other merchant fleet, the Ro-Ro vessels are designed to transport wheel-based cargo or cargo loaded on wheel-based equipment, therefore the efficient loading and unloading are characteristic of Ro-Ro vessels. Most of the Ro-Ro vessels also operate on short trades with frequent port calls. The vessels are often equipped with twin screws and a geared multiple 4-stroke diesel engine installation with thrusters giving the necessary flexibility and manoeuvring capability for the vessel. At present, there are also available other solutions for merchant fleet such as electric and hybrid machinery configurations, alternative fuels such as the LNG and gas, heat recovery options, as well as different automation concepts and controls (Wärtsilä 2002a, 9-10; Wärtsilä Corporation 2012b, 12).

4.1.2 Ship Operating Profile (Modes)

In normal operation at sea, the main 2-stroke engine or the main 4-stroke engine(s) are running at maximum of 85 % MCR (Maximum Continuous Revolution). Most of the ship owners specify the ship's contractual loaded service speed at 85 to 90 % of the contract maximum continuous rating (CMCR). Still, the CMCR is always a case specific, which is influenced by various parameters, such as propulsive power, propeller type and efficiency, operational flexibility, power and speed margins, possibility of a main-engine driven generator, and the ship's trading patterns (Wärtsilä Switzerland Ltd 2012b, 31).

Typically, at least one auxiliary diesel generator is supplying the electrical load or the shaft generator is engaged if installed. When more power is required for propulsion, more diesel generators can be started and synchronised to the network and the shaft generator can be disconnected, if engaged. With the 4-stroke installation when manoeuvring, the main engines can be running at nominal synchronous speed and the shaft generator, if installed, is connected to feed the possible bow thrusters. Otherwise the diesel generator(s) are providing the power for the thrusters along with other electric consumers. During normal unloading operations in port, auxiliary diesel generators are generating the required electric power while the remaining engines are in stand-by. During the loading operations, the ballast pumps are running, which are also powered by auxiliary diesel generators. Depending on other simultaneous operations, the number of running generator sets varies (Wärtsilä 2002a, 10-11; Wärtsilä 2002b, 10).

At present in the main stream scrubber installations, the scrubber unit is normally dimensioned according to the engine's maximum exhaust gas flow at 100 % MCR. The maximum output is selected because the scrubber should not limit the ship's operation. In case of the integrated scrubber unit, the dimensioning should cover all relevant operating modes, as an example:

- Sea going (Diesel-Mechanical machinery): Main engine(s) at 100 % MCR + Auxiliary engine(s) according to maximum needed hotel power, (unless the shaft generator(s) will be used with this operating mode). The oil-fired boilers are expected not to be in operation as the exhaust gas boilers (economizers) are in operation.
- Sea going (Diesel-Electric machinery): Generating set(s) providing full propulsion and hotel power. In this mode, the oil-fired boilers are expected not to be in operation as the exhaust gas boilers are in operation.
- In port: Auxiliary engine(s) or Generating set(s) and oil-fired boiler(s), as appropriate, at highest possible relevant load. This is highly related to the ship type as for example with the merchant ships, the unloading and loading may result a great power or produced heat demand (Wärtsilä 2012b, 13).

In most cases, the sea going conditions results the highest possible exhaust gas flow and therefore it should be used as design criteria. However, depending on selected scrubber configuration and/or the ship operating profile, the scrubber unit may not be necessarily dimensioned according to total installed machinery power, since such dimensioning might result in unnecessary over-dimensioning, as the total installed power will not be used in practice. Therefore, it is important to identify the ship's needed maximum propulsion power according to CMCR and the needed electrical power as well as the heat demand. The design conditions especially for the integrated scrubber should be examined case by case for accurate dimensioning (Wärtsilä 2012b, 13).

According to several ship operators, most of the shipping companies are not allowed to operate their engine(s) higher load levels than 85 % MCR. In some cases, the permissions for upper load level needs to be requested from the operative management. This may be so because in many cases, the engines' fuel oil consumptions, therefore also ship's operating efficiency, are optimized for load levels of 60-85 %, which can also be noticed from Appendix 9. In other cases, the maintenance schedules, engine operating profiles or other case specific factors may limit the maximum operating load level (Henriksson 2013; Häkkinen 2013). At present, most of the 2-stroke engine manufacturers offer different engine tunings, especially for the common rail engines, which allows further reduction of the specific fuel oil consumption while still complying with all existing (NO_X) emission legislation. Also slow-steaming, which is a practice of operating (merchant) ships at significantly less than their maximum speed, is one the future inspirer for the low load engine operation.

4.1.3 Fuel Oil Consumption

The combustion unit’s fuel oil consumption is an important parameter in scrubber performance study and should also be a part of the exhaust gas scrubber dimension process, since the needed sea water flow to the scrubber is highly related to fuel oil consumption, which will be demonstrated later in this study. The exhaust gas sulphur content is directly related to the fuel oil consumption as well as the fuel oil’s sulphur content and the exhaust gas flow. However, the fuel oil consumption is not included in Wärtsilä’s design parameters, although it may have been provided for dimensioning purposes from marine installation manuals (2-stroke) and performance manuals (4-stroke).

Some examples of Wärtsilä Marine diesel engines specific fuel oil consumptions (SFOC) are given in Table 11. For the 2-stroke engine, the values corresponds brake specific fuel consumptions (BSFC) in reference conditions. Both SFOC and BSFC measures of fuel efficiency within a shaft reciprocating engine, as they are rates of fuel consumption divided by the power produced. Generally, the fuel consumptions are lower with larger low speed 2-stroke engines and 10-20 g/kWh higher with medium speed 4-stroke engines. However, it highly depends on the engine type, its design and tuning.

Table 11. SFOC, exhaust gas flows and temperatures after turbocharger for different Wärtsilä engines (Wärtsilä Product guides; Marine Installation Manuals; WinGTD 3.0 2013).

Engine	Unit	W12V32-E [1]	W12V46F-A3 [1]	5RT-flex50-D	7RT-flex82T	14RT-flex96C-B
Engine type		4-stroke	4-stroke	2-stroke	2-stroke	2-stroke
Engine tuning		IMO Tier II	IMO Tier II + SCR optimization	IMO Tier II + Efficiency-optimised	IMO Tier II + Efficiency-optimised	IMO Tier II + Efficiency-optimised
Engine speed	rpm	750	600	124	80	102
Power output	kW	6960	14400	8725	31640	80080
SFOC [2]	g/kWh	191.0	184.8	171.0	166.0	173.0
Exhaust gas flow [2]	kg/s	13.5	25.2	17.1	64.9	165.3
Exhaust gas temperature after TC [2]	°C	360	377	281	290	308

1) Constant speed, DE or CPP
2) at 100 % load
3) BSFC according to reference conditions

Marine 2-stroke engines have a rating field, which is an area of engine power and speed, and it serves in determination of the specific fuel oil consumption, exhaust gas flow and temperature, fuel injection parameters, turbocharger and scavenge air cooler specifications for the specific engine. An example the engine's rating field can be seen in Figure 35. Rating points (R1, R2, R3 and R4) are corner points of the engine rating field. In this example, the point R1 represents the nominal maximum continuous rating (MCR) so it is the maximum power/speed combination, which is available for this particular engine. The point R2 defines 100 % speed and 70 % power, the point R3 defines 80 % speed and 80 % power, and the point R4 defines 70 % speed and 80 %. These three varies depending on the engine type, thus the rating field is the product and design specific. Also Figure 44 is actually showing the rating points (added with R1+ and R2+) for Wärtsilä 2-stroke engines. In addition to rating field, the selection of a suitable main engine, in order to meet the power demands of the merchant ship, acquires proper tuning in respect of load range (CMCR) and influence of operating conditions, which are likely to prevail throughout the entire life of the ship. The calculation of CMCR is done with assistance of the rating field hence both of them have a great influence to actual engines fuel oil consumption (Wärtsilä Switzerland Ltd 2012b, 31-32; Wärtsilä Switzerland Ltd 2012c, 39).

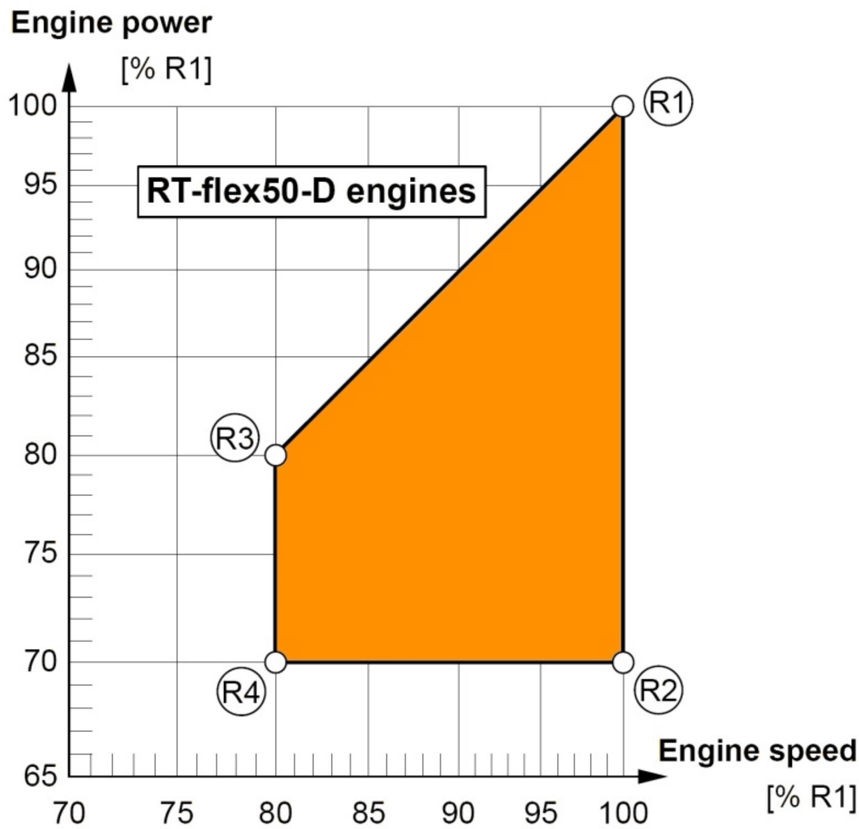


Figure 35. Wärtsilä RT-flex-50-D engine's rating field (Wärtsilä Switzerland Ltd 2010, 27).

Wärtsilä's latest 2-stroke engines are with common-rail fuel system when electrical controlled fuel injection pressures and timing can be freely modified at all load levels. Therefore, the engine can be tuned for optimized BSFC at individual engine loads. Wärtsilä has introduced this concept first as Delta Tuning, which reduces BSFC for Wärtsilä RT-flex engines in the operating range below 90 % engine load. At present, the concept is extended to Low-Load Tuning, which provides the lowest possible BSFC in the operating range of 40 to 70 % engine load. As can be seen from Figure 36, depending on the engine rating field and load range these tunings may also have an important role when determining the fuel oil consumption to the engine (Wärtsilä Switzerland Ltd 2012b, 14).

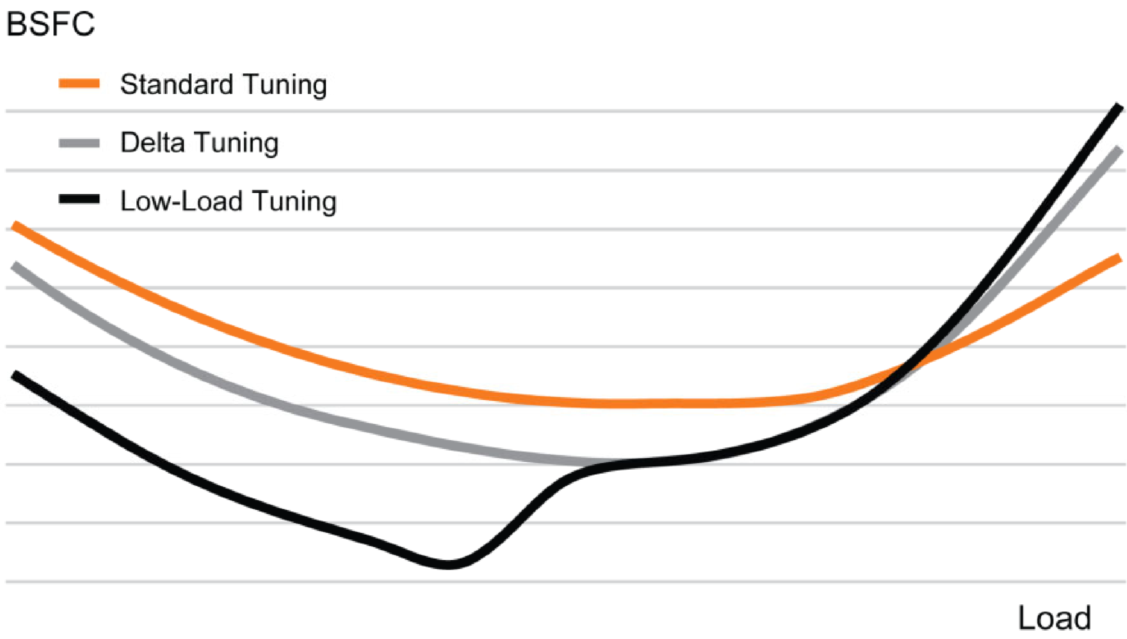


Figure 36. BSFC behaviour with different Wärtsilä 2-stroke engine tunings (Wärtsilä Switzerland Ltd 2012b, 15).

4.1.4 Exhaust Gas Mass Flow

The exhaust gas mass flow depends on the engine speed and load. Therefore, is needed to study first the ship's operating profile, which may affect on scrubber configuration selection and dimensioning by MCR percentage. The needed engine specific exhaust gas data can be obtained from the engine supplier's documentation in case of new ships or from the Technical File related to the EIAPP certificate in case of existing ships (Wärtsilä 2011d, 8-9). For rough orientation, typical specific exhaust gas flows at full power for 2-stroke engines can be something between 7.5-9.5 kg/kWh and for 4-stroke engines it can be 6.0-8.5 kg/kWh. Wärtsilä recommends that the maximum exhaust gas flow velocity in the exhaust pipe is 40 m/s at full load. With long exhaust gas pipes, or if an exhaust gas boiler is installed, the velocity should be lower. Typically, the flow velocity is around 35 m/s at the full engine (Nikulainen 2012, 47; Wärtsilä 2011d, 8-9). The maximum exhaust gas flow level is normally achieved with 100 % MCR. Table 11 contains some examples of exhaust gas mass flows for existing Wärtsilä engine types.

With 2-stroke engines, the engine tuning has some effect on exhaust gas flow like can be seen in Figure 37. Note that the exhaust gas flow in Figure 37 is shown as kg/kWh, so the actual exhaust gas flows (kg/s) are less with low load (kW) levels than with higher load levels.

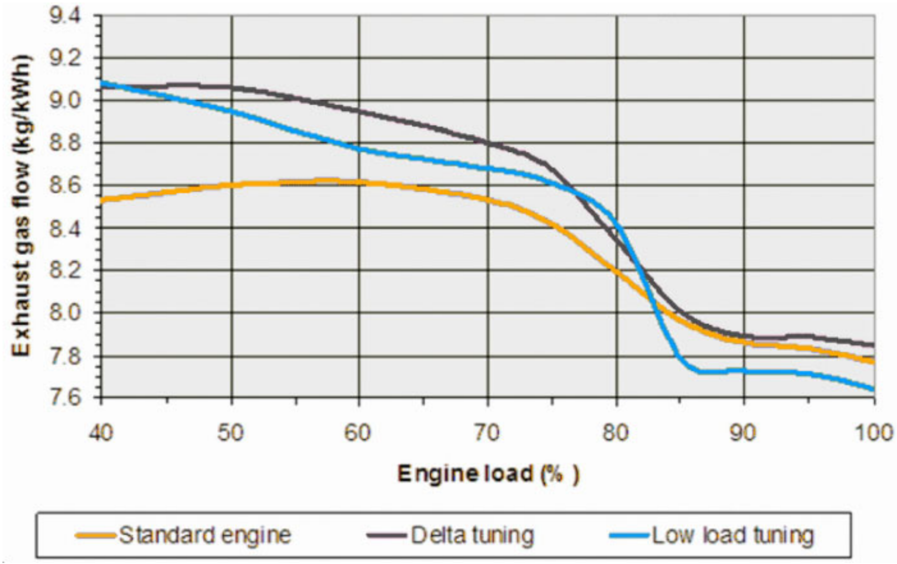


Figure 37. Exhaust gas flow behaviour with different Wärtsilä RT-flex82T engine tunings (Wärtsilä Switzerland Ltd 2012b).

At the moment Wärtsilä and also other exhaust gas scrubber manufacturers are using the exhaust gas flow values from engine 100 % MCR operation (Aalborg 2011, 3; Nikulainen 2013; Wärtsilä 2012c, 5). As discussed before, the main engines are normally running at maximum of 85 % MCR so the question is, should the scrubber system be dimensioned according to ship's maximum installed power or according to normal operating power? If only the Open loop and Hybrid mode are dimensioned according to reduced scrubbing load, such as 85 % CMR, the ship's safety and fulfilling of the regulations could be ensured with the scrubber automation system, when if the scrubber load exceeded the dimensioned value, the automation system could automatically transfer to Closed loop mode or by-pass the scrubber. Both of these scenarios will be discussed later on in this study. However, this kind of dimensioning should not effect on scrubber's other properties, such as the back pressure formation, which can have effect on the whole ship's exhaust gas system as well as the engine(s) operation.

4.1.5 Exhaust Gas Temperature

As discussed before, the scrubbing process relies highly into solubility phenomena but high temperatures have decreasing effect on the solubility, as less gas can be absorbed by the liquid at the higher temperatures due its larger volume (Joseph & Beachler 1998, chapter 11: 4). Therefore, the exhaust gas temperature has a great effect on scrubbing efficiency and it is also related to the scrubbing unit material selection. Typically, marine diesel engines' exhaust gas temperatures are related to the engine type, fuel in use, compression ratio and engine speed, where the 2-stroke engines usually have lower exhaust temperatures than with 4-stroke engines. In Table 11, are given some examples of exhaust gas temperatures for existing Wärtsilä engine. In general, the highest temperatures occur at 100 % MCR with all engine types (Wärtsilä 2011d, 8-9). However, with 2-stroke engine installations, this may not apply as with some engine types, the maximum exhaust gas temperatures are achieved with lower engine load levels as can be seen in Figure 38.

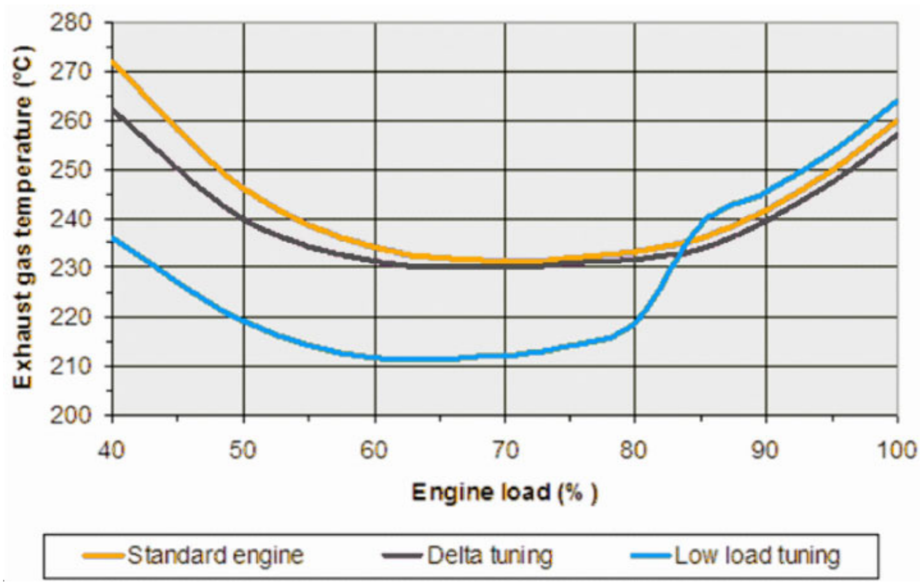


Figure 38. Exhaust gas temperature behaviour with different RT-flex82T engine tunings (Wärtsilä Switzerland Ltd 2012b).

For a basic exhaust gas scrubber project, the engine exhaust gas temperature along with other data can be obtained from the engine maker's documentation like Product guides and Installation manuals/ instructions, in case of new ships or from a Technical File related to the EIAPP certificate stored onboard, in case of existing ships. The exhaust gas temperature is typically given in ISO 3046 conditions at different engine loads.

In 4-stroke engine installations running with HFO and having a SCR system on board, the engines exhaust gas temperatures have to be tuned for optimal SCR operation. This is needed, because the working temperature of the SCR system is also depending on the fuel oil’s sulphur content. Figure 39 indicates the trade off between the minimum recommended exhaust gas temperature and the fuel oil sulphur content in Wärtsilä engine equipped the SCR exhaust gas after treatment system. The recommended temperatures for operation of the SCR system are between 300-450 °C but as can be seen from Figure 39, the needed operation temperature, when using high sulphur content HFOs, is between 340-350 °C. With 2-stroke engine installation, the SCR reactor is typically placed upstream of the turbocharger to provide the catalyst with a sufficiently high exhaust temperature, and therefore it don’t have a clear affect on exhaust gases leaving from the engine (Lloyd's Register 2012, 34; Wärtsilä Ship power technology 2010, 9).

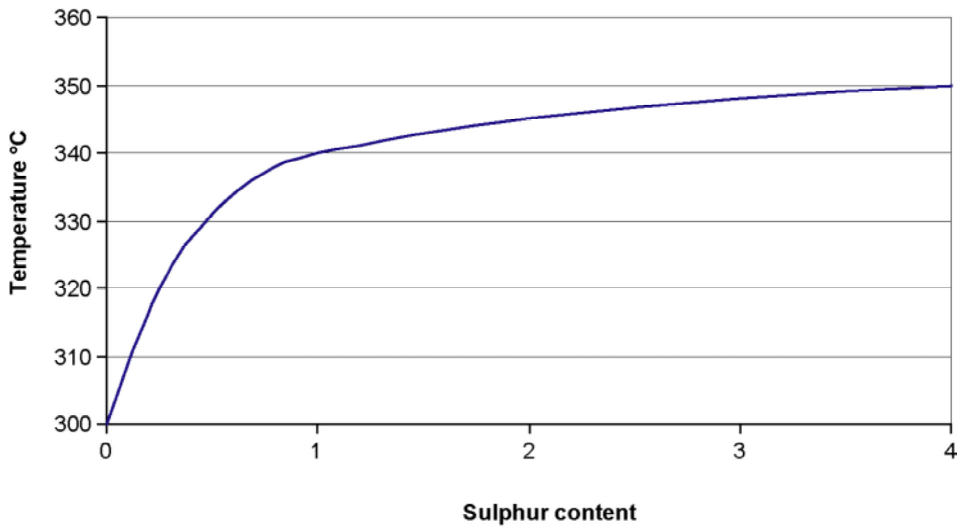


Figure 39. Recommended minimum catalyst operating temperature for continuous operations vs. sulphur content in fuel oil (Wärtsilä Ship power technology 2010, 9).

At the moment Wärtsilä is using two methods in the exhaust gas temperature determination for scrubber dimensioning. Its Open loop scrubbers are dimensioned with the engine(s) actual exhaust gas temperature after the turbocharger, therefore the value is in many cases over 300 °C and temperature reductions occurred by the other exhaust gas system components, are not considered in the calculations. The Closed loop and the Dual Water hybrid scrubber dimensioning notice the possible exhaust gas (E.G.) boiler and the temperature reduction caused by the boiler operation. As a result, the E.G. boiler parameters will be needed for the scrubber dimensioning.

4.1.6 Exhaust Gas Temperature after Exhaust Gas Boiler

Installation of the E.G. boiler will create a temperature drop and it will decrease the exhaust gas temperature on the scrubber inlet. Typically, the exhaust gas temperatures after the boiler are between 220-260 °C depending on the boiler's design and efficiency. In ships with diesel HFO operation, the exhaust gas temperature is normally kept above the sulphuric acid dew point in order to avoid a condensation of the sulphuric acid into liquid aerosol droplets in the exhaust gas piping. This dew point temperature results from many different factors in the exhaust gas composition and in the exhaust gas system operational environment but the temperature usually scales between 140-170 °C and therefore the boiler's exhaust gas temperature reduction may be limited to mach temperatures above 200 °C (Juoperi 2013; Lloyd's Register 2012, 22; Åkerberg 2013).

If the scrubber unit is dimensioned according to the decreased exhaust gas temperature caused by the E.G. boiler operation, the boiler must be always in operation when the scrubber is used in order to achieve a safe scrubber operating environment. The exhaust gas temperature at scrubber inlet has also a clear impact to fresh water consumption in Closed loop mode, so an efficient E.G. boiler can reduce the scrubber fresh water consumption by lowering the exhaust gas temperature and minimizing scrubbing water evaporation in the scrubber unit. The exhaust gas temperature affects also on plume visibility, which is furthermore affected by the ship's operational environment. When defining the exhaust gas temperature in the scrubber inlet, the expected temperature drop over the E.G. boiler may be devalued and a installation specific allowance, scaling between 30 to 100 °C, should be added for covering possible variations in ship's ambient, engine and E.G. boiler conditions (Wärtsilä 2011d, 8-9; Wärtsilä 2012b, 13). The value for exhaust gas temperature after the exhaust gas boiler for scrubber dimensioning is normally set for 240 °C (Nikulainen 2013).

4.1.7 Back Pressure of Exhaust Gas System

Most of the engine manufacturers include a permitted range of exhaust back pressure into their engines' technical specifications. Operating outside this given range may lead to reduced engine power output, increased fuel consumption, accelerated wear and greatly reduced maintenance intervals. In addition, the engine's NO_X Technical file may also be specified to a range of permitted back pressures, therefore if operating outside this range, it may invalidate the engine's NO_X approval. Most of the diesel engines can tolerate ~3.0 kPa of back pressure (0.03 bar or 305.92 mm/H_20) without a significant degradation of power or adverse effects. However, the engine back pressure toleration tents to increase slightly during the engine's lifetime (EPA 2008, 28; Lloyd's Register 2012, 10; Wärtsilä Ship power technology 2011, 10-107 Wärtsilä Switzerland Ltd 2012b, 22).

The total back pressure in the exhaust gas system must be calculated by the shipyard, basing on the actual piping design and the resistance of the every component installed in the exhaust system. In some cases, the total system may already include SCR for NO_X removal (with normal pressure lost of 1.5 kPa), E.G. boiler (1-1.5 kPa) and silencer(s) (0.1 kPa). Therefore with conventional back pressure tolerances, the maximum limits would be exceeded if the mainstream scrubber is added to the ship's exhaust gas system. Wärtsilä has already developed its 4-stroke ship engine portfolio so that they can now tolerance maximum 5 kPa (0.05 bar) as a sum of the maximum exhaust gas back pressure and the pressure drop at suction side of compressor at full engine load. Some of the engines have maximum allowed pressure loss before compressor of 1 kPa, so then the exhaust gas back pressure limit would be 4 kPa (SOCP 2011, 28; Wärtsilä Ship power technology 2011, 10-107 Wärtsilä Switzerland Ltd 2012b, 22).

The exhaust gas pressure loss over the main stream scrubber at full gas flow is typically 800-900 Pa. The integrated scrubber system does not increase the exhaust gas back pressure, as the pressure loss over the scrubber at full gas flow is neutralized with scrubber’s physical dimensions and by the exhaust gas fan(s). Therefore with the integrated configuration, the exhaust gas back pressure of the diesel engine and oil-fired boilers would be approximately the same with the scrubber in operation or by-passed. The integrated scrubber can be equipped more than one exhaust gas fan when those can be installed in parallel to suck the exhaust gases from the scrubber. The static pressure increase for the fans at the maximum exhaust gas flow can be set accordingly that it compensates the system pressure losses from the by-pass damper all the way to the exhaust gas outlet at the funnel top. The rest of the reserved static pressure is then available for compensating other pressure losses in the system like piping and outlet flow loss (Wärtsilä 2012b, 14; Wärtsilä Ship power technology 2010, 9-16).

4.1.8 Number and Design of Engine Casing(s) and Exhaust Gas Funnel(s)

The ship may have several engine casings and exhaust gas funnels with different amount of exhaust gas pipes installed to each route. With new buildings, the exhaust gas scrubber may be possible to fit in engine casing if the size demand and arrangements are acceptable along with weight allowances. With retro-fits, fitting scrubbers into existing, usually tight and fully-equipped, spaces will be a significant challenge and in many cases may require installation of the scrubber unit in or next to the exhaust gas funnel or above the main deck enclosure (EPA 2008, 28; SOCP 2011, 28).

If integrated scrubber with several exhaust gas connection is selected for the ship, following issues should also be considered:

- An exhaust gas backflow into the exhaust gas piping of combustion units which are not operating should be prevented. In Wärtsilä design, this is solved with the by-pass damper installed into every exhaust gas connection before the scrubber inlet.
- An increased back pressure may form when two or more combustion devices are combined that have different exhaust gas flow characteristics. In Wärtsilä design integrated scrubbers this is solved with exhaust gas fan(s) in scrubber outlet.
- The exhaust gas scrubber operates effectively over a wide range of designed exhaust gas flow rates (Lloyd's Register 2012, 10-11; Wärtsilä 2012b, 14-18).

In the integrated scrubber systems, the exhaust gases are normally collected into one common exhaust gas manifold installed before the scrubber unit. In order to compensate for pipe bends, the diameter of the manifold is slightly larger than diameters usually used in exhaust gas pipes. The each exhaust gas pipe connected to the manifold is equipped with the 3-way by-pass damper enabling the exhaust gas to be by-passed directly to atmosphere in case the scrubber is not in use. For by-pass flow the damper will create a pressure loss with factor of 1.1 (Wärtsilä 2012b, 17-19).

4.2 Operational Environment Related Design Parameters

Some of the design criteria and parameters are ship’s operational environment related, when those may vary depending on the ship type, its route, and other variables. Some merchant ships may sail on designated predefined routes but not all the ships, therefore these parameters should be selected so that they fulfil most of the ship’s operational and environmental scenarios in order to achieve the most optimum design and efficient operation. These design parameters are presented under following paragraphs.

4.2.1 Maximum Sulphur Content in Fuel Oil

The maximum fuel sulphur content is directly related to the bunker fuel quality, therefore ship's operating routes and regions are strongly affecting on this. As discussed before, the residual fuel sulphur content originates from crude oil quality, production process and with intermediate fuel oils also from blending quantities and blending fuel oil properties. As a result, the quality may vary from oil field, refinery, region, harbour and supplier to another. In section "Sulphur content" and in Appendix 2, the fuel oil sulphur contents are reviewed with the sulphur content developments in residual fuel oils from last five years. The results in the Appendix 2 indicates that the maximum tested sulphur contents are decreasing in all areas as the average values are staying constant or those are slowly decreasing. However, there are areas like South Asia in where the development is quite opposite and some areas have some up and downs with their sulphur contents in past five year period.

The fuel oil sulphur content has the biggest effect on the scrubber's unit and whole systems effectiveness and dimensioning. Wärtsilä and former Hamworthy PLC has been using the fuel sulphur content of 3.5 m-% for both Open loop and Closed loop scrubber system dimensioning as it is also the maximum sulphur content limit set by IMO (Hamworthy Moss AS 2011a, 7; Wärtsilä 2012c, 5). However, for example Alfa Laval Aalborg has used lower fuel sulphur contents of 2.7-3.0 m-% in their Hybrid scrubber feasibility studies (Aalborg 2011, 8; Alfa Laval 2011, 11). Also other scrubber manufacturer Belco has used 3.0 m-% content in their studies as it is in some cases justified as to be the global average HFO's sulphur content. In 2011-2012, this global average was something between 2.3-2.7 m-%, thus when comparing it to sulphur content of 3.5 m-%, the tested global average sulphur content is 23-34 % lower than the global 3.5 m-% sulphur content limit.

The sulphur content in fuel oil has direct impact to the scrubber's needed L/G ratio and also some impact to the exhaust gas temperature in scrubber inlet. The biggest advance of the decreased sulphur content is the reduced scrubbing water flow, which also affects on the pumping power demand. Some examples of needed sea water flows to the scrubber for 4-stroke engines with different sulphur contents in fuel oil and in exhaust gas after the scrubber are presented in Table 14. As can be seen in Table 14, the reductions in sea water flows are greater with remaining 0.5 m-% sulphur levels in exhaust gas than with 0.1 m-% sulphur levels. It should also be noticed, that with fuel sulphur content of 3.0 m-% and 2.8 m-%, the flows requirements are the same.

As the Dual Water hybrid scrubber can be operated in different modes, the global sulphur content level is quite low, and if the Closed loop stage is dimensioned according to 3.5 m-% sulphur content in fuel, the Open loop mode(s) would be possible to dimension according to deducted fuel oil sulphur content. However, if the scrubber is dimensioned this way, the following arguments should be noticed when operating with the fuel oil with exceeded sulphur content:

- There might be a need to operate in Hybrid mode also outside the ECA if the requested reduction limit is not fulfilled completely with Open loop mode(s).
- Operating in the Hybrid mode may increase the fresh water and the alkali consumptions as well as the bleed-off and the sludge formations.

Following examples in Figure 40 illustrates the situation in where the Open loop stage would be dimensioned according to 2.5 m-% sulphur content in fuel. In this case, the global bunker fuel markets would support this by shares of sulphur content in fuel samples, which are illustrated with different colours. The colours are explained in Table 12. According to figure 40, operating with IFO180 would be less risky if the reference dimensioning value is 2.5 m-% S in fuel. As can be seen from Figure 40, most of the samples are well under 1.0 m-% S in fuel or above 2.0 m-% S with both fuel oils. According to global sulphur content, the reference dimensioning value of 2.5-3.0 m-% S would be more feasible. If this is the reference, Figure 40 applies so that the yellow ones (neutrals) can be changed to green (feasible).

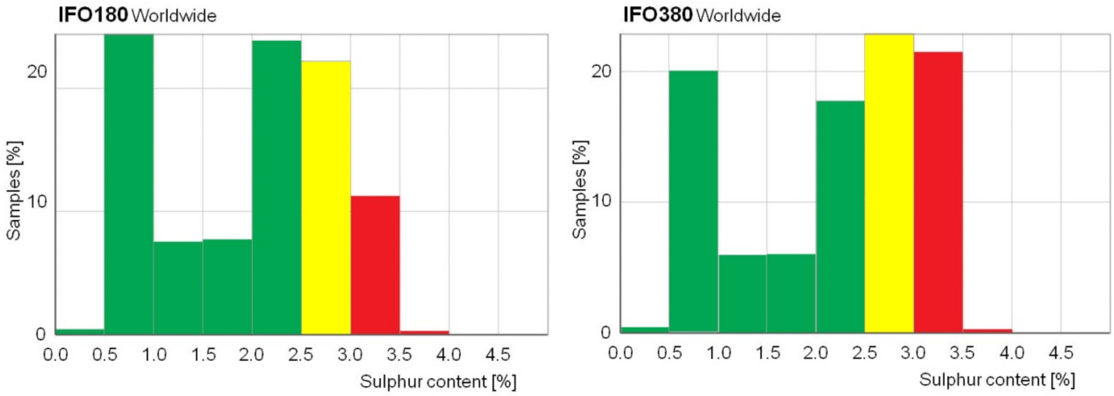


Figure 40. Global sulphur content of IFO180 and IFO380 in January-December 2012 (Bunkerworld 2013).

Regional differences in sulphur content probabilities are summarized in Table 12, where the reference dimensioning value is set for 2.5 m-% S in fuel.

Table 12. Regional sulphur content probability for less than 2.5 m-% S in bunkered fuel (Bunkerworld 2013).

	Africa	**East Asia**	**Mediterranean & Black sea**	**Middle East**	**North & West Europe**	**North America Atlantic**	**North America Pacific**	**Pacific, Australia, New Zealand**	**South America Atlantic**	**South America Pacific**	**South Asia**	**South East Asia**	**US Gulf & Caribbean**
IFO180	[green]	[green]	[green]	[red]	[green]	[green]	[green]	[green]	[green]	[green]	[red]	[yellow]	[green]
IFO380	[yellow]	[red]	[green]	[red]	[yellow]	[green]	[green]	[yellow]	[green]	[green]	[red]	[yellow]	[green]

[green]	*Feasible* = Average m-% S content < 2.5 m-%, and maximum m-% S content < 3.5 m-%
[yellow]	*Neutral* = 2.5 m-% < Average m-% S content < 3.0 m-%, and/or average m-% S content trend is increasing, and/or wide variations in sample contents
[red]	*Risky* = Average m-% S content > 3.0 m-%

It can be noticed that the regional level of 2.5 m-% would be more feasible for IFO180 with only with few exceptions. If the level is increased to 2.5-3.0 m-%, the feasibility would also be increased with IFO380 operation. Whatever the case may be the sulphur content of the purchased or delivered bunker fuel will not be any mystery to the ship owner/ operator because the MARPOL Annex VI requires that the bunker supplier must provide a bunker delivery note provided to the receiving ship. This has to include the sulphur content (in % m/m) along with the other information of: name and IMO number of receiving ship; port; date of commencement of delivery; name, address and telephone number of marine fuel oil supplier; product name(s); quantity (metric tons) and density in kg/m^3 at 15 ºC (IMO 2008, 42). However, there is no specific format for the note thus bunker suppliers may use their own formats when those contain the required information.

4.2.2 Minimum Sea Water Alkalinity

Sea water is slightly alkaline pH (close to 8), which means that it contains an excess of base over acid (Karle & Turner 2007, 10). This can be seen as a buffering capacity of water, which defines how much acid can be added to the liquid without causing a prominent change in the pH of the receiving liquid. In exhaust gas scrubbing with sea water, the SO_2 is absorbed into the sea water as SO_3 and finally as SO_4 by reaction with the alkaline material in the water. Therefore, the alkalinity of the sea water is important factor in the sea water scrubbing efficiency. The pH at surface of sea water, typically ranging from 8.1 to 8.9, originates from the presence of buffering materials primarily bicarbonate, carbonate, occasionally hydroxide, hydrogen ions and other minor species in natural sea waters (Behrends & Liebezeit 2003, 26; Bindoff all 2007, 405; IMO 2007, 8; Nikulainen 2012, 26).

The sea water alkalinity is regularly interrelated with its salinity and temperature. Low temperatures and high salinities have increasing effect on Total Alkalinity (TA) of the water. The salinity describes the salt content of water and in oceans the salinity is approximately 3.5 m-% or 35 m-‰, which is commonly expressed as 35 Practical Salinity Unit (PSU). The salinity does not effect on alkalinity but in oceanic water, the alkalinity-salinity ratio is usually constant and salinity can be used as an indicator of alkalinity (Lehikoinen 2006, 37). The salinity has a substantial effect on the absorption of the SO_2 gases and same with absorption of the CO_2. This absorbed CO_2 forms carbonate and bicarbonate in sea water, which are the main contributors to sea water’s alkalinity. Other factors which are strongly affecting the SO_2 absorption in sea water, are its temperature and the

SO_2 partial pressure, which is needed as direct proportion to the fuel sulphur content (IMO 2007, 8; Lee & all 2006, 1; Lehikoinen 2006, 37). In some extension, an indicative alkalinity in sea water has been calculated as a function of salinity according to the relation (IMO 2007, 8):

$$Alkalinity\ (mmol/l) = 0.0697\ \times salinity\ (PSU) \tag{5}$$

Figure 41 presents effects of different sea water alkalinities in the scrubbing process, when the temperature was kept at constant 25 °C with scrubber loads of 100 %, 75 %, 50 % and 25 %. However in the data from where the efficiencies were gathered, the full effect of TA was not presented as needed information concerning the initial sulphur content of fuel or the volume of the scrubbing sea water were unknown (Nikulainen 2013b). Figure 41 indicates that the scrubbing efficiencies improve with the increasing alkalinity and also with the decreased scrubber load. The efficiencies are measured until the alkalinity level of 2200 µmol/l, and efficiencies for alkalinity levels of 2400-2600 µmol/l are calculated from the measured values assuming that the efficiency increase stays linear. According to Figure 41, scrubbing efficiency increases by ~0.4 % with every 100 µmol/l increase in sea water alkalinity.

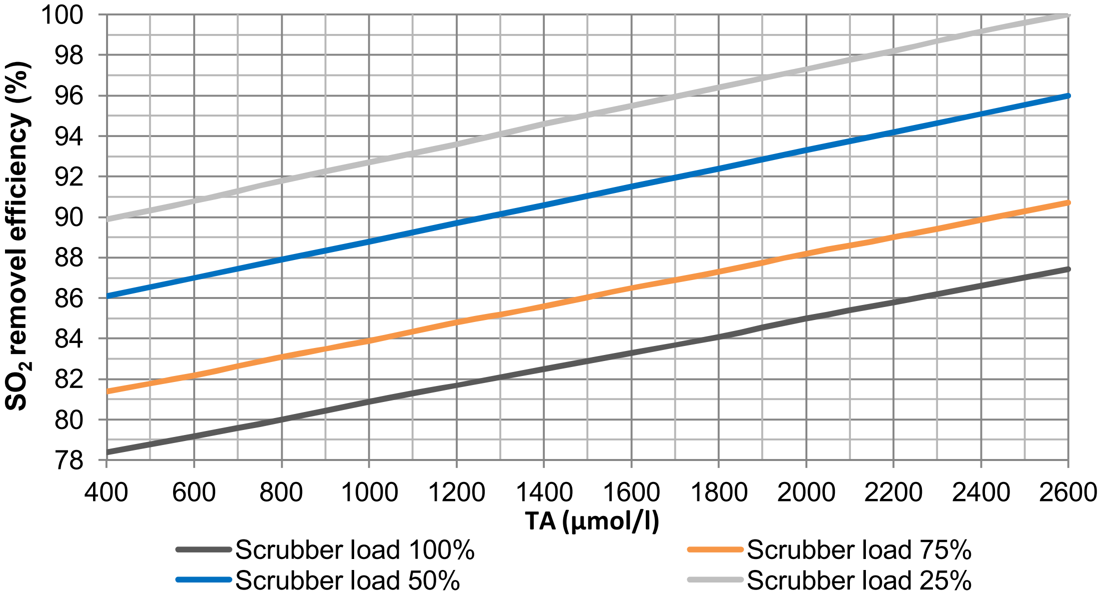


Figure 41. Scrubber efficiency versus sea water alkalinity at different engine loads of and sea water temperature of 25 °C when the pH of the effluent is 5.5.

The distribution of surface alkalinity in the open ocean is mainly controlled by the same factors that effects on the salinity. Other non-conservative processes, such as dissolution and precipitation of biogenic calcium carbonate, can also reflect some variability of TA. Biological processes like oxidation of organic matter or photosynthesis have only minor direct influence on the alkalinity. Therefore the TA variability in the oceans is controlled mainly by fresh water addition, caused by precipitation and sea-ice melting, or removal, which can occur by evaporation and sea-ice formation, and these can also change the salinity. In the (Sub)tropical oceans (i.e., 30 N 30 S), more than 80 % of total variability in TA are associated with water balance-induced changes in salinity account. At higher latitudes (i.e., north of 30 N or south of 30 S), the surface TA concentrations are increased by the mixing of deep waters during seasonal cooling. However during seasonal warming, the shoaling of the mixed layer makes the contribution of AT-rich deep waters, which can change the surface TA to minimal (Lee & all 2006, 1-4; Millero & all 1998, 111).

The alkalinities can vary considerably depending on the location as can be seen from the Appendix 7: Global ocean surface alkalinity. Typical alkalinity and salinity values for natural waters are given in Table 13. The salinity and the alkalinity values vary considerably in the Baltic Sea area and in other areas, where the water is mainly a type of brackish water. In this thesis, the focus is in oceans as those are optimal operation environments for Open loop and Hybrid scrubbing. An annual sea surface salinity is presented in Figure 42.

Table 13. Typical alkalinity and salinity levels of different natural water areas (Karle & Turner 2007, 11-15; Lehikoinen 2006, 37-41).

Natural water area	TA (µmol/l)	S (PSU)
Dead Sea	> 10000	217
Atlantic Ocean	2300	35
Pacific Ocean	2200	33
Indian Ocean	2200	34
North Sea	2200	32
Mediterranean Sea	2400	38
Kattegat	1950	18
Baltic Proper	1650	8
River and lake fresh water	210	< 0.1

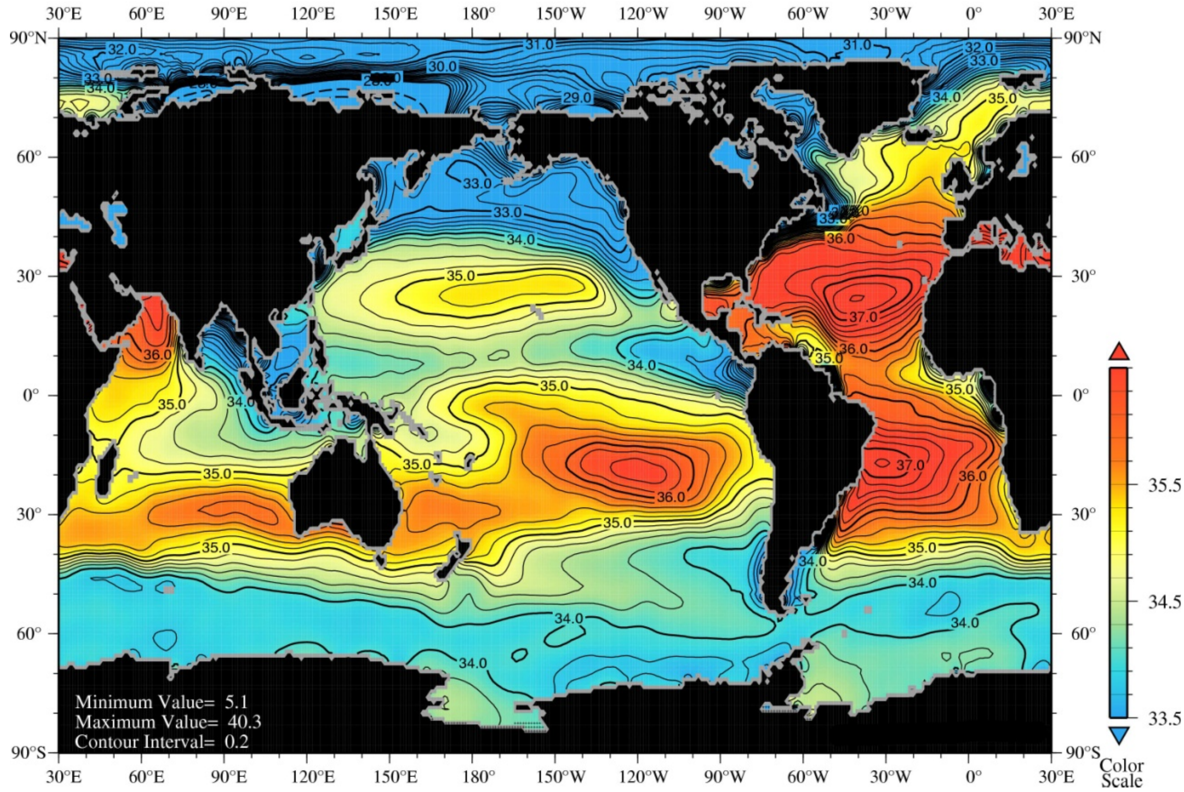


Figure 42. Annual sea surface salinity in 2009 (NOCD 2013).

In 2006, Lee & all estimated Surface Total Alkalinity fields from five regional TA relationships, using monthly mean sea surface temperature (SST) and salinity from the 2001's World Ocean Atlas. The data file consisted of 36 columns, including latitude, longitude and calculated total alkalinity from January through December (Lee & all 2006, 2-5). In Appendix 7, those values are illustrated with colours as averages surface sea water alkalinities in March, June, September and December. According to those figures, the oceans and regions with less alkalinity (< 2250 µmol/l) are the Gulf of Alaska, West coast of Central America (Panama's, Costa Rica's and Columbia's coast lines), Eastern parts of Gulf of Guinea, North and East parts of the Bay of Bengal, Andaman Sea coast line and Western part of Sea of Okhotsk. It can also be noticed that the oceanic alkalinity is quite stable hence the seasonal variability is generally very low. Therefore, significant changes can only occur over long time scales (i.e. hundreds to thousands of years).

Areas that were without the alkalinity data are North-western Passages, Hudson Bay, Gulf of Mexico, Caribbean Sea, Archipelago's areal waters in

South Chile, Baltic Sea, Mediterranean Sea, Black Sea, Caspian Sea, Red Sea, Persian Gulf, Java Sea, Calebes Sea, Banda Sea, Timor Sea, Arafura Sea, South China Sea, East China Sea and Sea of Japan. However, most of them are connected to the major oceans so the alkalinity level can be predicted to be in good or reasonable levels. Since the Figure 42 presents the annual sea surface salinity in 2009, which gives guidance that what kind of alkalinity would be in those sea areas, which are missing from Lee's & all's study. Higher salinity foretells higher alkalinity and vice versa.

One considerable issue which may affect on TA in the oceans is an ocean acidification (OA). It means a decrease in ocean pH over a period of time (decades or more), which is caused primarily by uptake of CO_2 from the atmosphere. At present, faster releasing of CO_2 into the atmosphere by human activities is changing the global ocean chemistry more quickly than ocean systems can handle. It may also affect on many organisms in the oceans and on land as some of them are very sensitive to small changes in pH. Also the ocean alkalinity would be affected. Like discussed before, the weak acids and bases, like the dissolved inorganic carbon species, are the base for sea water alkalinity and those have the largest impact on global ocean pH variations because their concentrations are changing quickly relative to other chemical species in the ocean (Bindoff all 2007, 405-406; EPOCA 2013). Consequently, the sea water alkalinity buffers also the OA.

Scientists have estimated that ocean surface pH has fallen by about 0.11 pH units from preindustrial times to present time. This would be equivalent to about a 29 % increase in the ocean hydrogen ion concentration or in other words, acidity. If the future estimation for the use of fossil-fuels and the rise of the atmospheric CO_2 comes true, the pH can drop by 0.3-0.4 units by the end of the 21^{st} century, which would correspond an increase in ocean hydrogen ion concentration by 100-150 % above what it was in preindustrial times. Also the global warming may boost the OA by melting of ice caps. Melted fresh water dilutes the oceans, which can also dilute its alkalinity. The fresh water would also contain less CO_2 than the surrounding sea water and the atmosphere. As it would have less alkalinity, which acts as a guard against changes in pH, the fresh water would uptake atmospheric CO_2 and contribute to more ocean OA. However, the oceans would still remain alkaline (pH > 7) after these decreases (Bindoff all 2007, 405-406; EPOCA 2013).

Wärtsilä is presently using the alkalinity of 2200 µmol/l in Dual Water hybrid scrubber dimensioning process. However, Alfa Laval Aalborg has used alkalinity of 2200-2300 µmol/l in their scrubber studies (Alfa Laval 2011, 11). As can be predicted from Figure 41, the increase in TA will increase the scrubber efficiency, thus with more TA, the sea water flow requirement would be less. The increase of TA by 100 µmol/l is increasing the efficiency with approximately 0.5 %, thus with alkalinities of 2200-2300 µmol/l the increase in scrubber efficiency would be less than 1.0 % but on the high alkalinity oceans, like on the Atlantic, the increase can be even over 2.0 % when comparing the alkalinity level of 2200 µmol/l. The ocean sea water alkalinity can be high as 2600 µmol/l, therefore especially with ships that operates constantly on high alkalinity waters the alkalinity potential should be fully utilized in scrubber's dimensioning.

4.2.3 Maximum Sea Water Temperature

The temperature has different effects on the sea water scrubbing process. One is that it affects the solubility of sulphates in the sea water, as the solubility of SO_2 decreases with increasing temperatures. Thus, sea water in lower temperatures dissolves the sulphur from the exhaust gases faster than in higher water temperatures, and therefore the water temperature affects on kinetics of the scrubbing process. Also the alkalinity of the sea water tents to increase in colder sea water because of the mixing during seasonal cooling. One reducing factor on warm ocean waters is the production of solid calcium carbonate ($CaCO_3$), which reduces alkalinity. The other is the photosynthetic consumption of nutrients because the nutrients in water increase the alkalinity, and as they are consumed the alkalinity decreases (Andreasen and Mayer 2007, 3276; Millero & all 1998, 111-128). As a result, the sea water temperature has an enormous effect on the scrubbing efficiency as can also be seen from Figure

43. In oceans, the sea water alkalinity and salinity are relatively constant, which is why the sea water temperature can be considered the most substantial contributor to the variance in the scrubbing efficiency (Nikulainen 2012, 87).

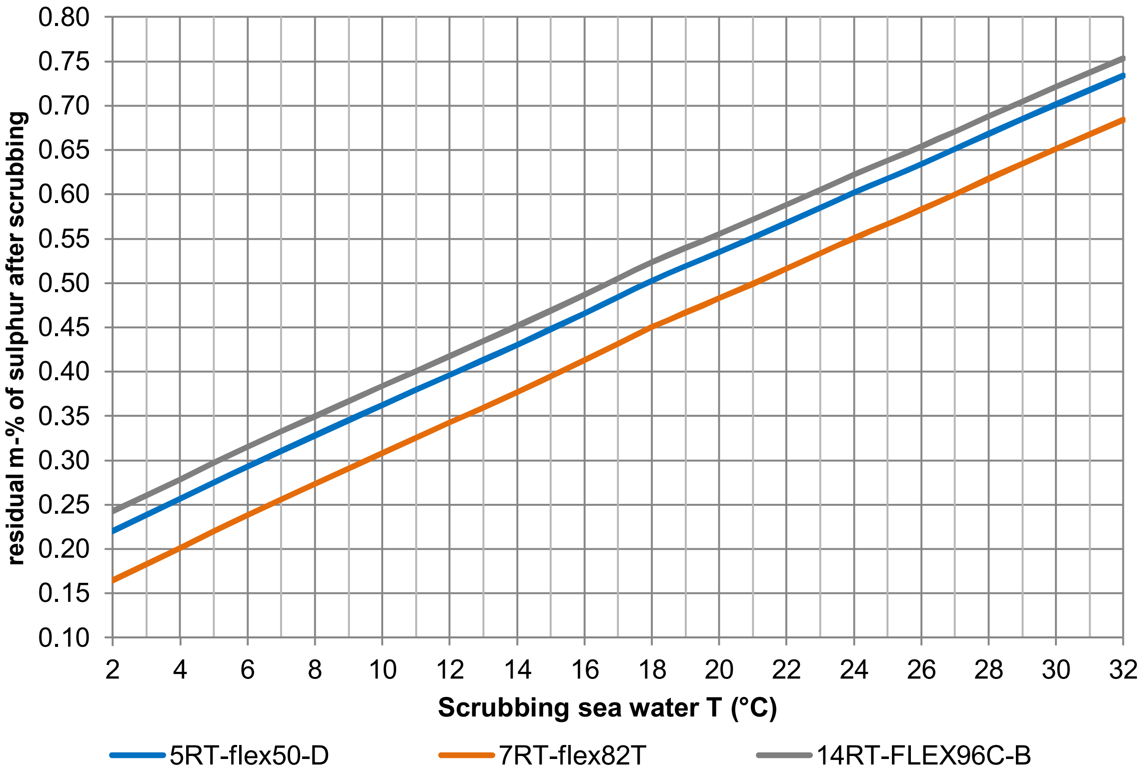


Figure 43. The corresponding fuel sulphur content after scrubbing for different Wärtsilä 2-stroke engines when using sea water with a 3.5 m-% fuel sulphur content, TA = 2300 µmol/l, S = 35 PSU and sea water flow of 30 l/kWh (Wärtsilä 2013a).

In oceans, the sea water is constantly churning underneath, bringing nutrients up to the top. Ocean's currents and upwelling originates from a difference in density of cold water versus density of warmer water. As the warm sea water tends to float and cold sea water, with temperature of 4 °C and density of 1 g/cm^3, tends to sink, ocean temperatures also vary across the surface and into the depths. The sea water is also saturated with salts and when temperatures go under 4 °C, this salinity origins actual density of 1.0278 g/cm^3. This density slightly heavier than with warmer water, so it causes the water molecules to roll over each other and therefore the salinity is another contributing factor to upwelling. A decrease in sea water temperature results an increase of density, so the sea water stratification by the temperature produces also stable density stratification. On the other hand, a decrease in salinity produces a density decrease. For these reasons, the salinity stratification would produce unstable density stratification but in oceans the effect of the temperature decrease is stronger than the effect of the salinity decrease, so the oceans are stably stratified (Marinebio 2013; Tomczack 2002).

This study is focusing on analysing sea surface temperatures as there are plenty of temperature data available from it. Meaning of a sea surface layer varies according to the measurement method used but generally it is between 1 mm and 20 metres. Usually, the surface (2-3 m) of the sea has a same heat capacity as the entire atmosphere above. It is heated up by the sunlight and mixed up by the wind, waves and streams. The average ocean temperature is near to 3.8 °C and even at the equator the average temperature is as low as 4.9 °C. In most cases, the ocean sea water temperatures range from -2 °C to 28 °C but can be hotter near hydrothermal vents or closer to land. In many ocean regions, temperature and salinity both decrease with depth (Marinebio 2013; Soloviev & Lukas 2006, 1; Tomczack 2002).

Ships' sea chest and sea water inlets are normally located near or on the bottom of the ship. Its distance to sea water surface depends on the ship's draft but in many cases it is at least 5-6 meters below sea level (Englund & Välimäki 2013). Therefore in ocean environment, the STT does not give a precise data for temperatures at the ship's sea water inlet but the STT can be used as guidance, since the temperatures in sea chest depths are generally lower, than the temperatures at the surface.

The SST varies mainly with latitude. Polar seas on higher latitudes can be even -2 °C, while low latitude seas, like Persian Gulf, can be as warm as 36 °C. Ocean waters have an average salinity of 35 PSU and freezes at -1.94 °C, which means that on high latitudes, sea ice can form. The average temperature of the STT is about 17 °C, so it is much higher than average ocean temperature

(Marinebio 2013). Average weekly sea water surface temperatures from March, June, September and December from world's oceans are shown in Appendix 8.

Wärtsilä scrubber's Open loop sea water systems are typically designed for sea water temperature maximum of 32 °C. Same is with the Closed loop's sea water system for scrubbing water cooling. However, for cooling water dimensioning point, a different temperature can be specified if requested. With Closed loop and in cold environment a minimum cooling water temperature is ensured by a thermostatic valve and a recirculation line to avoid crystallization of the sulphates in scrubbing water booted with alkaline (Nikulainen 2013; Wärtsilä 2011d, 24). Figure 43 shows that with studied 2-stroke engines with full 100 % MCR and constant scrubbing sea water flow of 30 l/kWh, the scrubbing efficiency is linearly decreasing. With this sea water flow level, depending on engine type and configuration, i.e. mainly its fuel oil fuel oil consumption, the 0.5 m-% of sulphur level is exceeded in temperatures of 17-21 °C. By increasing the scrubbing sea water flow, this temperature limit will get higher. From the Appendix 8 can be noticed that temperatures below 29 °C are quite common in oceans, except on warmest sea areas in South-Asia's oceans and Caribbean. Therefore if the ship is operating on areas with lower sea water temperatures, the scrubber design maximum sea water temperature should be optimized to match maximum sea water temperatures occurring on ship's operating areas.

4.2.4 Maximum Sea Water Inflow to the Scrubber

In the Dual Water hybrid scrubbers, the scrubbing water flow rate in the Open loop mode is higher, usually ~45 m^3/MWh (~45 l/kWh), than in the Closed loop scrubbing, usually ~20 m^3/MWh (~20 l/kWh), because the buffering capacity of sea water is less than the buffering capacity of fresh water boosted with alkali (Lloyd's Register 2012, 28). At present, Open loop scrubbers and sea water systems in Open loop modes operates at their full designed sea water pumping capacity constantly, regardless of exhaust gas flow to the scrubber unit, i.e. scrubber load or ambient conditions (like sea water alkalinity and temperature). Therefore, even the SO_2 cleaning efficiency in the Open loop stage may change during the ship's change in ship's geographical location, the constant designed sea water flow, i.e. maximum sea water inflow to the scrubber, guarantees the needed remaining sulphur content reduction in exhaust gas.

Depending on scrubber dimensioning principle, the maximum sea water inflow to scrubber can be set as a result of the other dimensioning parameters, such as the sulphur content in fuel, sea water alkalinity and temperature; or it can be pre-set in some maximum allowance level, since it is directly related to the scrubber's total power consumption. Wärtsilä has been using a dimensioning principle in where the sea water flow is set in some level and its sufficiency is then calculated in theory, and according to the calculation result, if needed, the value is then iterated with new calculations. Since Wärtsilä's Open loop scrubbers are dimensioned according to direct engine exhaust gas temperatures with large water excess, the scrubbing sea water volumes are normally set at the level of ~45 l/kWh, when residual S content in exhaust gas after scrubber is set for the level of 0.1 m-% and for the level of 0.5 m-% the volumes are ~40 l/kWh. For the Dual Water hybrid scrubber the maximum sea water inflow to scrubber in Open loop mode is normally something between 30.0-45.0 l/kWh and 30 l/kWh in Hybrid mode (Metso Power 2012a, 22-23; Metso Power 2012b, 22-23; Nikulainen 2013).

As a rule of thumb, the volume of required scrubbing sea water increases with the increasing temperature and also with the decreasing alkalinity. Thus the cleaning efficiency can be improved when larger water volumes are used (Karle & Turner 2007, 24; Nikulainen 2012, 87). In Table 14, the needed sea water flows for reaching sufficient scrubbing efficiency are presented. These have been calculated with the sea water alkalinity of 2200 µmol/l and sea water temperature of 32 °C. The values presented at intervals of every 5 l/kWh as approximate combinations based on different four-stroke engine types, which are W6L20, W6L32, W8L46F and W12V46F (Nikulainen 2012, 74).

Table 14. Examples of the needed sea water flows for gaining sufficient scrubbing efficiencies at TA = 2200 µmol/l and sea water temperature of 32 °C (Nikulainen 2012, 74).

m-% sulphur in fuel	m-% sulphur in ex. gas after scrubbing	Sea water flow (l/kWh)	Reduction in sea water flow (%) [1]
3.5	0.5	40	0 %
3.0	0.5	30	-25 %
2.8	0.5	30	-25 %
2.5	0.5	25	-38 %
3.5	0.1	45	0 %
3.0	0.1	40	-11 %
2.8	0.1	40	-11 %
2.5	0.1	35	-22 %

1) Flows are compared to flow values of 3,5 m-% sulphur content in fuel

As can also be seen in Table 14, the degree of sulphur oxide emission reduction has a great importance in the scrubbing process. The increase in sea water flow when moving from level of 0.5 m-% sulphur after scrubbing to level of 0.1 m-% is something between 5-10 l/kWh for these selected 4-stroke engines. According to Table 14, fuel oil with 3.0 and 2.8 m-% sulphur content have same needed scrubbing water amount. One should also pay attention to sea water flow quantity since it is given in l/kWh, hence the needed sea water flow is directly related to installed power connected to the scrubber. As could be noticed from Figures 33 and 34, most of ships in merchant fleet are equipped with powerful engine installation. More installed power on the ship, bigger the sea water flow to the scrubber unit and to water treatment plant, and therefore more pumps with bigger pumping quantities are needed. Similar needed sea water flows to the scrubber unit when using 2-stroke engines, are presented in case study section in Table 22 for selected Wärtsilä 2-stroke engines. It can be noticed, that the cleaning efficiency varies with the studied 2-stroke and 4-stroke engine types. This occurs because the ratio of the engine's output and fuel consumption as well as the excess air ratio determines the L/G ratio for the specific engine, which again has a major effect on the cleaning efficiencies of the scrubber since with bigger liquid to gas ratio the scrubbing efficiency is improved (Nikulainen 2012, 87).

Other function for the sea water entering to the scrubber is to act as a diluent in order to achieve required pH level from exiting scrubbing water. In many cases, dilution to pH of 6.5 may require larger water volumes than the initial uptake of sulphur dioxide (Karle & Turner 2007, 17). This quantity of needed sea water for the dilution of the scrubbing water is directly related to SO_2 removal efficiency and it is not dependent on the sea water temperature. As an example, in order to achieve requested pH of 6.5 with a 12 MW engine burning fuel with 3 m-% sulphur at sea water salinity of S = 35 PSU and alkalinity of 2300 µmol/kg, the needed dilution sea water quantity for total sulphur reduction of 100 m-% S is approximately 1500 ton/h meaning 125 l/kWh. It should also be noticed that even the sea water scrubbing efficiency is increasing with lower scrubbing sea water temperature, in the dilution process the lower temperature decreases the dilution and therefore increases the needed dilution water amount (Karle & Turner 2007, 17; Nikulainen 2012, 51).

When the scrubbing water flow is produced with large sea water pumps, the water flow is directly related to scrubber system power consumption, and with Open loop modes, the total scrubber system's power consumption may rise even above the 2.7 % of MCR (Wärtsilä 2013b, 1). Therefore, there is a great interest to optimize the needed pumping capacities and sea water flows to the scrubber. Since the scrubber(s) increase the whole ship's total power consumption, it has also have some effect on ship's EEDI. Other issue with the scrubbing water flows to the scrubber is that the scrubbing water spraying nozzles are designed for particular pressure in order to achieve efficient droplet formation. Therefore even if the pumping capacity is designed so that it could be reduced according to scrubber's load by reducing operating pumps or their capacities, the needed pressure level has to be fulfilled before the spaying nozzles. This is the reason why the scrubbing water pumps are equipped with the frequency converters, which are controlled by the pressure information coming from the scrubber unit but those are mainly utilized during the scrubber start-ups.

4.3 Other Dimensioning Related Design Aspects

There are also other relevant design aspects that should be considered when developing compact and efficient scrubber solution. Some of those can be a result of the scrubber performance affected by the design parameters presented before; a compromise which needs to be set by other limitation like for example weight issues; or more related to the product's design and operational control. Some of these are presented as fallowing.

4.3.1 Electrical Power Consumption

The electrical power consumption is a result of scrubber dimensioning and performance. Electrical power demands of wet exhaust gas scrubber systems can be significant reaching over 3 % of installation nominal power (SOCP 2011, 28). However, there can be a maximum electrical power consumption level set for reaching efficient and combust design. The power demand of Wärtsilä Dual Water hybrid scrubber in normal conditions varies depending on operating mode and with integrated configuration, in where the exhaust gas fan(s) is installed, the demand is also depending on scrubber's load. For integrated scrubber with de-plume system, when operating in normal design conditions, the variation in power consumption is roughly between 1.3-2.8 % of the connected engine power, depending on the operating mode, when the Closed loop mode is having the most economical electrical power consumption and "full" Open loop (sprint) mode is having the biggest consumption. With integrated scrubber installations the power demand increases towards top ship speed (load) and with the maximum scrubber load, it may reach over 20 % of whole scrubber system´s total power consumption. The overall power for the whole system should be somewhat higher than needed, in order to allow for variations in operating and ambient conditions along with system tuning. However, installed frequency converters and control algorithms enables optimizing of the power demand at reduced power and reduced sea (cooling) water temperatures (Wärtsilä 2012b, 33; Wärtsilä 2013b, 1; Wärtsilä Ship power technology 2010, 27).

Biggest energy consumers in the Dual Water hybrid scrubber system are the scrubbing sea water pumps (with 1.0-1.5 % of MCR and ~46 % of scrubber's total power consumption) and wash (return) water pumps (with 0,5-0,8 % of MCR and ~29 % of scrubber's total power consumption), which both together in Open loop mode may consume up to 2 % of MCR (Wärtsilä 2013b, 1). These pumps provide huge water flow(s) to scrubber unit(s), which can be located even tens of meters above the pumps, however, the location of the scrubber unit(s) and the needed water volumes are very installation and ship type specific. Also the electrical power consumption of washwater pumps is directly related to scrubbing sea water volumes. Therefore, there is a great interest to optimize the Open loop mode(s)/ stage dimensioning so that it fulfils the scrubbing efficiency limits set by the dimensioning parameters, and in order to minimize sea water pumping requirements as those are the biggest energy consumers in the whole system. According to Hamworthy, the minimum amount of water required by scrubbers in Open loop mode is approximately 25 l/kWh and the volume is already fixed by the requirement to cool the exhaust gas. This volume is approximately half of the current volume used in conventional Open loop scrubbers. However, in their design, extra pumping power is used in reaction water pumps, which increase the system's total power consumption (Hamworthy Krystallon Limited 2007, 4).

As discussed before, the biggest power savings could be achieved with sea water pumping, which would be controlled according to scrubber load. Another option for reduction of sea water pumping capacities, in addition to efficient system dimensioning, would be utilization of Venturi-technology in scrubber inlet connection. This would boost the cooling of the exhaust gases before the scrubber and reduce the needed scrubbing water demand from the unit itself. Problem with the Venturi-technology is that it has to be dimensioned for certain exhaust gas flow, thus with integrated scrubber configuration, all the combustion units connected to the scrubber, would need a separated Venturi of their own. Another issue with the Venturi is its power consumption, since the sea water pressure is increased with a booster pump before the Venturi's nozzle and depending on the required sea water flow and pressure, these pumps can be very energy consuming. However, this kind of arrangement is already in use with Wärtsilä's (old Hamworthy) integrated Open loop scrubbers.

Other pumping power related issue is the dilution water demand for increasing the scrubbing water's pH. As these dilution water demand volumes are relatively high, those should not be added to the (vertical) scrubbing water flow to the scrubber unit as the pumping to higher locations increases the pumping power demand, in addition this would also affect on wash (return) water pumping by increased washwater capacities, thus increasing pumping capacities in both ends. On the contrary, if the dilution water is needed, it should be provided by separated pumps with horizontal flow, under the ships water line, as it is arranged in Wärtsilä's Open loop scrubbers.

Depending on installation and ship type, Wärtsilä's Open loop and Dual Water hybrid scrubbers can have pumping power demand of (max.) 2.0 % of MCR, so clearly further scrubber development should focus on reducing the sea water inflow to scrubber and through that, reduce the power demand required for the operation (Wärtsilä 2012e, 42; Wärtsilä Hamworthy 2012, 12). At the moment Wärtsilä's Open loop scrubbers have a power consumption of 2.4 % of MCR with current technology and dimensioning manners.

4.3.2 Scrubber Unit Material Selection

Since the Dual Water scrubber unit may use sea water as scrubbing washwater, and in Closed loop mode, fresh water plus added alkali with absorbed sulphur, the washwater can be highly corrosive. Therefore, the scrubber components that come into contact with the scrubbing media should be constructed from suitable corrosion-resistant materials. Also the scrubber unit weight is affected by its material selection. As with standard Wärtsilä scrubber concepts, the unit is made of a suitable corrosion resistant metal. However, the scrubber unit made of Glass-reinforced plastic (GRP) can be considered to minimize weight, making it suitable for mounting high up in stability sensitive ships. With the plastic design, the weight saving compared to metallic scrubber unit is 20-30 %. Also the external piping can be considered to be made of plastics and as with less weight it would be easier to handle in retro-fit installations. In that case, it would be necessary to install appropriate bracketing for the plastic piping in excess of that required for steel pipe and the piping must be protected from the hot exhaust gases (Lloyd's Register 2012, 22; SOCP 2011, 28; Wärtsilä 2011d, 7-8; Wärtsilä 2012b, 13).

The main concern with the GRP or other plastics is a fire endurance or fire performance. Where plastics are used in systems which are essential to the safe operation of the ship, the fire endurance of system is be fulfilled by obtaining the capability to maintain units strength and integrity (i.e. capable of performing its intended function) for some predetermined period of time, while exposed to fire that reflects anticipated conditions. In order to achieve the IMO's and the Classification Societies' requirements, there can be a need for some fire extinguishing system or other special arrangements (IMO 1993).

Typically it is not necessary to change the materials of the exhaust pipes and systems downstream of the exhaust scrubber, if the exhaust gas temperature is kept above the sulphuric acid dew point. Therefore, corrosion-resistant materials should be used if the temperatures below dew point occurs (Lloyd's Register 2012, 22; Schenelle & Brown 2002, chapter 18: 19).

4.3.3 Statutory Certification and Class Approval

Like with most of the equipment installed onboard, also the exhaust gas scrubbers require both statutory certification (issued by/ or on behalf of a flag administration) to show that the equipment meets the required performance criteria, and Classification Society approval (class approval) to show that the equipment does not present an unacceptable risk to the ship itself and the essential equipment required for the ship's continues operation are installed and working properly. At present, there are numerous different statutory and class approvals associated with exhaust gas treatment systems and their ship-specific installations. Equipment manufacturers and operators may also acquire independent verification of the performance, either given to equipment design by Type Approval, or performance of a ship-specific installation by Verification of performance (Lloyd's Register 2012, 12).

IMO has set in IMO MEPC 184(59) - 2009 Guidelines for Exhaust Gas Cleaning System, two optional methods for statutory approval: Scheme A and Scheme B. The Scheme A is an EGC system approval, survey and certification using parameter and emission checks, in where the compliance demonstrated by emission tests. There is also a possibility to obtain this approval for serially manufactured units and for a certain production range. The Scheme B is an EGC survey and certification using continuous monitoring of SO_X emissions, in where the compliance demonstrated in service by continuous exhaust gas monitoring. Wärtsilä offers its Closed loop scrubbers with both schemes A and B but for Open loop scrubbers and Dual Water hybrid scrubbers it recommends scheme B to be used (Det Norske Veritas 2012c, 14-19; IMO 2009a, 2-11; Lloyd's Register 2012, 12; Wärtsilä 2012e, 20-42).

A SO_X Emissions Compliance Plan (SECP) is approved by the Administration in where ship’s each item of fuel oil combustion equipment are listed, which are to meet the requirements for operating in accordance with the requirements of MARPOL Annex VI regulations. It should also contain an information that how the continuous monitoring and/or the demonstrations are to be done or to be checked, and that the needed parameters are maintained within the manufacturer’s recommended specifications. These differ depending on which one of the Schemes (A or B) is selected. If the EGC unit is dimensioned for some optimized value, for example reduced exhaust gas flow, it should be marked to SECP and agreed with the ship operator and with the Administration in a way that if the engines or other combustions units are operated under different (in this case higher) design parameters as have used for dimensioning, the EGC can be by-passed and the ship operator will respond of fulfilling regulations by some other method like fuel switching (Henriksson 2013; IMO 2009a, 13).

Classification Societies may certificate exhaust gas scrubbers by “Class unit approval” or “Class approval of ship-specific scrubber installation”. However, these designations vary from Classification Society to another. The “class unit approval” contains is a desk top review and includes a review of system principles with an assessment of all of the hazards introduced by the system and any proposed mitigation measures. Basically, the Classification Society gives reinsurance to owners/ manufacturers that it will accept solution before an installation is done/ planned. “Class approval of ship-specific scrubber installation” is required for a ship to remain in class with rules set by ship’s Classification Society. This covers a document review and an onboard survey, and is informed by the class unit approval. The approval focuses on an impact of the system to the safety of the ship covering at least ship-specific piping system, electrical and control system, structural modifications and stability, and fire safety. In all cases, the scrubber manufacturer is required to submit a comprehensive risk assessment for their system. Hazards might include major risk factors, clogging and flooding, rise of back pressure and overpressure, corrosion, loss of containment of hazardous chemicals, and fire in engine room and casing (Det Norske Veritas 2012c, 13-15; Lloyd's Register 2012, 13).

4.4 Existing Design Parameters

The Wärtsilä Dual Water hybrid scrubber can be connected to diesel engines of any make, 2-stroke or 4-stroke, type or configuration (Wärtsilä 2012b, 11). The scrubber is capable of reducing the SO_X emissions from the exhaust gas with following process conditions. However, most of the used design parameters, as well as operating modes, are highly project specific at the moment. These parameters are mainly same as listed in IMO’s MEPC 184(59) - 2009 Guidelines for Exhaust Gas Cleaning System, which needs to be given in Technical manual for both optional methods for statutory approval: Scheme A and Scheme B. Therefore, these parameters will also give the best information about the scrubber operation and filling the emission reduction requirements, and these are normally included to EGC Technical specification regardless of the manufacturer or the scrubbing technology. The present design parameters for the Wärtsilä Dual Water hybrid scrubber are listed in Table 15.

Table 15. Existing design parameters for Wärtsilä Dual Water hybrid scrubbers (Lahtinen 2011, 1; Wärtsilä 2012c, 4-15; Wärtsilä 2013b, 1).

Mode	Open loop	Hybrid	Closed loop #1[1]	Closed loop #2 [2]
Fuel S content, max.	3.0-3.5 % (CS)	3.5 %	3.0-3.5 %	2.5-3.5 %
Residual S in exhaust gas after scrubber (as fuel S content), max.	0.1-0.5 % (CS)	0.1 %	0.1 %	0.1 %
Sea water alkalinity, min.	2200 µmol/l	Any	Any	Any
Sea water temperature, max.	32 °C	32 °C	32 °C	32 °C
Scrubber load, max.	100 %	100 %	100 %	CS [3]
Alkali (50% NaOH solution) consumption, max. [4]	Not applicable	0.0039 l/kWh [5] (CS)	0.0176 l/kWh (CS)	CS
Sea water flow to scrubber, max. [6]	30.0-45.0 l/kWh (CS)	30 l/kWh (CS)	-	-
Electric power consumption, max. [7]	2.4 % (CS)	1.9 % (CS)	0.9 % (CS)	CS
Bleed-off rate, max.	Not applicable	Not applicable	Not applicable	1.5 m^3/h
Exhaust gas pressure loss over scrubber, max. [8]	800-1300 Pa			
CS = Case Specific. Values given are just for guidance. 1) Normal operation mode on Closed loop. 2) Zero discharge mode in Closed loop. 3) According to ship's load profile in port. 4) With +/- 10 % tolerance. Based on make-up water pH 7.0. 5) Consumption depends on ambient and operating conditions 6) With +/- 20 % tolerance. SW flow to cooling not included. 7) Of connected engine power with +/- 30 % tolerance. 8) To be measured in stabile flow conditions. Not applicable to loads above 100 %. Compensated with fan(s) in integrated scrubber(s).				

5 CASE STUDY

In this chapter a case study from three merchant ship projects is introduced. All the ships have Wärtsilä 2-storke engines as main engines with different outputs and all operate with HFO. The design parameters are obtained according to findings from the previous sections. The engine performance data is gathered with WinGTD 3.0, which is a General Technical Data -calculation tool for Wärtsilä two-stroke engines. All the target ships represent the latest and the most efficient ship design and technology. Therefore, it can be predicted that these kinds of ships would also require a most efficient scrubbing solution if one would be installed on board. All ships are considered to operate their auxiliary engines only with MDO/ MGO so these hypothetical Dual Water hybrid scrubber installations would be with the main stream configuration when only the main engine has an influence on the scrubber efficiency.

5.1 Target Merchant Ships

The merchant ships, which are used in this case study, are presented in Table 16 along with some installation data. Only their main engine data is used in this study.

Table 16. Ship details of case study merchant ships (Equasis 2013; Wärtsilä eTools 2013).

Ship	Algoma Equinox	Samco Amazon	CMA GCM Marco Polo
Ship type	Bulk carrier	Crude oil tanker	Container vessel
DWT	39400	318129	187625
Classification Society:	Lloyd’s Register	American Bureau of Shipping	Bureau Veritas
Lloyd's Register / IMO Ship ID Number:	9613927	9528794	9454436
Main engine	5RT-flex50-D	7RT-Flex82T	14RT-FLEX96C-B
Total power (kW)	8725	31640	80080
Fuel oil in use	HFO	HFO	HFO

5.2 Wärtsilä RT-flex 2-stroke Engines

All case study engines are selected to be the type of Wärtsilä RT-flex, which are camshaftless low-speed, direct-reversible, electronically controlled 2-stroke engines with Common rail injection -technology. The design represents the latest 2-stroke diesel engine technology and the engines are fully compliant with IMO Tier II NO_X limits specified in Annex VI of the MARPOL 73/78. The engines can be equipped with the SCR catalyst to meet IMO Tier III NO_X emission levels and the exhaust gas scrubber to reduce SO_X emissions (Wärtsilä Corporation 2012a, 78; Wärtsilä Switzerland Ltd 2012b, 2-11). Wärtsilä IMO Tier II compatible 2-stroke marine diesel engines portfolio is shown in Figure 44.

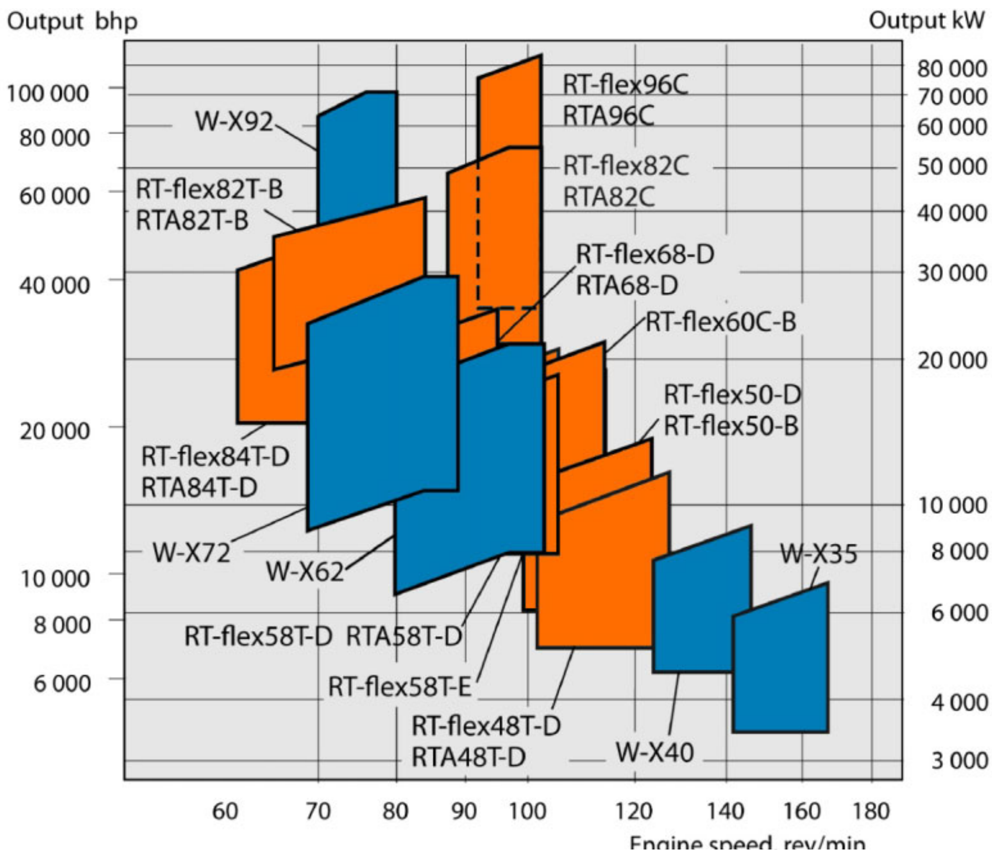


Figure 44. Power/speed range of IMO Tier II compatible Wärtsilä 2-stroke marine diesel engines (Wärtsilä Switzerland Ltd 2012b, 2).

Wärtsilä low-speed, 2-stroke engines are available propulsion solutions for merchant vessels with directly driven propellers. The engine concept enables the lowest possible fuel consumption over the whole operating range, especially in part-load range along with low cylinder oil feed rate. Common rail technology enables also smokeless operation at all running speeds and lower “steady” running speeds (Wärtsilä Corporation 2012a, 56-57).

5.3 Engine Performance Data

In the case study calculations, design condition values are used as reference values but in real projects, reference condition values should be used if/ when ship’s operating conditions are known. The reference conditions are mainly lower than with Design conditions, so when using design condition values, there will be more safety factors in calculations. The calculation of the performance data for BSFC, Brake specific exhaust gas flow (BSEF) and Temperature of exhaust gas after turbine (tEaT) have been done with the winGTD. Used calculated values are valid for Efficiency-optimised tuned engines (Wärtsilä Switzerland Ltd 2012b, 22).

The engine performance values and capacities are specified according to ISO Standard 3046-1 following the International Association of Classification Societies (IACS) and are defined as design conditions (Wärtsilä Switzerland Ltd 2012b, 21):

- Air temperature before blower: 45 °C
- Engine room ambient air temperature: 45 °C
- Coolant temperature before scavenge air cooler: 36 °C for FW
- Barometric pressure: 1000 mbar
- Relative air humidity: 60 %

Design values for selected RT-flex engines can be found from Appendix 9: Engine performance data. All the values used in this case study have tolerances of following: with BSFC of + 5 %; with BSEF of ± 5 % and with tEaT of ± 10 %. For the scrubber performance calculation two dimensioning scenarios are selected: Design scenario and Operation scenario. Both scenarios are studied with two design value set points for each studied engine: the set point of 100 % MCR, which values are marked with red colour in the

Appendix 9, and the set point of 85 % MCR marked with green colour. These selected design values are also summarized for three selected engines in Tables 17-19.

5.3.1 Ship A: Bulk Carrier

Algoma Equinox is the first of Equinox Class series, which will include total eight vessels consisting of four gearless bulk carriers (requiring shore-side equipment for cargo discharge) and four self-unloading bulk carriers. The ships are specially designed to optimize fuel efficiency and operating performance. Even the engines are capable of burning low-sulphur fuel oils those will be using residual fuels in combination with Closed loop scrubbers (Algoma 2013). The ship was selected to the case study as the engine type represents Wärtsilä's low power 2-stroke engines and the ship will have an integrated Closed loop scrubber onboard, which will enable possible technology comparison in the future. The ship's main engine's performance data is shown in Table 17.

Table 17. Wärtsilä 5RT-flex50-D main engine performance values (WinGTD 3.0 2013).

Engine	**5RT-flex50-D**	
Engine type	2-stroke	
Engine tuning	IMO Tier II + Efficiency-optimised	
Power (%)	100	85
Power (kW)	8725.0	7416.3
Engine speed (rpm)	124.0	117.5
BSFC (g/kWh)	174.0	170.4
Exhaust gas flow (kg/s)	17.09	15.22
Exhaust gas temperature after TC (°C)	281.1	259.1

5.3.2 Ship B: Crude Oil Tanker

Samco Amazon is a crude oil tanker with cargo layout of 15 cargo tanks and two slop tanks. Also with this ship design the fuel economy have been considered and that is not the only environmental consideration on the vessel, as it can claim the title of the first VLCC equipped with a ballast water treatment system (Fairplay 2013). The ship's main engine's performance data is shown in

Table 18. The engine was selected as it represents one of the Wärtsilä's most efficient 2-stroke engine type with minimal consumables and most optimal performance values.

Table 18. Wärtsilä 7RT-flex82T main engine performance values (WinGTD 3.0 2013).

Engine	7RT-flex82T	
Engine type	2-stroke	
Engine tuning	IMO Tier II + Efficiency-optimised	
Power (%)	100	85
Power (kW)	31640.0	26894.0
Engine speed (rpm)	80.0	75.8
BSFC (g/kWh)	169.0	165.4
Exhaust gas flow (kg/s)	64.86	56.55
Exhaust gas temperature after TC (°C)	290.1	266.1

5.3.3 Ship C: Container Vessel

One of the world's largest containerships, CMA CGM Marco Polo have a capacity of 16000 TEU (twenty-foot equivalent unit containers) is 396 m long, 54 m wide, with a draft of 16 m. The ship is the first of a series of three 16 000 TEU vessels, which all will be named after great explorers (Marinelog 2013). Its engine represents the world's most powerful 2-stroke engine so with 14 cylinder engine configurations the engine performance values are as big as they can be within Wärtsilä's engine portfolio and its performance data is shown in Table 19.

Table 19. Wärtsilä 14RT-FLEX96C-B main engine performance values (WinGTD 3.0 2013).

Engine	14RT-flex96C-B	
Engine type	2-stroke	
Engine tuning	IMO Tier II + Efficiency-optimised	
Power (%)	100	85
Power (kW)	80080.0	68068.0
Engine speed (rpm)	102.0	96.6
BSFC (g/kWh)	176.0	172.4
Exhaust gas flow (kg/s)	165.28	145.40
Exhaust gas temperature after TC (°C)	308.1	289.1

5.4 Dual Water Hybrid Scrubber Configuration

The case study is made with an assumption that the most economical Dual Water hybrid scrubber configuration for selected installations would be the main stream scrubber, which would be connected only to ship's main engine. This would mean that all the auxiliary engines would operate with LFO (including MGO), at least after 2020, and the scrubber would run in Hybrid or Closed loop mode inside the ECAs or near the cost lines and on the harbours.

5.5 Open Loop Scrubbing Performance Calculations

Engine operating parameters for the exhaust gas concentration calculation are taken from sources presented above. The BSFC values are added with +5 % by tolerance from winGTD and additional +5 % margin to cover variations in engine condition and heavy fuel properties. Also the exhaust gas temperatures in the scrubber unit inlet are determined according to continuous E.G. boiler operation so the value is set to 240 °C. Selected design parameters for Design and Operation scenarios are given in Table 20.

Table 20. Selected design parameters for Open loop scrubbing.

Design parameter	Unit	Design scenario				Operation scenario			
Fuel S content, max	%	3.5				2.8			
Scrubber load, max	%	100		85		100		85	
Sea water alkalinity, min	µmol/l	2300				2300			
Sea water salinity, min	PSU	35				35			
Sea water flow to scrubber	l/kWh	30	35	40	45	30	35	40	45
Sea water temperature	°C	2-32							

Main difference with these scenarios is the fuel sulphur content, which is optimized into level of 2.8 m-% in the Operating scenario. The sea water alkalinity and the sea water salinity are selected to match optimized levels for world's oceans. No dilution factor is added to the scrubbing sea water flow in calculations. Maximum sea water temperature is set for 32 °C in these calculations.

The performance calculations for Open loop scrubbing are made according to methods and equations presented by Nikulainen in 2012 in her study: The Basic Theory of Seawater Scrubbing. As presented in that study, analytically derived equations for solving the absorbed sulphur are long and those can be complex with a lot of room for errors. Therefore, these equations are solved by the iteration as then the equations become simpler and the calculation can be done with Microsoft Excel. The main iteration process calculation equations are presented as following and those are made by using assumptions based on ideal gas law. A carbonate balance can to be calculated at first according to Equations (6-10) (Nikulainen 2012, 58-59).

$$\dot{V}_{water} \times [HCO_3^-]_0 = \dot{V}_{water} \times ([HCO_3^-] + [CO_2(aq)]) + \frac{p_{CO_2} \times \dot{V}_{exhaust}}{RT} \tag{6}$$

$$p_{CO_2} = k_{H,CO_2} \times [CO_2(aq)] \tag{7}$$

$$[CO_2(aq)] = K_{13} \times [HCO_3^-] \times [H^+] \tag{8}$$

$$[HCO_3^-]_0 = [HCO_3^-] \times \left(1 + K_{13} \times [H^+] \times \left(1 + \frac{\dot{V}_{exhaust}}{\dot{V}_{water}} \frac{k_{H,CO_2}}{RT}\right)\right) \tag{9}$$

$$[HCO_3^-] = \frac{[HCO_3^-]_0}{1 + K_{13} \times [H^+] \times \left(1 + \frac{\dot{V}_{exhaust}}{\dot{V}_{water}} \frac{k_{H,CO_2}}{RT}\right)} \tag{10}$$

The sulphur balance can to be calculated according to Equations (11-16) (Nikulainen 2012, 59-61).

$$\frac{p_{SO_2,0}}{RT} = \frac{k_{H,SO_2} \times [SO_2(aq)]}{RT} + \frac{\dot{V}_{water}}{\dot{V}_{exhaust}} \times \left([SO_2(aq)] + [HSO_3^-] + [SO_3^{2-}]\right) \tag{11}$$

$$K_7 = \frac{[HSO_3^-] \times [H^+]}{[SO_3^{2-}]} \tag{12}$$

$$K_8 = \frac{[SO_3^{2-}] \times [H^+]}{[SO_2(aq)]} \tag{13}$$

$$K_7 \times K_8 = \frac{[HSO_3^-] \times [H^+]^2}{[SO_2(aq)]} \tag{14}$$

$$[HSO_3{}^-] = \frac{K_7 \times K_8 \times [SO_2(aq)]}{[H^+]^2} \quad (15)$$

$$\left[SO_3{}^{2-}\right] = \frac{K_7 \times [SO_2(aq)]}{[H^+]} \quad (16)$$

The amount of remaining sulphur after the scrubbing can be determined according to Equation (17), which solved from the Equations (11-16) (Nikulainen 2012, 60).

$$[SO_2(aq)] = \frac{p_{SO_2,0}}{RT \times \left(\frac{k_{H,SO_2}}{RT} + \frac{\dot{V}_{water}}{\dot{V}_{exhaust}} \times \left(1 + \frac{K_7 \times K_8}{[H^+]^2} + \frac{K_8}{[H^+]}\right)\right)} \quad (17)$$

After this an electroneutrality of the solution can be checked according to Equation (18). The concentration of the hydrogen ion can then be estimated according to Equation (19) (Nikulainen 2012, 61).

$$[H^+] + [HCO_3{}^-]_0 = 2 \times \left[SO_3{}^{2-}\right] + [HSO_3{}^-] + [HCO_3{}^-] \quad (18)$$

$$[H^+] = 2 \times \left[SO_3{}^{2-}\right] + [HSO_3{}^-] + [HCO_3{}^-] - [HCO_3{}^-]_0 \quad (19)$$

In the calculation process, the first step is to guess the initial value of the formed hydrogen ions. Then the Equation (10) needs to be solved and after that the Equation (17). Next the Equations (15 and 16) are to be solved by using the data from the Equation (17). Finally, the new hydrogen ion concentration from the Equation (19) is to be solved. After these calculations a reference point iteration -method is used to calculate the true concentration of hydrogen ions in the solution (Nikulainen 2012, 61).

The effect of the scrubbing process on the pH of the effluent can be checked with Equation (20) in where the hydrogen ions formed in the scrubbing process are assumed to react with the hydroxide ions in the water. In here for the sake of simplicity it is assumed that the pH of the effluent is not depended on the temperature but is depended on the cleaning efficiencies and the used water properties (Nikulainen 2012, 61-62).

$$pH = \log([H^+] - [OH^-]_0) \quad (20)$$

5.6 Open Loop Scrubbing Performance Comparison

As the sea water flow to the scrubber is one of the main interests in this thesis, the calculation results are given in corresponding fuel sulphur content after scrubbing when using parameters (Open loop scrubbing operating conditions) presented above with the selected sea water flow. The cleaning efficiency results are presented as figures of corresponding fuel sulphur content after scrubbing when using sea water with temperature range of 2 to 32 °C. Engine specific results are calculated according to 100 % and 85 % engine loads, which means also scrubber load in term of the exhaust gas flow. Selected calculation results are presented in Tables 21-23 and in Figures 45-47, and all the calculated results are presented as figures in Appendix 10.

5.6.1 Open Loop Scrubbing Performance with Sulphur Reduction Level of 0.5 m-%

Selected results are presented in Figures 45 and 46 and all the results are given as figures in Appendix 10. As can be seen from results presented in Figure 45 and in Appendix 10, the needed sulphur reduction level (0.5 m-% sulphur content) can be achieved in Design scenario by sea water flow of 35 l/kWh with whole sea water temperature range when other parameters/ process requirements presented in Table 20, are fulfilled. As could be expected, the sulphur reduction is more efficient with lower engine load due to lower exhaust gas flow. However, also engine design have a great effect on results due to differences in BSFC and BSEF, as even with 100 % load the 7RT-flex82T would have better connected scrubber performance than the other engines would have. Generally 2-stroke engines have better scrubber performance and relatively lower sea water flows to the scrubber when comparing to 4-stroke engines and their sea water flow levels, like presented in Table 14. This can be explained with lower BSFC of 2-stroke engines. The consumptions are generally about 10-20 g/kWh lower than with 4-stroke engines.

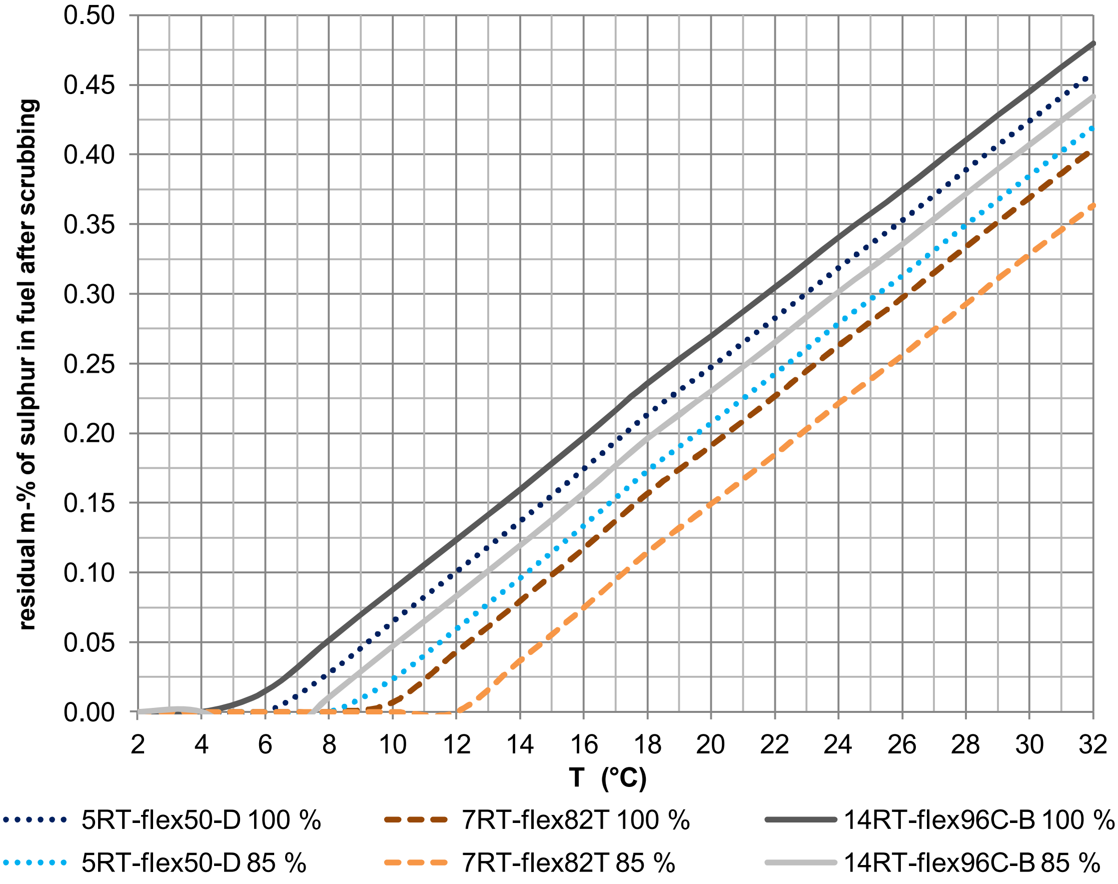


Figure 45. The corresponding fuel sulphur content after scrubbing when using sea water with a 3.5 m-% fuel sulphur content, TA = 2300 μmol/l, S = 35 PSU and sea water flow of 35 l/kWh as set by Design scenario (Wärtsilä 2013a).

With Operating scenario the 0.5 m-% sulphur content after scrubbing can be achieved with sea water flow of 30 l/kWh at any sea water temperature and as can be seen in Figure 46. Still there would also be plenty of margins left for sulphur reduction even when the entire studied scenario's other parameters/ process requirements are fulfilled. The loads of the connected engines have some effect on scrubber performance but the effects are engine/ product related, as from the case study engines the biggest 14RT-flex96C-B engine the difference in scrubbing efficiencies is in this scenario very small. Again 7RT-flex82T engine would have better scrubber performance than other engines would have. It should also be noticed that the 0.1 m-% sulphur content after scrubbing could be achieved with approximately sea water temperatures of 19-26 °C.

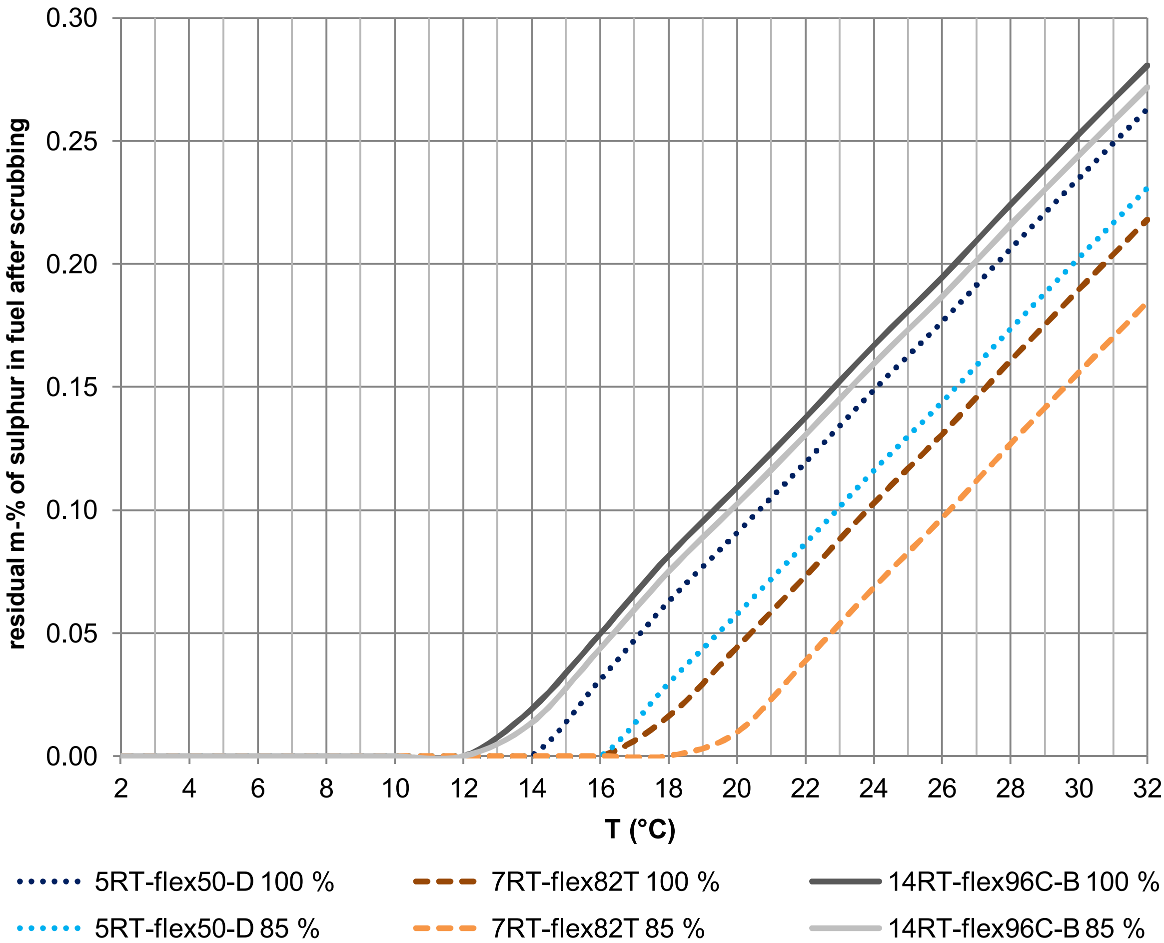


Figure 46. The corresponding fuel sulphur content after scrubbing when using sea water with a 2.8 m-% fuel sulphur content, TA = 2300 µmol/l, S = 35 PSU and sea water flow of 30 l/kWh as set by Operating scenario (Wärtsilä 2013a).

5.6.2 Required Minimum Sea Water Flows to Scrubber

Table 21 summarizes scrubbing efficiency results for two studied scenarios in a case when the target would only be to minimize the sea water flow to the scrubber. In here the lowest sea water flow is selected regardless what the needed sea water temperature would be required in order to achieve the requested sulphur reduction level. Even the sulphur content limit in exhaust gas after the Open loop scrubbing is normally set for 0.5 m-%, also level of 0.1 m-% is added to Table 21.

Table 21. Required minimum sea water flows and maximum sea water temperatures for Open loop scrubbing with different scrubber loads in Design and Operating scenarios.

		Parameter	**Unit**	**5RT-flex50-D**		**7RT-flex82T**		**14RT-flex96C-B**	
				0.1 %	**0.5 %**	**0.1 %**	**0.5 %**	**0.1 %**	**0.5 %**
Design[1]	**100%**	**Min. SW flow**	l/kWh	35	30	35	30	35	30
		Max. SW temp.	°C	10	16	14	20	10	16
	85%	**Min. SW flow**	l/kWh	35	30	35	30	35	30
		Max. SW temp.	°C	14	20	16	22	12	16
Operating[1]	**100%**	**Min. SW flow**	l/kWh	30	< 30	30	< 30	30	< 30
		Max. SW temp.	°C	20	> 32	22	> 32	18	> 32
	85%	**Min. SW flow**	l/kWh	30	< 30	30	< 30	30	< 30
		Max. SW temp.	°C	22	> 32	26	> 32	18	> 32

1) Scenario

As can be seen in Table 21, in most of the cases sulphur reduction from 0.5 m-% level to 0.1 m-% level requires 5 l/kWh bigger scrubbing water flow. However, the sea water temperatures needed for efficient scrubber operation and sulphur reduction, are relatively low. In many cases this would mean that predominant operating conditions at oceans would not meet these sea water temperature levels. Nevertheless, with Operating scenario, the needed 0.5 m-% level would be achieved with sea water flow of 30 l/kWh and temperatures over 32 °C.

When optimizing the sea water flow to the scrubber, the sea water temperature acts an important role as discussed in section 4.2.3. The scrubber system should be capable to reduce sulphur in warmer sea areas. In Table 22 are presented the needed sea water flows when the maximum sea water temperature is selected to be 28 °C. In again, it should be noticed that no dilution factor is added to the sea water flow. With these sea water flows the scrubbing sea water (effluent) leaving from the scrubber unit would have a pH value of 2.4-2.7. So in order to meet requirements set for washwater discharge, there would a need for some dilution water increase to the pumping capacities or the utilization of the reaction water after the scrubber from which the reaction water system would be most efficient.

Table 22. Required minimum sea water flows with sea water temperature of 28 °C for Open loop scrubbing with different scrubber loads in Design and Operating scenarios.

		Parameter	Unit	5RT-flex50-D		7RT-flex82T		14RT-flex96C-B	
				0.1 %	**0.5 %**	**0.1 %**	**0.5 %**	**0.1 %**	**0.5 %**
Design [1]	**100%**	**Min. SW flow**	l/kWh	45	35	40	35	45	35
	85%	**Min. SW flow**	l/kWh	40	35	40	35	45	35
Operating [1]	**100%**	**Min. SW flow**	l/kWh	< 35	< 30	< 35	< 30	< 35	< 30
	85%	**Min. SW flow**	l/kWh	< 35	< 30	< 35	< 30	< 35	< 30

1) Scenario

The sulphur content reduction to level of 0.5 m-% can be achieved with 35 l/kWh sea water flow for all the case study engines when using design parameters of Design scenario. With Operating scenario same level is achieved with less than 30 l/kWh sea water flow and according to results even smaller sea water flow could be feasible. With this scenario the level of 0.1 m-% sulphur content could be achieved less than 35 l/kWh sea water flow. Even the scrubber (i.e. connected engine) load do not have much effect on needed sea water flow, as can be noticed from Table 21, the reduced load do have some effect on the scrubbing performance by the means of increased maximum sea water temperature. Reduced 85 % MCR would most likely have a great effect on scrubber unit size since the exhaust gas flow levels are also less than with 100 % MCR.

An actual sea water flow (kg/s or l/s) to the scrubber unit can be relatively high with 2-stroke engine installations as the installed power can be very high reaching up to 80 MW per one engine. This can have enormous effect on the scrubbing sea water and washwater pumping capacities, which thereby also affects on total power consumption of Open loop scrubbing system. For comparison, the calculated actual sea water flows for case study engines are presented in Table 23.

Table 23. Engine specific actual sea water flows for different designed sea water flow levels.

Design SW flow	Engine load	Engine specific actual SW flow (l/s)		
		5RT-flex50-D	7RT-flex82T	14RT-flex96C-B
30 l/kWh	85 %	62	224	567
	100 %	73	264	667
35 l/kWh	85 %	72	261	662
	100 %	85	308	779
40 l/kWh	85 %	82	299	756
	100 %	97	352	890
45 l/kWh	85 %	93	336	851
	100 %	109	396	1001

Finally for comparison, engine specific different sea water flows to the scrubber for 7RT-flex82T engine are presented in Figure 47. With this engine type, the reduction in residual sulphur content after scrubbing is about 0.018 m-% S/ -1 °C with different sea water flows according to Design scenario. This means that one degree drop in scrubbing sea water temperature reduces sulphur emissions by 0.018 m-% in exhaust gas. With Operating scenario corresponding reduction is a bit lower approximately 0.014 m-% S/ -1 °C.

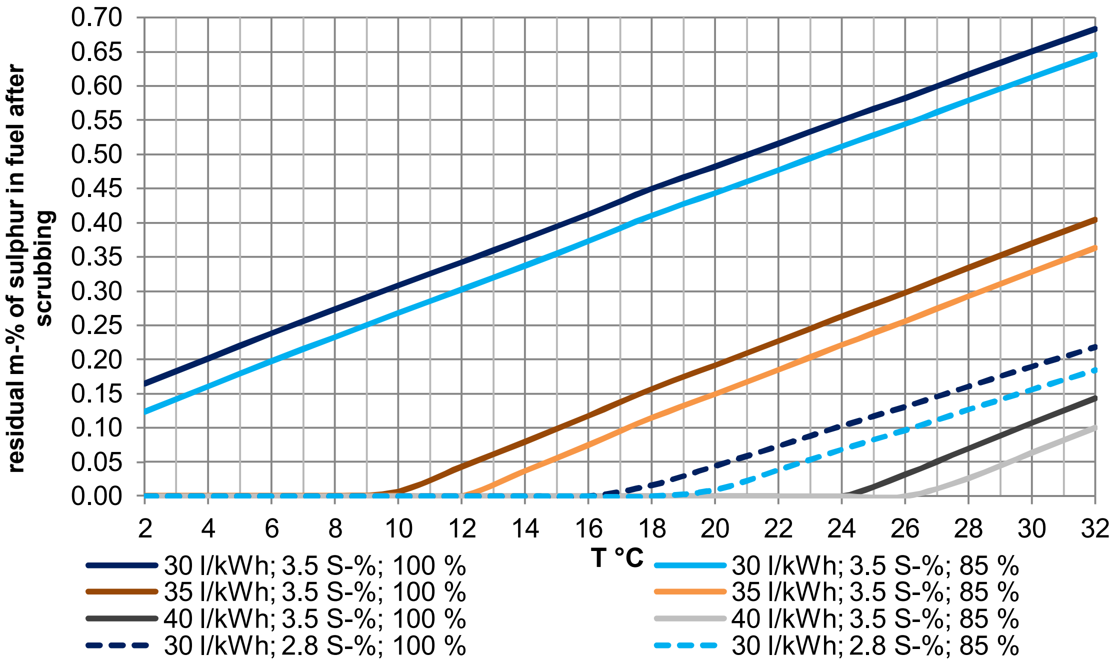


Figure 47. The corresponding fuel sulphur content after scrubbing for 7RT-flex82T engine when using sea water with different fuel sulphur contents, TA = 2300 µmol/l, S = 35 PSU and different sea waters flows (Wärtsilä 2013a).

6 CONCLUSIONS

Since the exhaust gas scrubbing is quite a new technology in the marine sector and there are only few installations in operation, the main concerns from ship owners' side have been focusing on the size of the equipment, the reliability of the technology and the efficiency of the systems but also some concerns reflect from uncertainties in the legislation and finance. When evaluating a new scrubber design or scrubbing technology, especially from a regulatory viewpoint, the major issue is whether the proposed new design will achieve the required sulphur removal levels. From the marine point of view SO_X are at the moment the biggest concern but the technology should be prepared also for particulate reduction although those are not regulated yet. Generally there are three main approaches when evaluating the capability of scrubbing systems:

1. Empirical evaluations, which can be based on historical data from similar scrubbers.
2. Theoretical models or simulations, which can be based on scrubber engineering principles.
3. Test data from pilot or test installation (Joseph & Beachler 1998, chapter 1: 9). After this, there might be a need to update models, parameters or calculation methods used in earlier stages so the development continues.

This study was made using only the first two approaches and before any pilot test data was available from the Dual Water hybrid scrubber. However, as the study mainly focuses on Open loop scrubbing process, the findings should be valid also for conventional Sea water/ Open loop scrubbers. Even though the study is focuses on the Merchant fleet, the findings may also be utilized with other shipping segments where there would be a request for the Hybrid scrubber solutions with enough space reservation for the equipment installation.

6.1 Compactness and Efficiency Evaluation

The main design and also operation of the exhaust gas scrubbers are based on the basic laws of physics and general chemical engineering principles. In the end, the rate of exhaust gas i.e. exhaust gas flow (gas velocity) from the combustion unit(s) determines the size of the scrubber. All the wet exhaust gas scrubbers require a certain residence time (or velocity) through the scrubber unit to obtain the required emission removal efficiency. This parameter has to be set by the size of the scrubber in relation to the volume of exhaust gas to be treated. The scrubber unit's diameter increases the total surface area and the height increases residence time, which enhances absorption as the amount of mass transferred is equal to the rate of mass transfer times the time of contact. In order to improve the residence time, some packing material may be acquired with the cost of back pressure formation. Then again this can be controlled with a wider diameter of the unit. So when performing a comprehensively evaluation of the Dual Water hybrid scrubbing system, there are certain design parameters that have to be verified, such as those presented in this study.

Earlier studies made by Wärtsilä have shown that a compact size when discussing the scrubber unit's physical dimensions can be achieved with following methods:

1. By choosing the right scrubber configuration. In many cases with multiengine installations, the most compact design can be achieved with integrated scrubber(s).
2. By removing packing material when the diameter of the unit may be reduced (by ≤ 18 %). However, this will have an increasing effect on the unit's height (by ≤ 18 %) as the certain reaction time is still needed.
3. By relocating the demister (droplet separator) when the diameter of the unit may be reduced (by ≤ 22 %). In some cases, the demister could be an external component and located separately after the scrubber unit.
4. By Dual Water unit design utilizing both chambers in both loops, i.e. possibility to spray scrubbing media to both chambers during the Open

and Closed loop modes. This way a more efficient multilevel spaying pattern can be achieved and the reaction time can be decreased.

5. With vertical inlet to the scrubber unit, when the length of the unit could be minimized (WIO-PCE 2011).

The percentage values are given as for guidance and those are calculated according to earlier studies made about the Dual Water hybrid scrubber size optimization. However, those studies were made about four cases in where the hypothetical main stream Dual Water hybrid scrubber was connected to different 4-stroke engines with the sea water flow of 30 l/kWh. Later calculations have shown that this flow would not be sufficient for those engine types. Consequently, it should also be noticed that when minimizing the size, some other operating parameters, such as the needed scrubbing water flow may have to be increased in order to fulfil the needed scrubber sulphur removal performance expectations.

Even though the size may also be an issue with Merchant fleet scrubber projects, the ship designs are more suitable for installing the needed scrubber system equipment, especially when the scrubber solution will be designed so that location would not reduce cargo space and it would have a minimum effect on the ship’s balance. But at present, the constantly changing fuel oil prices have increased the cost-consciousness among the ship owners when they have started to look more deeply into the required technologies and the solution’s efficiencies along with the functional and reliable technology feasibilities. When evaluating the efficiency of exhaust gas scrubber, in many cases this would mean guaranteed performance values from the maximum sulphur reduction or reduction to the designed level along with the minimum operating consumables by the means of the electrical and the chemical consumptions. Naturally, other cost based features can also be included in the efficiency discussion.

When optimizing the efficiency or creating a more compact design, one should pay attention to correlations between different features as well as the design parameters. Some of these have been summarized in Figure 48, which presents the features and their relations to different design aspects and design parameters in a simplified fishbone diagram when designing a compact and efficient Dual Water hybrid scrubber. In this study the focus has been on the efficiency and the sea water flow (highlighted with orange and blue colour in Figure 48) but also other features, such as the scrubber unit size has a direct effect on them. Also features presented on the upper level should be considered when design-study, -testing and -evaluation are made.

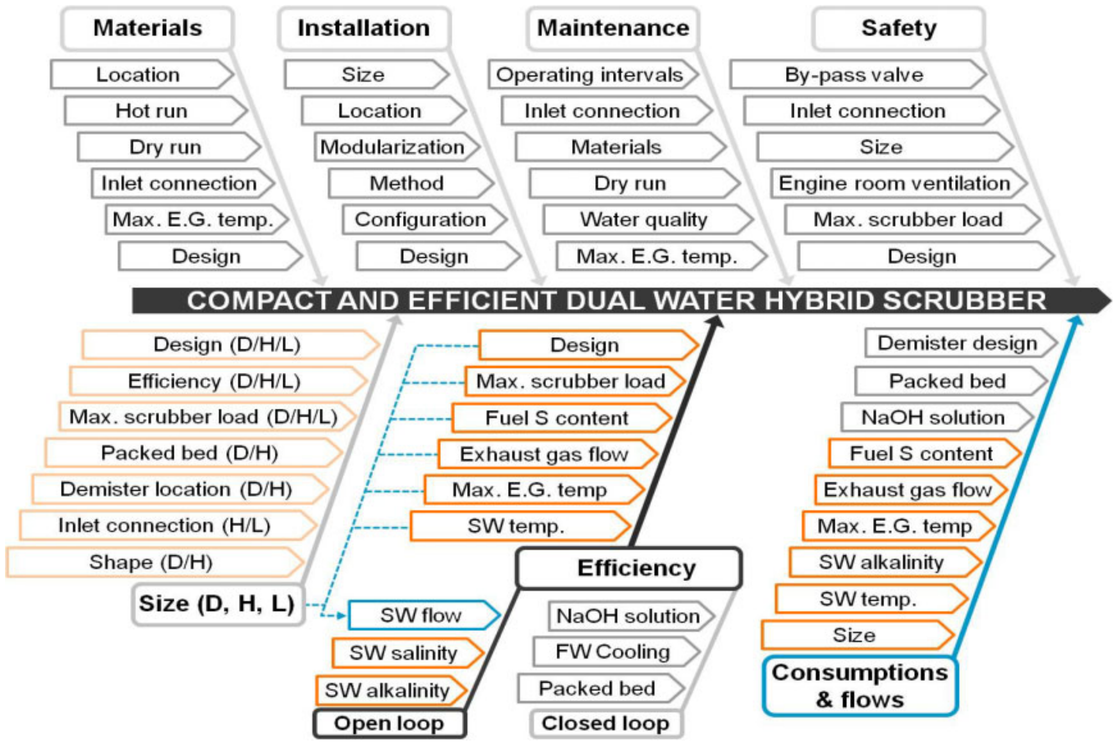


Figure 48. Simplified fishbone diagram of compact and efficient Dual Water hybrid scrubber related features and their relations to different design aspects and parameters.

As discussed earlier, the exhaust gas scrubber's sulphur removal efficiency can be increased by an increase in the liquid-injection rate to the scrubber unit, which in this case means the sea water flow to the scrubber as well as the washwater flow from the unit. However, this amount of liquid can be limited by the dimensions of the scrubber unit especially if the flooding may occur. More critically increasing liquid-injection rates will also increase the operating costs through increased pumping capacity. Therefore the optimum liquid-injection rate should be set by the exhaust gas flow rate, by the operating conditions and by the scrubber economy. As this study mainly focuses on the Open loop mode/ stage, most of the design parameters' influence and optimization are examined through their effect on sea water flow to the scrubber as its pumping is the most energy consuming process in the whole system.

6.2 Proposal for Optimized Design Parameters for Further Testing

In present Hybrid scrubber design, the Open loop stage/ systems consume reasonably much energy since the sea water pumping capacities are quite large and the dimensioned scrubbing sea water flow is always constant to the scrubber regardless of the engine(s) load. Still some power consumption savings can be utilized by different operating modes in Open loop scrubbing. Efficient design parameters should reduce the size of the scrubber unit and also cut the power demand by optimizing the needed sea water flow to the scrubber in Open loop mode. Therefore, those can have a direct effect on both CAPEX (Capital expenditures) and OPEX (Operational excellence).

Along with the fuel oil sulphur content and the needed sulphur reduction from exhaust gases, the three most significant sea water properties that affect the Open loop scrubbing are its alkalinity, salinity and temperature. These properties are highly operational environmental related as the alkalinity and the salinity of sea water vary substantially in different sea areas, as well as the temperature may vary significantly depending on the seasonal variance and the location. By setting design parameters so that the most of the ship's ambient and operating conditions are fulfilled when the ship is sailing on pre-designated or pre-assumed routes, if those are known, the Open loop stage efficiency can be matched for economical operation and compact design.

With the following design parameters presented in Table 24, the operating conditions in most of the oceans are achieved and the quality of HFO, in most of the bunkering locations, is fulfilled. Also the Open loop mode would be more economical in terms of the decreased power consumption. If the operating environment cannot fit in designed window, the scrubber could utilize the Hybrid mode or even the Closed loop mode when ever needed in order the fulfil scrubber sulphur reduction requirements. In that case, the costs of increased alkali consumption would most likely be less than the increased ship's fuel oil consumption in terms of the increased system's power consumption. Existing design parameter values are given in parentheses for comparison.

Table 24. Proposal for Wärtsilä Dual Water hybrid scrubber's design parameters (bolded values).

Mode	Open loop	Hybrid	Closed loop #1[1]	Closed loop #2 [2]
Fuel S content, max.	**≤ 3.0 %** (3.0-3.5 %)	3.5 %	**3.5 %** (3.0-3.5 %)	**3.5 %** (2.5-3.5 %)
Residual S in exhaust gas after scrubber (as fuel S content), max.	**0.5 %** (0.1-0.5 %)	0.1 %	0.1 %	0.1 %
Sea water alkalinity, min.	**2300 µmol/l** (2200 µmol/l)	Any	Any	Any
Sea water temperature, max.	**28 °C** (32 °C)	32 °C	32 °C	32 °C
Scrubber load, max.	**85 %** (100 %)	100 %	100 %	CS [3]
Alkali (50% NaOH solution) consumption, max.	Not applicable	CS	CS	CS
Sea water flow to scrubber, max.	**30 l/kWh** (30.0-45.0 l/kWh)	**< 30 l/kWh** (30 l/kWh)	-	-
Electric power consumption, max.	**≤ 2.0 %** (2.4 %)	**≤ 1.5 %** (1.9 %)	CS	CS
Bleed-off rate, max.	Not applicable	Not applicable	Not applicable	1.5 m^3/h
Exhaust gas pressure loss over scrubber, max.	**< 1000 Pa** (800-1200 Pa)			
1) Normal operation mode on Closed loop. 2) Zero discharge mode in Closed loop.				

With optimized design parameters introduced in Table 24, the sea water flow to the scrubber can be reduced by 15 l/kWh when the requested sulphur level after scrubbing is 0.5 m-%. With the engines presented in the case study, the needed reductions could be achieved with the sea water flow of less than 30 l/kWh, which is 15 l/kWh less than the quantity used at present with the Dual Water hybrid scrubbers and the Open loop scrubbers. For example, approximately 32 MW 2-stroke engine this would mean the reduction of 132 l/s (475.2 m^3/h) from needed sea water pumping capacity. According to the results presented in the case study, the sulphur content reduction to the level of 0.1 m-% could be feasible with the sea water flow of 35 l/kWh for every engine. However, the sea water flow of 30 l/kWh has already been used as the design parameter in the integrated Dual Water hybrid scrubber but in that case the maximum sulphur content in operating fuel oil has been set to 3.0 m-% with level of 0.1 m-% of the residual S in exhaust gas after scrubber.

The scrubber load in the Open loop mode has been set for 85 %, which enables economical Dual Water hybrid scrubber operation by the reduced scrubbing sea water pumping capacity. This kind of dimensioning would be most feasible with main stream scrubber installations. The ideology of the operating set-up is illustrated in Figure 49. With the normal scrubber operation on areas where the 0.5 % sulphur reduction is needed, the scrubber would operate in the Open loop mode (1). If the scrubber load exceeded 85 % (2), the system could transfer to the Hybrid more or to the Closed loop mode (3). This would be the scrubber operating principle when the system would be efficiently dimensioned as discussed in this study.

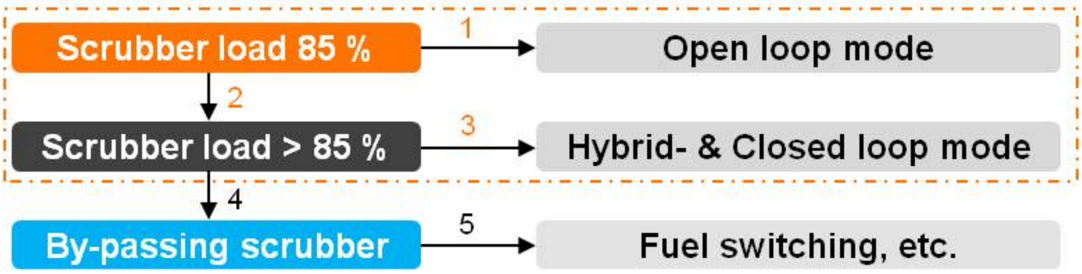


Figure 49. Scrubber operating principles according to scrubber load.

In situation where the scrubber system's main optimization criteria would be the size (along with the efficiency), also the Hybrid and Closed loop modes/ stages could be dimensioned according to reduced (85 %) scrubber load if it is feasible in compliance with the ship's operating profile. In that case, if the scrubber load exceeded the 85 % (2), the scrubber should be by-passed (4) in order to secure the safe operation of the ship and therefore fulfilling the sulphur content requirements must to be achieved by some other methods (5) such as fuel switching. Although this kind of arrangement should originate from the customer's needs as the solution expects commitments also from ship operator side.

At present, Wärtsilä is dimensioning the exhaust gas scrubber products according to the design parameters presented in this study. Ship (customer) specific design criteria meaning the engine power, the fuel oil type and its sulphur content, the maximum engine load, the exhaust gas flow, the E.G temperature or the E.G. temperature after E.G. boiler and the measured E.G. back pressure are collected for dimensioning and scrubber performance calculation process into Wärtsilä's SO_X Scrubber Questionnaire -form. The Picture 1 is a capture taken from the original form.

Machinery data				
Main Engine(s)				
Amount, make and type				Exhaust Gas Boiler(s) ☐
Power and speed (kW and rpm)				Variable speed ☐ / Constant speed ☐
Shaft generator power, if applicable (kW)				
Fuel type and sulphur content			Total ME fuel consumption (ton/year)	
Engine Load (%)	Exhaust Gas flow (kg/s)	E.G. temperature (°C)	E.G. temperature after E.G. boiler, if applicable (°C)	Measured E.G. back pressure (bar)
100				

Picture 1. Capture from Wärtsilä's SO_X Scrubber Questionnaire form.

Studies made from Open loop scrubbing have reflected that the needed sea water flow is highly dependent on the combustion unit's fuel oil consumption. Therefore, this information would be needed for future scrubber efficiency calculation. In scrubber projects where Wärtsilä engine products are installed, the SFOC or BSFC can be acquired from the documents presented earlier in this study but with the projects where the ship is equipped with other manufacturer's engines or with retro-fit projects, the valid and (measured) present fuel oil consumption value should be used with reasonable margin.

6.3 Dual Water Hybrid Scrubber Design and Performance Standardization

The case study results indicate that 2-stroke engine design and performance properties, mainly BSFC and BSEF, have great variations, which also reflect to the scrubber performance and the needed scrubbing sea water flows. Also the temperature of exhaust gas after turbine would have some effect on the needed sea water flows, if the E.G. boiler operation is not added to the calculations. This variation questions the possibility to standardize the design and the performance of the Dual Water hybrid scrubbers. A wide range of possible connected combustion unit power, changing and case specific ship's operating environments, along with untested scrubbing technology requests for more research and testing before the solution standardizing would be feasible.

Differing from the scrubber performance, the scrubber unit design is already better known although some dimensions may still change. As discussed at the end of the chapter 3, the ship's exhaust gas system modularization concepts are still missing from Wärtsilä's Ship power's solution portfolio. In some of the real customer sales cases and pre-studies, there has been raised an observation that the space reservations on ships for SCRs and exhaust scrubbers are hard to achieve and the ship yards have had problems to fit especially the exhaust gas scrubbers in conventional engine casings. Therefore, it would be beneficial to make available pre-design of different engine casings with Wärtsilä equipment installed and with most common exhaust gas boilers included. With this kind of pre-design the ship yard and Wärtsilä's project team could more easily prepare the final casing design for the ship with enough space and connection requirements for scrubber installation along with the most economical costs and the most feasible design. Also other concerns related to the exhaust gas systems, such as the back pressure formation, would be easier to solve and with Wärtsilä Compact Silencer System (CSS), the most optimal equipment locations could be achieved with the accurate dimensioning in pre-design phase. In the future, there will also be a need for different scrubber concepts for matching different machinery concepts for merchant ships. This should include the Wärtsilä's whole scrubber portfolio with pre-designs and economical calculations as base information for upcoming commercial projects.

The past few years have been challenging for the ship yards and the ship owners especially from the merchant ship ordering and the fleet side. However, some improvement in order intake have been seen at the end of 2012 but the merchant ship segment still represents only approximately 30 % (2012) of the total order from Wärtsilä’s Ship power side. The company has a quite stable market share of 18 % (2012) with low-speed (2-stroke) marine engines. The market position leader has been MAN Diesel & Turbo with approximately 30 % (2012) of market share (Wärtsilä Corporation 2013a, 20-26). Even though Wärtsilä has a smaller market share on the low-speed engine side, if the company was capable to offer feasible solutions combining marine low speed or medium speed diesel engine(s) + exhaust gas scrubber(s), this would most probably be recognized in the markets. This could increase the Wärtsilä’s market share, especially on the low-speed marine engine side. Through the well-planned and the well-designed exhaust gas system modularization, the company, as a full marine solution provider, could achieve even bigger market share than at present.

MAN Diesel & Turbo is at the moment mainly focusing on dry exhaust gas scrubbing technologies as they agreed on 1st August 2010 a development partnership and a close marketing cooperation with Couple Systems, which offers DeSOx -dry scrubber solution to marine markets (Couple Systems 2013). Therefore, even if the future merchant ship was still equipped with MAN engine, some of the shipping companies would most likely also have an interest towards wet scrubbing technologies, so Wärtsilä’s exhaust gas scrubber products should serve marine diesel engines of any make and kind. This would mean that more study of other suppliers’ engine designs and their performance features should be carried out as well as the study of engine behaviour with older installations for serving upcoming retro-fit scrubber installations.

6.4 Suggestions for Further Research

As the result of this study, the reduction in sea water inflow to the scrubber can be achieved with the optimized design parameters presented in here. Thus, with assumed reduced power consumption the system total efficiency would increase. However, more detailed research about how these parameters influence to the scrubber unit compactness (mainly the size) and also some economical calculations should be carried out in where the influence to system's CAPEX and OPEX could be studied. Also a possibility of utilizing the reduced scrubber load also in Closed loop stage dimensioning and performance calculations should be studied more, as it would most likely have some effect on the unit size and especially consumables by the means of fresh water and alkali consumption.

Pilot and field tests should be done for the Dual Water hybrid scrubber in order to test how the design will operate and fulfil the design requirements. In order to achieve more economical scrubber operation, the (scrubbing/ wash) sea water pumping should be executed so that the pumping capacities follow the combustion unit's fuel oil consumption, which will indicate the needed sulphur reduction by the sulphur content in the exhaust gas and the exhaust gas flow. This kind of arrangement would need some solution for maintaining the needed pressure before the nozzles in the scrubber unit as well as provide the sufficient spaying pattern(s) inside the scrubber unit. One solution for this could be several spraying levels in the scrubber unit with individual scrubbing sea water pump(s) for each level. With this kind of solution and with less scrubber load, some of the levels could be shut-downed, which would cut pumping power demand but still provide efficient spaying pattern(s). This is already implemented into some installations in terms of different Open loop (operating) modes when the scrubbing sea water is pumped only to the other scrubber unit's chamber during the Open loop mode. However, this kind of solution would most likely increase the investment cost, require more sea water piping inside the engine casing as well as request a more advanced control system. Still the feasibility of this solution should be studied and how it would actually affect on scrubber economics. Also utilizing the Venturi-technology in Dual Water hybrid scrubbers should be studied through its effect on sea water flows and scrubbing efficiencies in Closed loop and Hybrid modes.

As some of the design parameters are location/ operational environment related, diverse measuring results of the scrubber operation and predominant operational conditions should be collected from wide geographical ocean areas in order to collect sufficient test information for the base of dimensioning future commercial Dual Water hybrid scrubbers. When selecting feasible design parameters, the scrubbing process target should always be the same: achieving the sulphur dioxide removal efficiency level set by the design and the authorities, regardless of heavy fuel oil quality, fuel oil consumption, exhaust gas flow, sea water temperature and alkalinity. These variations are depending on the ship equipment, actual operating routes and conditions as presented earlier. It should be noticed that the values used in this study would be in real life very product- and case-specific.

Dual fuel engine technology, which enables the gas operation, is one solution for NO_X and SO_X emission reduction and with MGO operation present and upcoming SO_2 emission limits can be achieved. However, neither of these solutions can remove all the particulates and the BC emissions. Also when operating with residual fuels (HFO), the engines generate particulates, which contain ash components and sulphates. Consequently these HFO based particulates tend to have less radiative force than those generated during operation on distillate fuels (LFO) and the overall contribution of shipping to global warming will change from cooling to warming due to reduction in fuel sulphur content (CIMAC 2012, 13). According to CIMAC, also NO_X -reducing techniques, like SCRs, tend to increase particle formation (CIMAC 2010, 3). Also PM and BC issues have been highlighted in this study. The solution for a more efficient PM removal could be the utilization of the Venturi-technology also in Dual Water hybrid scrubbers. So this option should be studied along with its influence to the system’s total sea water flow requirements.

Scrubbing technology as well as the competing marine LNG storing & supplying technology are both still relatively immature technologies in the marine use, so there are still some uncertainties, particularly on costs and expected cost reductions, partly due to learning effects, which are high in these initial stages of technology innovation. Upcoming NO_X limits with their reduction technologies, mainly the SCR-technology, might also have some effect on scrubber solutions at least from the sales' point of view. In 2015-2016 the starting transitional phase may require customized solutions, which would minimize life-cycle costs under different operating schemes for different scrubber solutions, fleet segments and customer needs. This will put additional demand on the solutions to be developed for fulfilling future emission standards.

SOURCE MATERIAL

Aalborg. 2011. Technical specification: Exhaust gas system type EGC 30. Aalborg Industries.

Al-Enezi, G; Ettouney, H.; El-Dessouky, H. & Fawzi N. 2001. Solubility of Sulfur Dioxide in Seawater. Ind. Eng. Chem.

Alfa Laval. 2011. Meet sulphur regulations with the best economical solution: Exhaust gas cleaning. Alfa Laval Corporate AB.

Algoma. 2013. Algoma EQUINOX Class. Referred 19.3.2013. http://www.algonet.com > Business Units > Domestic Shipping > Fleet renewal.

Andreasen, A. & Mayer, S. 2007. Use of Seawater Scrubbing for SO_2 Removal from Marine Engine Exhaust Gas. Energy Fuels, 2007, 21 (6), pp 3274–3279 DOI: 10.1021/ef700359w.

Behrends, B. & Liebezeit, G. 2003. A Theoretical Environmental Impact Assessment of the Use of a Seawater Scrubber to Reduce SOx and NOx Emissions from Ships. http://www.dieselduck.ca/machine/01%20prime%20movers/2003%20Scrubber%20technology%20study.pdf.

Bindoff, N & all. 2007. Observations: Oceanic climate change and sea level (part of the Climate change 2007: The physical science basis, Fourth Assessment Report). Cambridge: Cambridge University Press.

Bond,T; Streets, D; Yarber, K; Nelson, S; Woo, J-H & Klimont, Z. 2004. A technology-based global inventory of black and organic carbon emissions from combustion. Journal of geophysical research: Vol. 109.

British Petroleum (BP). 2012. BP Energy Outlook 2030. London: British Petrolum.

Bunkerworld. 2012a. Bunker prices database. Referred 29.10.2012. http://www.bunkerworld.com > Bunker Prices.

Bunkerworld. 2012b. Fuel quality database. Referred 29.10.2012. http://www.bunkerworld.com > Fuel Quality.

Bunkerworld. 2012c. IMO report shows upward creep in global sulphur average. Referred 29.10.2012.

Bunkerworld. 2013. Fuel quality database. Referred 6.1.2013. http://www.bunkerworld.com > Fuel Quality. http://www.bunkerworld.com/news/i116595/IMO_report_shows_upward_creep_in_global_sulphur_average.

CE Delft; Germanischer Lloyd; MARINTEK & Det Norske Veritas. 2006. Greenhouse Gas Emissions for Shipping and Implementation of the Marine Sulphur Directive. CE Delft: Delft.

Chevron Products Company. 2008. Everything you need to know about marine fuels. http://www.chevronmarineproducts.com/docs/EverythingAboutFuels_v0108_LO.PDF.

CIMAC. 2008. Guide to Diesel Exhaust Emissions Control of NO_X, SO_X, Particulates, Smoke and CO_2. Wärtsilä Internal document.

CIMAC. 2010. Paper No. 26: High Cetane Number Paraffinic Diesel Fuels and Emission Reduction in Engine Combustion. Bergen: CIMAC Congress.

CIMAC. 2012. Background information on black carbon emissions from large marine and stationary diesel engines - Definition, measurement methods, emission factors and abatement technologies. Wärtsilä Internal document.

Corbett, J.; Winebrake, J.; Green, E.; Kasibhatla, P; Eyring, V. & Lauer, A. 2007. Mortality from Ship Emissions: A Global Assessment. Environ. Sci. Technol.

Corbett, J. 2010. Impacts of Shipping Emissions - Focus: International Arctic Transportation Assessment. http://www.htap.org/meetings/2010/2010_03/documents/presentations/CorbettHTAPArctic2009 handout.pdf.

Couple Systems. 2013. MAN Diesel & Turbo and Couple Systems. Referred 21.3.2013. http://couple-systems.de/index.php/start.117.html > Partners.

Det Norske Veritas. 2010. Assessment of measures to reduce future CO_2 emissions from shipping. Høvik: DNV.

Det Norske Veritas. 2012. ISO 8217 Fuel Standard: Fourth Edition 2010-06-15. Referred 15.9.2012. http://www.dnv.com/industry/maritime/servicessolutions/fueltesting/fuelqualitytesting/iso8217fuel standard.asp.

Det Norske Veritas. 2012. Shipping 2020: Executive Summary. Høvik: DNV Research & innovation.

Det Norske Veritas. 2012c. SO_X and scrubbers: Requirements and DNV involvement from a Class perspective. Høvik: DNV Approval Centre.

Dou, B; Pan, W; Jin, Q; Wang, W & Li, Y. 2008. Prediction of SO_2 removal efficiency for wet Flue Gas Desulfurization. Energy Conversion and Management 50 (2009) 2547-2553.

Earth System Research Laboratory: Global Monitoring Division (GMD). Recent Global CO_2. Referred 6.1.2013. http://www.esrl.noaa.gov/gmd/ > Products > Interactive Data Viewer > Products > Trends in CO_2 > Global.

Earth System Research Laboratory: Physical Sciences Division (PSD). Sea Surface Temperature (STT). Referred 10.1.2013. http://www.esrl.noaa.gov/psd/ > Products > Map Room > Sea Surface Temperature (STT).

Englund, M & Välimäki, J. 2013. Private conversation with Senior Development Engineer and External Engineer from Wärtsilä Ship Power Exhaust gas cleaning -organization about ship's sea chest design and location. Turku 26.2.2013.

European Environment Agency. 2011. Air quality in Europe - 2011 report. Luxembourg: Publications Office of the European Union.

European Marine Safety Agency (EMSA). 2012. The World Merchant Fleet in 2011. Equasis database. http://www.emsa.europa.eu > News & Media > Latest News > The world merchant fleet - statistics from Equasis.

Equasis. 2013. Equasis online tool database. Referred 23.2.2013. http://www.equasis.org.

European Parliament. 2012. Directive 2012/33/EU of the European Parliament and of the Council of 21 November 2012 on amending Council Directive 1999/32/EC as regards the sulphur content of marine fuels. Referred 9.5.2013. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:327:0001:0013:EN:PDF

European Project on OCean Acidification (EPOCA). 2013. Ocean acidification. Referred 18.4.2013. http://www.whoi.edu/OCB-OA/ > Info & media > FAQs about ocean acidification > OA Primer > Introduction to OA / The chemistry.

European Union. 2007. Sulphur content of certain liquid fuels. Referred 13.6.2012. http://europa.eu/legislation_summaries/other/l21050_en.htm.

Exhaust gas cleaning systems association (EGCSA). 2012. De-SOX via Scrubbers an Overview. Gothenburg: SAE 2012 - Emission Control from Large Ships.

Eyring, V.; Isaksen, I.; Berntse, T.; Collins, W.; Corbett, J.; Endresen, O.; Grainger, R.; Moldanova, J.; Schlager H. & Stevenson, D. 2009. Transport impacts on atmosphere and climate: Shipping. Atmos. Environ.

Fairplay. 2013. Samco Amazon. Referred 19.3.2013. http://www.fairplay.co.uk/login.aspx?reason=denied_empty&script_name=/secure/displayMagArticles.aspx&path_info=/secure/displayMagArticles.aspx&articlename=sofe20120202028fe

Germanischer Lloyd. 2010. Environmental Passport for Ten Percent of GL fleet. Referred 29.8.2012. http://www.gl-group.com/en/press/news_20877.php.

Hasenberg, L. 2008. Corrosion handbook: Sulfate Dioxide, Sodium Sulfate. DECHEMA e.V.

Hamworthy Krystallon Ltd 2012a. Exhaust gas cleaning systems. ref: HMO 4009 0810. Referred 20.3.2012 http://www.hamworthy.com > Products > Marine > Emission Reduction > SO_X Scrubber System.

Hamworthy Moss AS. 2011a. Outline technical proposal to Polsteam for exhaust gas cleaning system. Moss: Hamworthy Krystallon Ltd.

Hamworthy Krystallon Limited. 2007. Sea Water Scrubbing - Does it Contribute to increased Global CO_2 Emissions.

Henriksson, T. 2013. Private conversation with General manager from Wärtsilä Ship power Exhaust gas cleaning organization about IMO’s Guidelines for exhaust gas cleaning systems. Turku 19.3.2013.

Hesketh, H & Schifftner, C. 1996. Wet scrubbers. 2nd edition. Boca Raton: Taylor & Francis Group.

Häkkinen, E. 2013. Private conversation with Application manager from Wärtsilä Ship power about the maximum engine load on ships related to Wärtsilä’s retro-fit scrubber projects so far. Helsinki 15.3.2013.

Institute of Maritime Engineering, Science and Technology (IMarEST). 2012. Marine engineers review magazine September 2012. London: Aldgate House.

Institute of Maritime Engineering, Science and Technology (IMarEST). 2012. Marine engineers review magazine November 2012. London: Aldgate House.

International Energy Agency (IEA). 2012. World Energy Outlook 2012: Executive summary. Paris: OECD/IEA.

International Maritime Organization (IMO). 1993. IMO Resolution A.753(18): Guidelines for the Application of Plastic Pipes on Ships. Lloyd’s Register Rulefinder 2011.

International Maritime Organization (IMO). 2007. Prevention of Air Pollution from Ships: Washwater Discharge Criteria for Exhaust Gas-SOx Cleaning Systems. MEPC 56/INF.5: Agenda item 4.

International Maritime Organization (IMO). 2008. Revised MARPOL Annex VI: Regulations for the Prevention of Air Pollution from Ships. MEPC 58/23/Add.1: ANNEX 13.

International Maritime Organization (IMO). 2009a. 2009 Guidelines for exhaust gas cleaning systems. MEPC 59/24/Add.1: ANNEX 19.

International Maritime Organization (IMO). 2009b. Interim on the method of calculation of the energy efficiency design index for new ships. MEPC.1/Circ.681: Ref. T5/1.01.

International Maritime Organization (IMO). 2009c. Second IMO GHG Study 2009. Reading: CPI Books Limited.

International Maritime Organization (IMO). 2011a. Development of a mandatory code for ships operating in polar waters: Reducing black carbon emissions from vessels in Polar regions. Sub-committee on ship design & equipment: DE55/12/X.

International Maritime Organization (IMO). 2011b. RESOLUTION MEPC.203(62): Inclusion of regulations on energy efficiency for ships in MARPOL Annex VI. MEPC 62/24/Add.1: ANNEX 19.

International Maritime Organization (IMO). 2012a.Greenhouse Gas Emissions. Referred 28.9.2012. http://www.imo.org > Our Work > Marine Environment > Pollution Prevention > Air Pollution and GHG Emissions > GHG Emissions.

International Maritime Organization (IMO). 2012b. International Shipping Facts and Figures - Information Resources on Trade, Safety, Security, Environment. IMO: Maritime Knowledge Centre.

International Maritime Organization (IMO). 2012c. North American emission control area comes into effect on 1 August 2012. Referred 28.8.2012. http://www.imo.org/MediaCentre/PressBriefings/Pages/28-eca.aspx.

International Maritime Organization (IMO). 2012d. Technical and Operational Measures. Referred 28.9.2012. http://www.imo.org > Our Work > Marine Environment > Pollution Prevention > Air Pollution and GHG Emissions > Technical and Operational Measures.

Irwin, R. 1997. Environmental contaminants encyclopaedia: Fuel oil. Fort Collins: National Park Service.

Joseph, G & Beachler, D. 1998. Scrubber Systems Operation Review. 2nd edition. North Carolina: North Carolina State University.

Juoperi, K. 2013. Private conversation with Manager of Engine fluids expertise from Wärtsilä 4-st PowerTech about the sulphur content and origin in HFO. Turku 3.1.2013.

Kalli, J.; Karvonen, T. & Makkonen, T. 2009. Sulphur content in ships bunker fuel in 2015. Turku: University of Turku: The Centre for Maritime Studies.

Karle, I. & Turner, D. 2007. Seawater Scrubbing - reduction of SOx emissions from ship exhausts. Götenhenburg: The Alliance for Global Sustainability.

Lack, D.; Thuesen, J. & Elliot, R. 2012. Investigation of appropriate control measures (abatement technologies) to reduce Black Carbon emissions from international shipping - Study report. Holte: Litehauz Aps.

Lahtinen, J. 2011. Dual water scrubber Design Criteria. Wärtsilä Internal document.

Lassila, H. 2012. Hybrid scrubber test plan. Wärtsilä Internal document.

Lee, C. 2005. Environmental engineering dictionary. 4th edition. Maryland: Government institutes.

Lee, K. 2006. Global Surface Ocean Alkalinity Climatology. Refered 10.1.2013. http://cdiac.ornl.gov/oceans/Lee_Surface_Alk_Climatol.html.

Lee, K.; Tong, L.; Millero, F.; Sabine, C.; Dickson, A.; Goyet, C; Park, G.; Wanninkhof, R.; Feely, R. & Key, R. 2006. Global relationships of total alkalinity with salinity and temperature in surface waters of the world's oceans. Geophysical Research Letters: VOL. 33, L19605, doi:10.1029/2006GL027207, 2006.

Lehikoinen, M. 2006. The Impact of Sea Water Quality on the Performance of a Sea Water Scrubber. Master's thesis. Espoo: Helsinki University of Technology/ Department of Mechanical Engineering.

Lloyd's Register. 2012. Understanding exhaust gas treatment systems: Guidance for ship owners and operators. London: Lloyd's Register.

Marinebio. 2013. The Ocean and Temperature. Referred 21.1.2013. http://marinebio.org/oceans/temperature.asp.

Marine and Energy Consulting Limited (MECL). 2011. Outlook for Marine Bunkers and Fuel Oil to 2030. London: FGE & MECL.

Marinelog. 2013. Fairplay. 2013. World's largest containership starts maiden voyage. Referred 19.3.2013.
http://www.marinelog.com/index.php?option=com_content&view=article&id=3178:worlds-largest-containership-starts-maiden-voyage&catid=1:latest-news&Itemid=195

Millero, F.; Lee, K. & Roche, M. 1998. Distribution of alkalinity in the surface waters of the major oceans. Elsevier: Marine Chemistry.

Mäenpää, L. 2011. Sea Water Flue Gas Desulfurization Effluent Treatment. Master's thesis. Tampere: Tampere University of Technology/ Faculty of Science and Environmental Engineering.

National Oceanic and Atmospheric Administration (NOAA). OI SST Maps. 2.1.2013. http://www.ncdc.noaa.gov/oa/climate/research/sst/images.php?string=navy-sst-b-&_submit_check=1.

National Oceanographic Data Center (NODC). Annual salinity at the surface. Referred 19.2.2013. http://www.nodc.noaa.gov/ > Ocean Climate Laboratory > OCL Products > WOA09F > Salinity figure search > Climatology.

Naturvårdsverket 2012. Sulphur tax. Referred 16.7.2012. http://www.naturvardsverket.se/en/ > Operations with impact on the environment > Energy > Sulphur tax.

Næringslivets Hovedorganisasjon 2012. Referred 16.7.2012. http://www.nho.no/ > The NOx Fund > The NOx Fund.

Nikulainen, K. 2012. The Basic Theory of Seawater Scrubbing. Master's thesis. Espoo: Aalto University: School of Chemical Technology.

Nikulainen, K. 2013a. Private conversation with Development Engineer about scrubber dimensioning and calculation processes. Turku 13.2.2013.

Nikulainen, K. 2013b. Email from Development Engineer about a study of sea water alkalinity to scrubbing efficiency made by third party for Wärtsilä. Turku 6.3.2013.

Organization of the Petroleum Exporting Countries (OPEC). 2011. World Oil Outlook 2011. Vienna: OPEC Secretariat.

Patterson, D & Springer, S. 1973. Engine emissions: pollution formation and measurement. New York - London: Plenum Press.

Perry, R & Green, D. 2008. Perry's Chemical Engineers' Handbook: 8th edition. New York: McGraw-Hill Companies

Platts. 2012a. Methodology and Specifications Guide: Asian Oil Products. http://www.platts.com/IM.Platts.Content/MethodologyReferences/MethodologySpecs/asiaoilproductspecs.pdf.

Platts. 2012b. Methodology and Specifications Guide: China Fuel Oil. http://www.platts.com/IM.Platts.Content/MethodologyReferences/MethodologySpecs/chinafueloilspecs.pdf.

Platts. 2012c. Methodology and Specifications Guide: European Products. http://www.platts.com/IM.Platts.Content/MethodologyReferences/MethodologySpecs/europeanoilproductspecs.pdf.

Platts. 2012d. Methodology and Specifications Guide: Petroleum Products & Gas Liquids: US, Caribbean and Latin America. http://www.platts.com/IM.Platts.Content/MethodologyReferences/MethodologySpecs/usoilproductspecs.pdf.

Purvin & Gertz. 2010. Residual Fuel Market Outlook: Impact of Bunker Quality Changes on Marine Fuels and Refining. London: Purvin & Gertz.

Rodríguez-Sevilla, J.; Álvarez, M.; Díaz, M. & Marrero, M. 2004. Absorption Equilibrium of Dilute SO_2 in Seawater. J. Chem. Eng. Data.

Rozmarynowska, M & Ołdakowski, B. 2012. Implications of new regulation regarding sulphur content in ship's fuel on maritime transport sector within Baltic Sea Region. Helsinki: Baltic Ports Organization Secretariat.

Schenelle, K. & Brown, C. 2002. Air pollution control technology handbook. Florida: CRC Press LLC.

Schäfer, K; Emanuel Söding, E & Zeller, M. 2010. World Ocean Review 2010: Maritime highways of global trade. Hamburg: Maribus gGmbH.

Ship Operations Cooperative Program (SOCP). 2011. Exhaust Gas Cleaning Systems Selection Guide. Seattle: The Glosten Associates.

Skema. 2010. Impact Study of the future requirements of Annex VI of the MARPOL Convention on Short Sea Shipping. European Commissioning: Grant Agreement No. TREN/FP7/TR/218565/"SKEMA".

Slotte, M. 2010. A design tool for SO_2 scrubbers for marine application. Master's thesis. Turku: Åbo Akademi University/ Department of Chemical Engineering.

Soloviev, A & Lukas, R. 2006. The Near-Surface Layer of the Ocean. Dordrecht: Springer.

Surhone, M; Tennoe, T & Henssonow, S. 2010. Wet scrubber. Beau Bassin: VDM Publishing House Ltd.

Svensson, E. 2011. The Regulation of Global SOx Emissions from Ships IMO proceedings 1988-2008. Licentiate's thesis. Gothenburg: Chalmers University of Technology/ Department of Shipping and Marine Technology.

Tomczack, M. 2002. An Introduction to Physical Oceanography/ Lecture 7: Thermohaline processes, water masses. Referred 21.1.2013. http://www.es.flinders.edu.au/~mattom/IntroOc/lecture07.html.

United Nations Conference on Trade And Development (UNCTAD). 2011. Review of Maritime Transport 2011: Report by the UNCTAD secretariat. New York and Geneva: United Nations Conference on Trade and Development, United Nations.

United Nations Conference on Trade And Development (UNCTAD). 2012. Review of Maritime Transport 2012: Report by the UNCTAD secretariat. New York and Geneva: United Nations Conference on Trade and Development, United Nations.

United States Environmental Protection Agency (EPA). 1999. In-Use Marine Diesel Fuel. http://www.epa.gov/oms/regs/nonroad/marine/ci/fr/dfuelrpt.pdf.

United States Environmental Protection Agency (EPA). 2008. EPA420-R-08-021. Global Trade and Fuels Assessment: Future Trends and Effects of Requiring Clean Fuels in the Marine Sector. North Carolina: RTI International.

United States Environmental Protection Agency (EPA). 2010. EPA-420-F-10-015. Designation of North American Emission Control Area to Reduce Emissions from Ships: Regulatory Announcement. Referred 18.7.2012. http://www.epa.gov/ > Transportation and Air Quality > Nonroad Engines, Equipment, and Vehicles > Diesel Boats and Ships > Oceangoing Vessels > Designation of North American Emission Control Area to Reduce Emissions from Ships.

United States Environmental Protection Agency (EPA). 2012a. 18 AAC 50.070. Diesel Boats and Ships. Referred 18.7.2012. http://www.epa.gov/ > Transportation and Air Quality > Nonroad Engines, Equipment, and Vehicles > Diesel Boats and Ships.

United States Environmental Protection Agency (EPA). 2012b. 18 AAC 50.070. Marine vessel visible emission standards. Referred 17.7.2012. http://www.epa.gov/ > Region 10 > Air Page > SIPs/ALASKA > SIPAlaska50.070.

United States Environmental Protection Agency (EPA). 2012c. Sulfur dioxide. Referred 8.8.2012. http://www.epa.gov/ > Air & Radiation > Six Common Pollutants > Sulfur Dioxide.

United States Environmental Protection Agency (EPA). 2013. Vessel General Permit for Discharges Incidental to the Normal Operation of Vessels (VGP). EPA-HQ-OW-2011-0141; FRL-9733-7.

U.S. Energy Information Administration (EIA). 2011. The International Energy Outlook 2011. Washington: U.S. Energy Information Administration Office of Communications.

Vaezi, M.; Pasandideh-Fard, M.; Moghiman, M. & Charmchi, M. 2010. Gasification of heavy fuel oils: A thermochemical equilibrium approach. Environ. Sci. Technol.

Wahlström, J.; Karvosenoja, N. & Porvari, P. 2006. Ship emissions and technical emission reduction potential in the Northern Baltic Sea. http://www.ymparisto.fi/download.asp?contentid=55273.

Watson, D. 1998. Practical ship design. Oxford: Elsevier Science Ltd.

WinGTD 3.0. 2013. General Technical Data: Wärtsilä two-stroke engines -calculation tool. Referred 23.2.2013. Wärtsilä Business Application.

Wärtsilä. 2002a. Outline description: 40000 DWT Product/ chemical tanker – Medium speed main engine. Wärtsilä Internal document: DAAB019080.

Wärtsilä. 2002b. Outline description: 40000 DWT Product/ chemical tanker – Low-speed main engine. Wärtsilä Internal document: DAAB019083.

Wärtsilä. 2002c. Tanker considerations. Wärtsilä Internal document: DAAB019051.

Wärtsilä. 2003a. Machinery selection guide for ferries. Wärtsilä Internal document: DAAB026535.

Wärtsilä. 2003b. Machinery selection guide -RoRo vessels. Wärtsilä Internal document: DAAB025402.

Wärtsilä. 2008. Wärtsilä Fuel strategy: Study on Primary Energy Sources and Fuels. Wärtsilä Internal document.

Wärtsilä. 2009a. General description of Wärtsilä scrubber system. Revision A. Vaasa: Wärtsilä Finland Oy.

Wärtsilä. 2009b. Wärtsilä Low Sulphur Guidelines. Revision III. Wärtsilä Corporation Oyj.

Wärtsilä. 2010a. Reducing medium-speed marine engine emissions. Vaasa: Wärtsilä Finland Oy.

Wärtsilä. 2010b. Wärtsilä SO_x scrubber: Leading the way in SO_x abatement. Wärtsilä Finland Oy.

Wärtsilä. 2011a. Hybrid SOx scrubber equipment data sheet: WSC0021- FoS. Wärtsilä Finland Oy.

Wärtsilä. 2011b. Safety concept for marine SO_x scrubber. Revision H (8.10.2011). Vaasa: Wärtsilä Finland Oy.

Wärtsilä. 2011c. Technical specification SO_x scrubber system: WSC0021- FoS. Wärtsilä Finland Oy.

Wärtsilä. 2011d. Wärtsilä scrubber installation guide. Revision B. Wärtsilä Finland Oy. DBAB285337.

Wärtsilä. 2012a. Hybrid SO_x scrubber technical data sheet: Project WSC1046, document WSC1046.002 revision D. Wärtsilä Finland Oy.

Wärtsilä. 2012b. Installation Planning Instructions for Algoma: Wärtsilä Fresh Water Scrubber. Version a1. Wärtsilä Finland Oy.

Wärtsilä. 2012c. Technical specification SO_x scrubber system: Project WSC1046, document WSC1046.001 revision F. Wärtsilä Finland Oy.

Wärtsilä. 2012d. Wärtsilä Scrubber Process Description: Project WSC1046, document WSC1046.004 revision E. Wärtsilä Finland Oy.

Wärtsilä. 2012e. Wärtsilä SO_X Scrubbers. Document ID: DBAB285337.

Wärtsilä. 2013a. Case study SW stage calculations -Microsoft Excel calculation document. Internal document.

Wärtsilä. 2013b. Project WSC1046 Hybrid scrubber operating cases - expected performance based on the current system design (for one scrubber). Internal document.

Wärtsilä Corporation. 2012a. Marine solutions. Second edition. www.wartsila.com > Marine Solutions > Products > Marine Solutions 2012.

Wärtsilä Corporation. 2012b. Solutions for merchant vessels. DBAC310827 / 08.2012.

Wärtsilä Corporation. 2013a. 2012 Result Presentation (25 January 2013). Internal document from Company’s intranet.

Wärtsilä Corporation. 2013b. Twentyfour7 -Issue 1/2013: The Exhaust Gas Cleaning Evolution. Referred 8.3.2013. http://www.twentyfour7magazine.com/en/ > Issue 01.2013 > In-Depth Trapping sulphur.

Wärtsilä eTools. 2013. Customer specific installation database. Referred 23.2.2013. Wärtsilä Internal Application.

Wärtsilä Hamworthy. 2012. Wärtsilä Exhaust gas cleaning system. Internal document.

Wärtsilä Industrial Operations - Product Centre Ecotech (WIO-PCE). 2011. Hybrid scrubber development and pre-study project WSC0021: Phase 1 & Phase 2 end reports. Internal documents.

Wärtsilä Infoboard@intranet. Performance manual database. Referred 12.2012-01.2013. Wärtsilä Internal Application.

Wärtsilä Italia S.p.A. 2010. Installation Manual for Wärtsilä 46F - A. 2012 issue a4. Trieste: Product information.

Wärtsilä Land & Sea Academy (WLSA). 2011. Requirements and treatment of fuel oil: 0-000R05CBA202A002L_02en. Turku: Wärtsilä Finland Oy, Services.

Wärtsilä Land & Sea Academy (WLSA). 2012. Wärtsilä Closed Loop Operation: FWS-000TMCB001L_01en. Turku: Wärtsilä Finland Oy, Services.

Wärtsilä Ship power technology. 2010. Wärtsilä Environmental Product guide. 3/2011 issue. Vaasa: Wärtsilä Finland Oy.

Wärtsilä Ship power technology. 2011. Wärtsilä 46F Product guide. 1/2011 issue. Vaasa: Wärtsilä Finland Oy.

Wärtsilä Switzerland Ltd. 2012a. Marine Installation Manual RT-flex96C-B. Issue October 2012. Winterthur: Wärtsilä Switzerland Ltd.

Wärtsilä Switzerland Ltd. 2012b. Marine Installation Manual RT-flex82T. Issue June 2012. Winterthur: Wärtsilä Switzerland Ltd.

Wärtsilä Switzerland Ltd. 2010. Marine Installation Manual RT-flex50-D. Issue December 2010. Winterthur: Wärtsilä Switzerland Ltd.

Åkerberg, J. 2013. Private conversation with Senior Mechanical Trainer from Wärtsilä Land and Sea academy about exhaust gas temperatures in ship’s exhaust gas system when operating with HFO. Turku 4.1.2013.

ISO 8217 Fuel Standard, Fourth Edition

For marine distillate fuels and for marine residual fuels.

MARINE DISTILLATE FUELS

Parameter	Unit	Limit	DMX	DMA	DMZ	DMB
Viscosity at 40°C	mm^2/s	Max	5.500	6.000	6.000	11.00
Viscosity at 40°C	mm^2/s	Min	1.400	2.000	3.000	2.000
Micro Carbon Residue at 10% Residue	% m/m	Max	0.30	0.30	0.30	-
Density at 15°C	kg/m^3	Max	-	890.0	890.0	900.0
Micro Carbon Residue	% m/m	Max	-	-	-	0.30
Sulphur [a]	% m/m	Max	1.00	1.50	1.50	2.00
Water	% V/V	Max	-	-	-	0.30 [b]
Total sediment by hot filtration	% m/m	Max	-	-	-	0.10 [b]
Ash	% m/m	Max	0.010	0.010	0.010	0.010
Flash point	0°C	Min	43.0	60.0	60.0	60.0
Pour point, Summer	0°C	Max	-	0	0	6
Pour point, Winter	°C	Max	-	-6	-6	0
Cloud point	°C	Max	-16	-	-	-
Calculated Cetane Index		Min	45	40	40	35
Acid Number	mgKOH/g	Max	0.5	0.5	0.5	0.5
Oxidation stability	g/m^3	Max	25	25	25	25 [c]
Lubricity, corrected wear scar diameter (wsd 1.4 at 60°C [d]	um	Max	520	520	520	520 [c]
Hydrogen sulphide [e]	mg/kg	Max	2.00	2.00	2.00	2.00
Appearance			Clear & Bright [f]			[b, c]

a) Sulphur limit of 1.00% m/m applies in the Emission Control Areas designated by the International Maritime Organization. As there may be local variations, the purchaser shall define the maximum sulphur content according to the relevant statutory requirements, notwithstanding the limits given in this table.
b) If the sample is not clear and bright, total sediment by hot filtration and water test shall be required.
c) Oxidation stability and lubricity tests are not applicable if the sample is not clear and bright.
d) Applicable if sulphur is less than 0.050% m/m.
e) Effective only from 1 July 2012.
f) If the sample is dyed and not transparent, water test shall be required. The water content shall not exceed 200 mg/kg (0.02% m/m).

(Det Norske Veritas 2012a)

MARINE RESIDUAL FUELS

Parameter	Unit	Limit	RMA [a]	RMB	RMD	RME
			10	**30**	**80**	**180**
Viscosity at 50°C	mm²/s	Max	10.00	30.00	80.00	180.0
Density at 15°C	kg/m^3	Max	920.0	960.0	975.0	991.0
Micro Carbon Residue	% m/m	Max	2.50	10.00	14.00	15.00
Aluminium + Silicon	mg/kg	Max	25	40		50
Sodium	mg/kg	Max	50	100		50
Ash	% m/m	Max	0.040	0.070		
Vanadium	mg/kg	Max	50	150		
CCAI	-	Max	850	860		
Water	% V/V	Max	0.30	0.50		
Pour point (upper) [b], Summer	°C	Max	6		30	
Pour point (upper) [b], Winter	°C	Max	0		30	
Flash point	°C	Min	60.0			
Sulphur [c]	% m/m	Max	Statutory requirements			
Total Sediment, aged	% m/m	Max	0.10			
Acid Number[e]	mgKOH/g	Max	2.5			
Used lubricating oils (ULO): Calcium and Zinc; or Calcium and Phosphorus	mg/kg	-	The fuel shall be free from ULO, and shall be considered to contain ULO when either one of the following conditions is met: Calcium > 30 and zinc >15; or Calcium > 30 and phosphorus > 15.			
Hydrogen sulphide [d]	mg/kg	Max	2.00			

a) This residual marine fuel grade is formerly DMC distillate under ISO 8217:2005.
b) Purchasers shall ensure that this pour point is suitable for the equipment on board, especially in cold climates.
c) The purchaser shall define the maximum sulphur content according to the relevant statutory requirements.
d) Effective only from 1 July 2012.
e) Strong acids are not acceptable, even at levels not detectable by the standard test methods for SAN.
As acid numbers below the values stated in the table do not guarantee that the fuels are free from problems associated with the presence of acidic compounds, it is the responsibility of the supplier and the purchaser to agree upon an acceptable acid number.

(Det Norske Veritas 2012a)

Appendix 1

Parameter	Unit	Limit	RMG				RMK		
			180	**380**	**500**	**700**	**380**	**500**	**700**
Viscosity at 50°C	mm²/s	Max	180.0	380.0	500.0	700.0	380.0	500.0	700.0
Density at 15°C	kg/m^3	Max	991.0				1010.0		
Micro Carbon Residue	% m/m	Max	18.00				20.00		
Aluminium + Silicon	mg/kg	Max	60						
Sodium	mg/kg	Max	100						
Ash	% m/m	Max	0.100				0.150		
Vanadium	mg/kg	Max	350				450		
CCAI	-	Max	870						
Water	% V/V	Max	0.50						
Pour point (upper) [b], Summer	°C	Max	30						
Pour point (upper) [b], Winter	°C	Max	30						
Flash point	°C	Min	60.0						
Sulphur [c]	% m/m	Max	Statutory requirements						
Total Sediment, aged	% m/m	Max	0.10						
Acid Number[e]	mgKOH/g	Max	2.5						
Used lubricating oils (ULO): Calcium and Zinc; or Calcium and Phosphorus	mg/kg	-	The fuel shall be free from ULO, and shall be considered to contain ULO when either one of the following conditions is met: Calcium > 30 and zinc >15; or Calcium > 30 and phosphorus > 15.						
Hydrogen sulphide [d]	mg/kg	Max	2.00						

a) This residual marine fuel grade is formerly DMC distillate under ISO 8217:2005.
b) Purchasers shall ensure that this pour point is suitable for the equipment on board, especially in cold climates.
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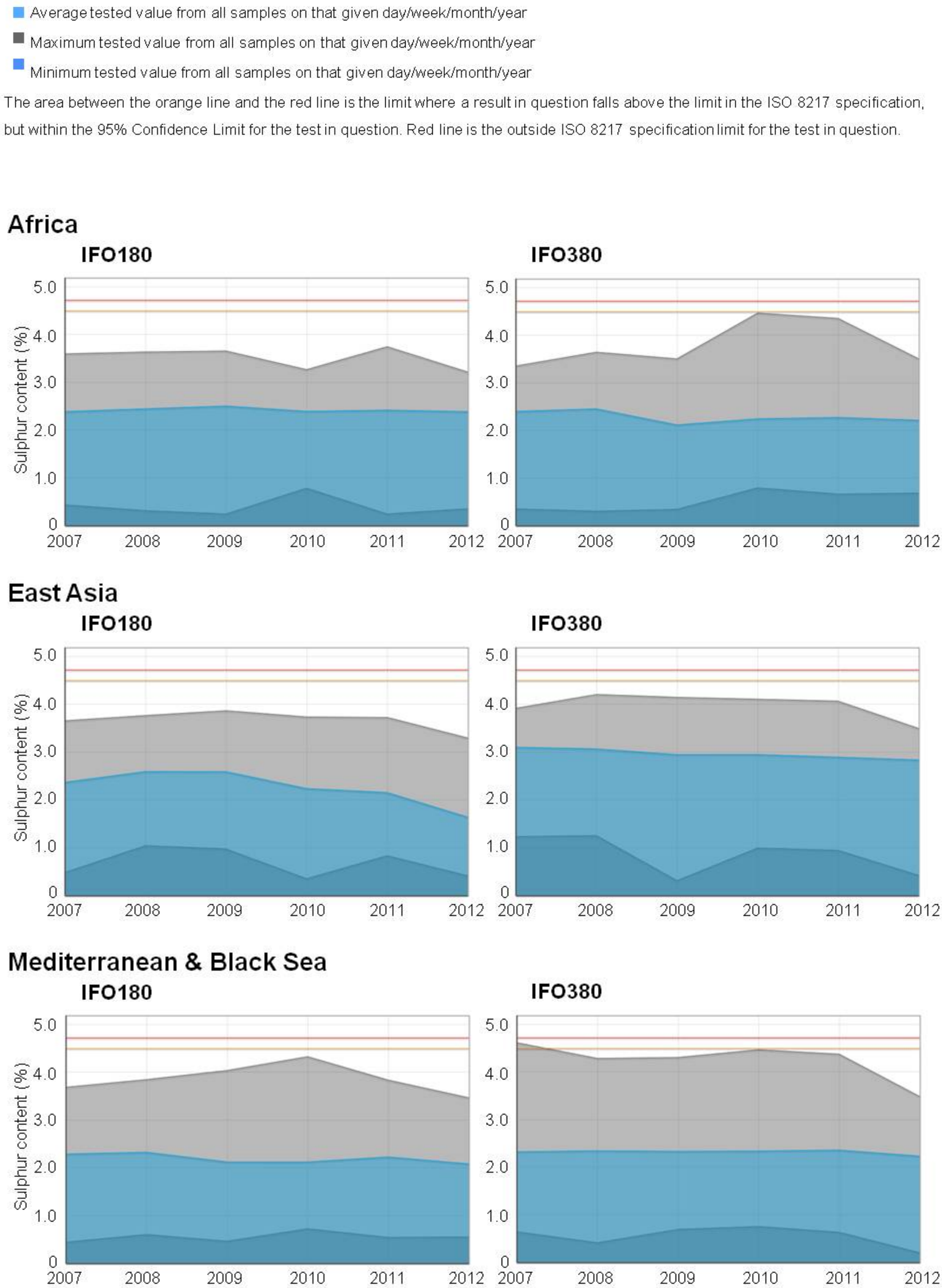
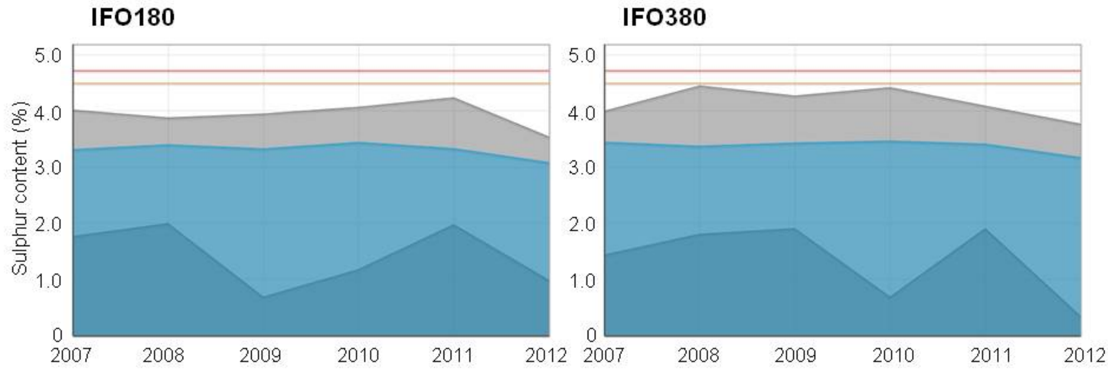
(Det Norske Veritas 2012a)

IFO180 and IFO380 sulphur contents by regions between 2007-2012

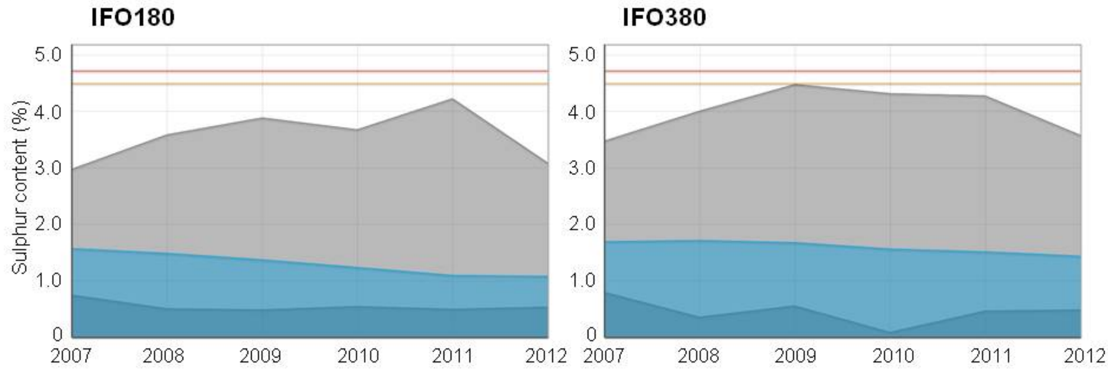


Appendix 2

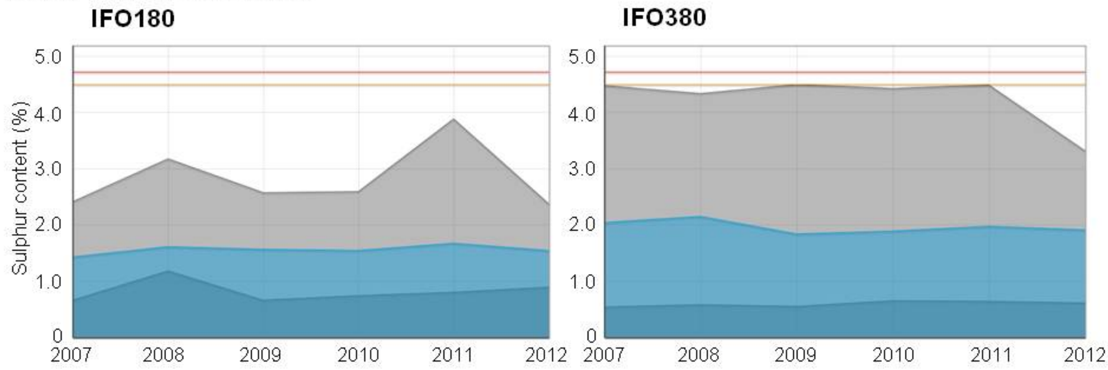
Middle East



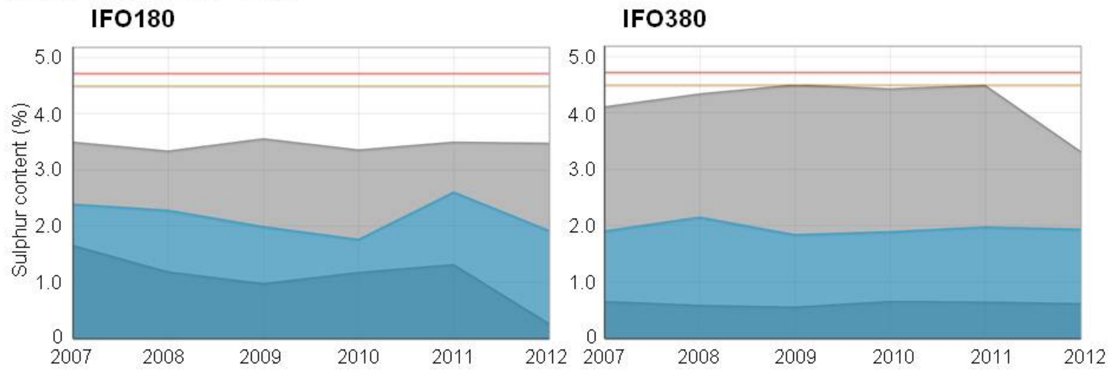
North & West Europe



North America Atlantic



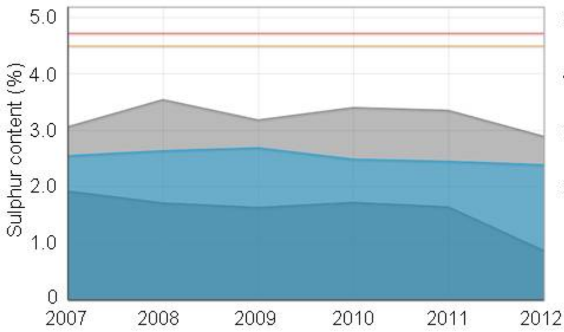
North America Pacific



Appendix 2

Pacific, Australia, New Zealand

IFO180



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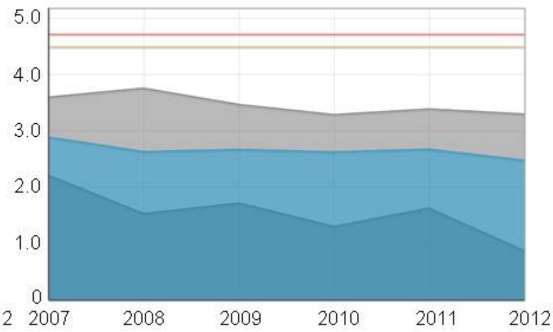
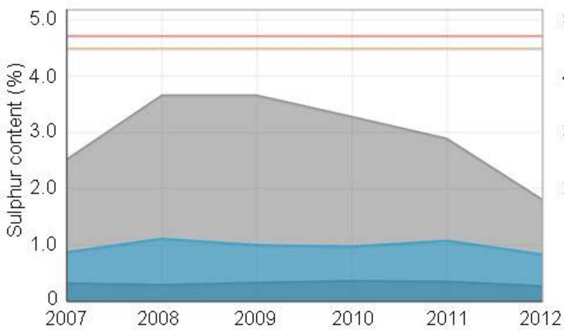
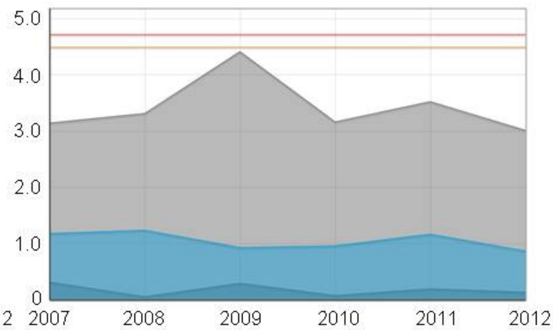


South America Atlantic

IFO180

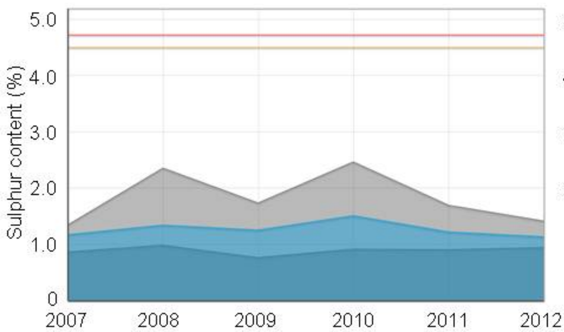


IFO380



South America Pacific

IFO180



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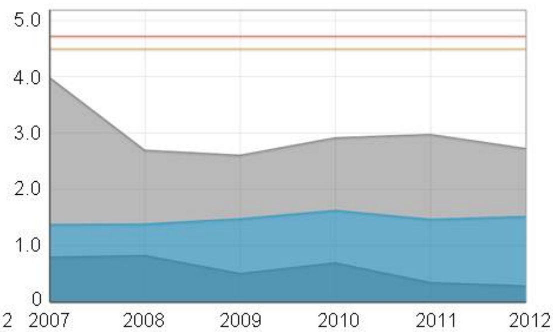
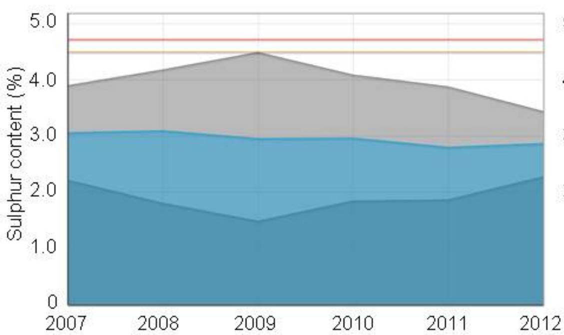
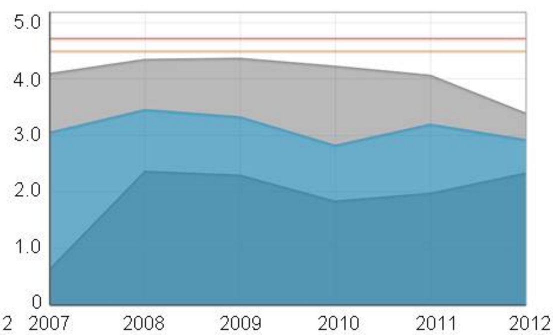


South Asia

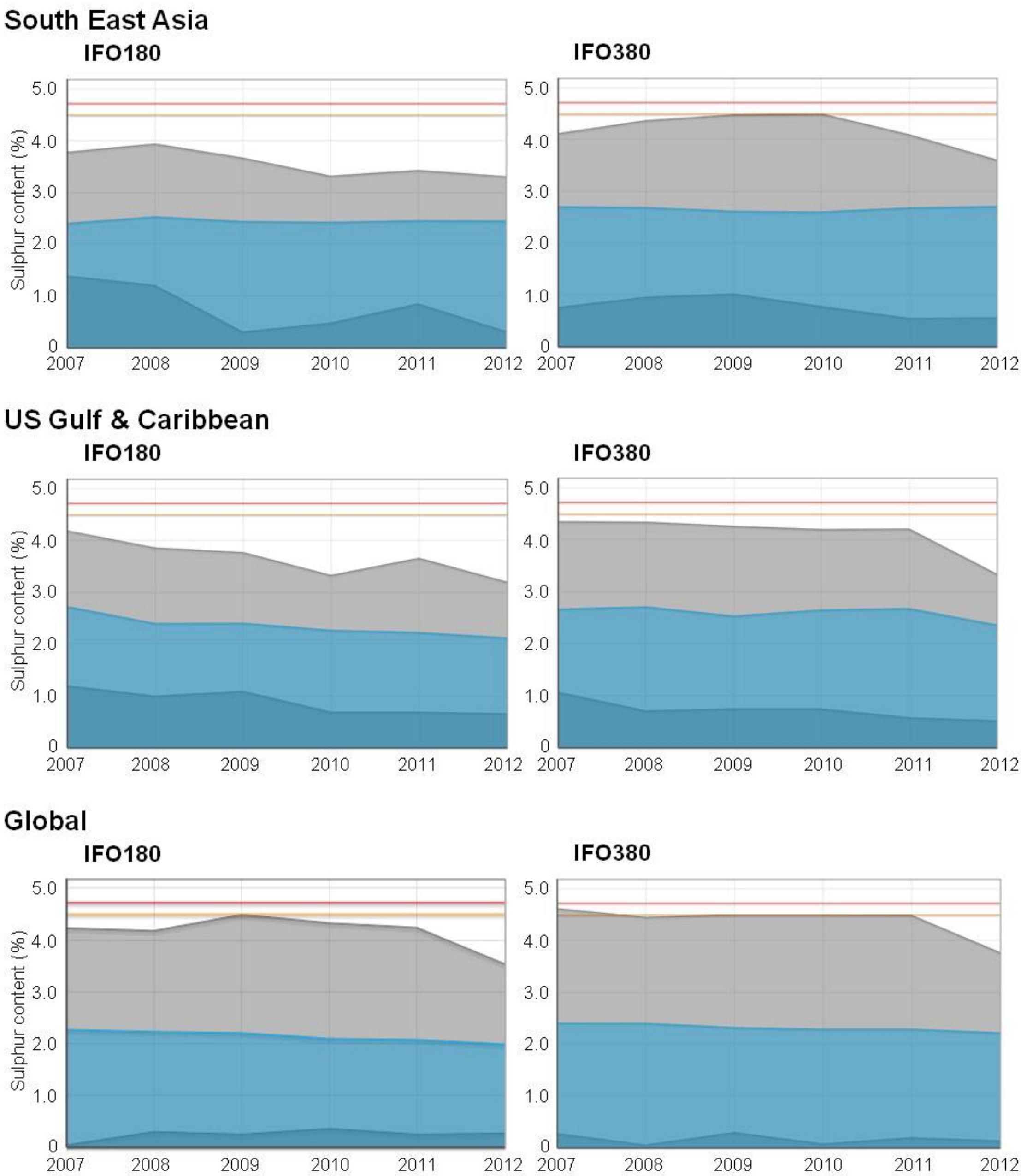
IFO180



IFO380



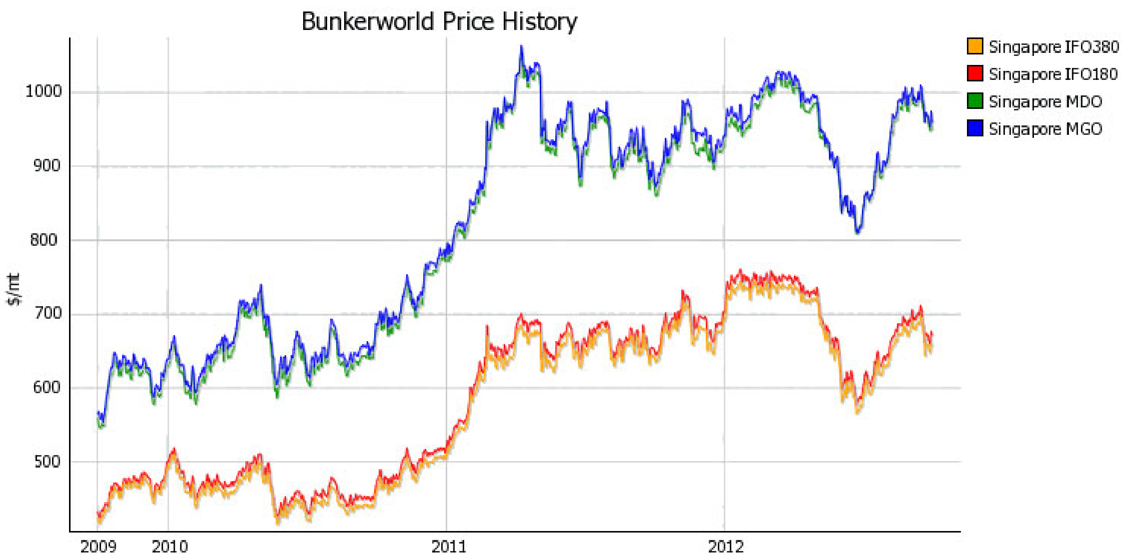
Appendix 2

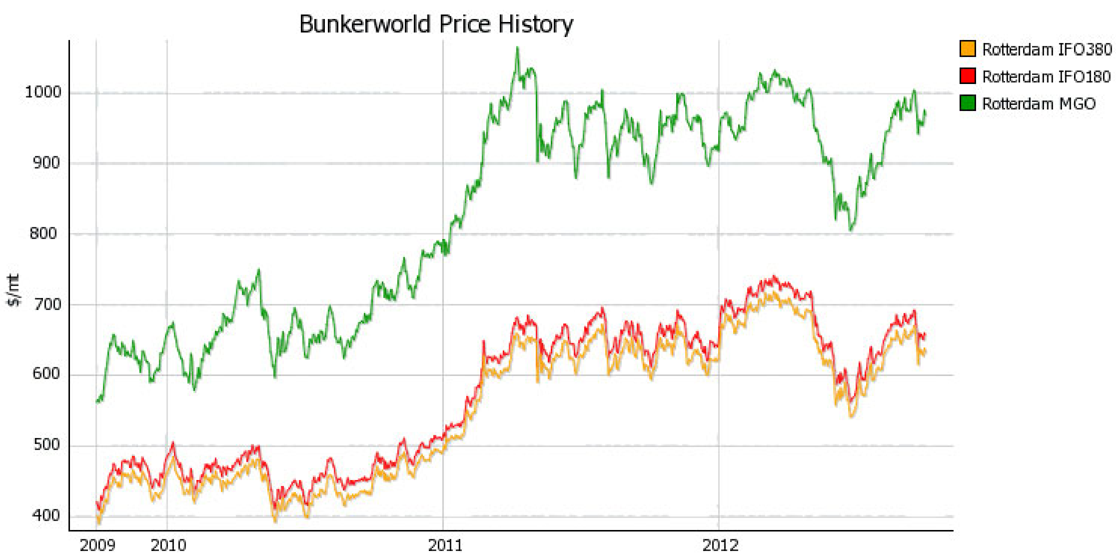


(Bunkerworld 2012b)

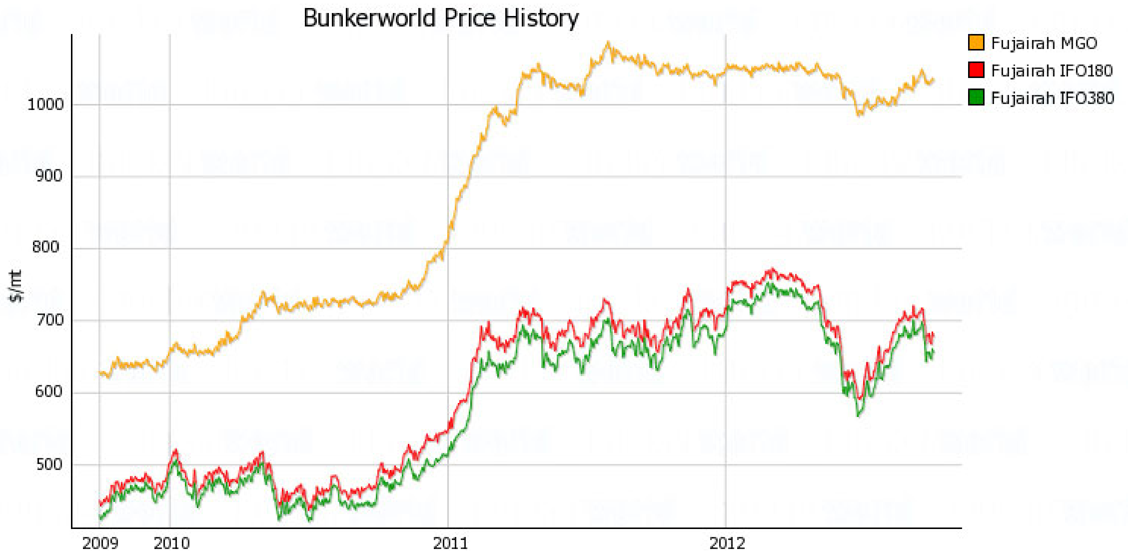
Appendix 3

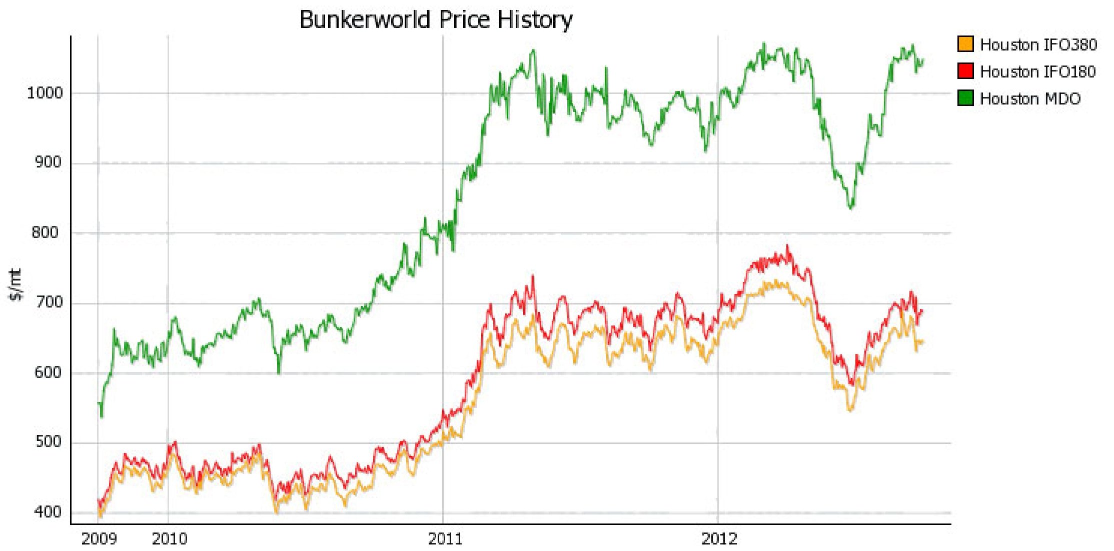
Bunkerworld Benchmark Prices between 2009-2012 for different bunker fuels from Singapore, Rotterdam, Fujairah and Houston





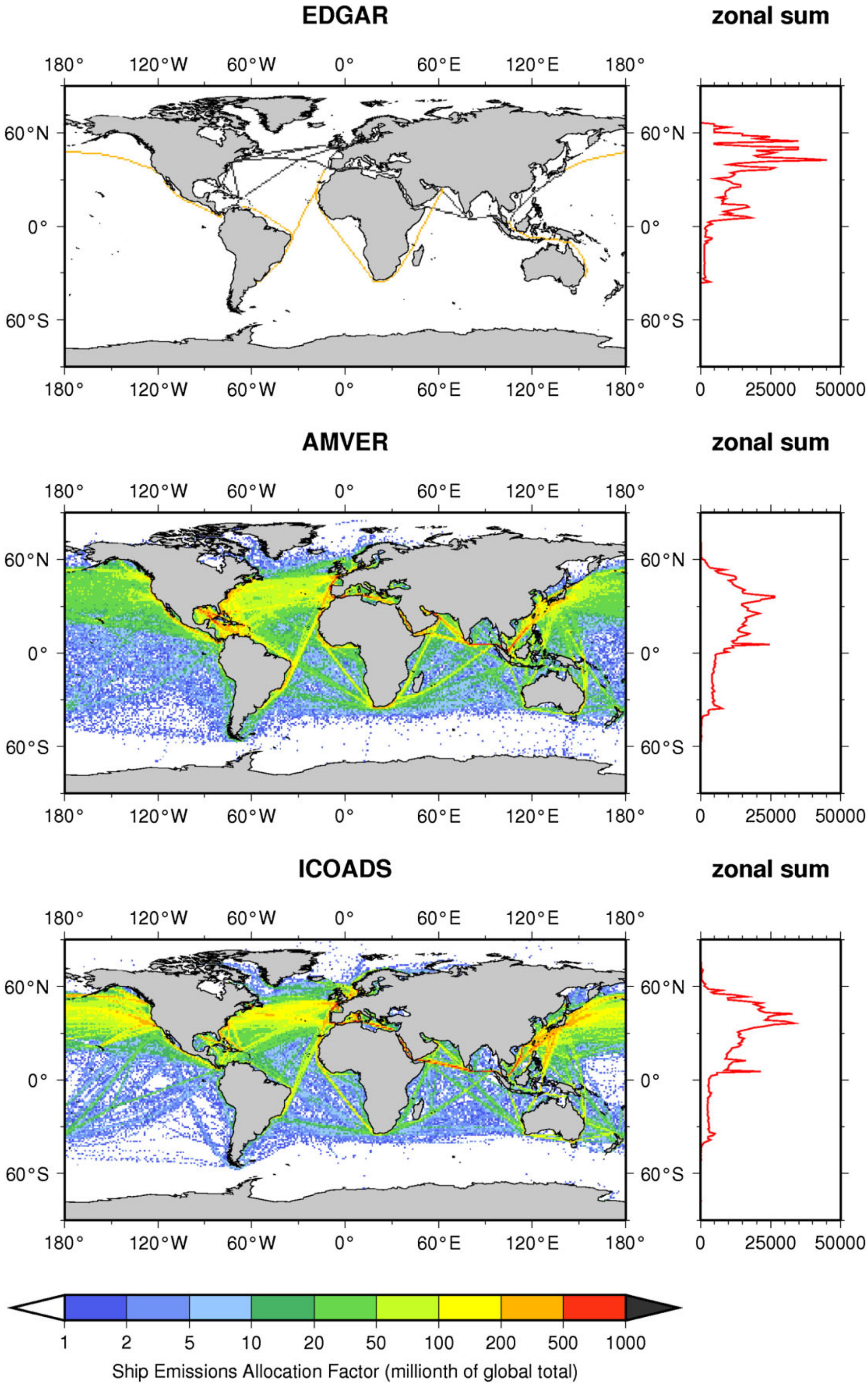
Appendix 3





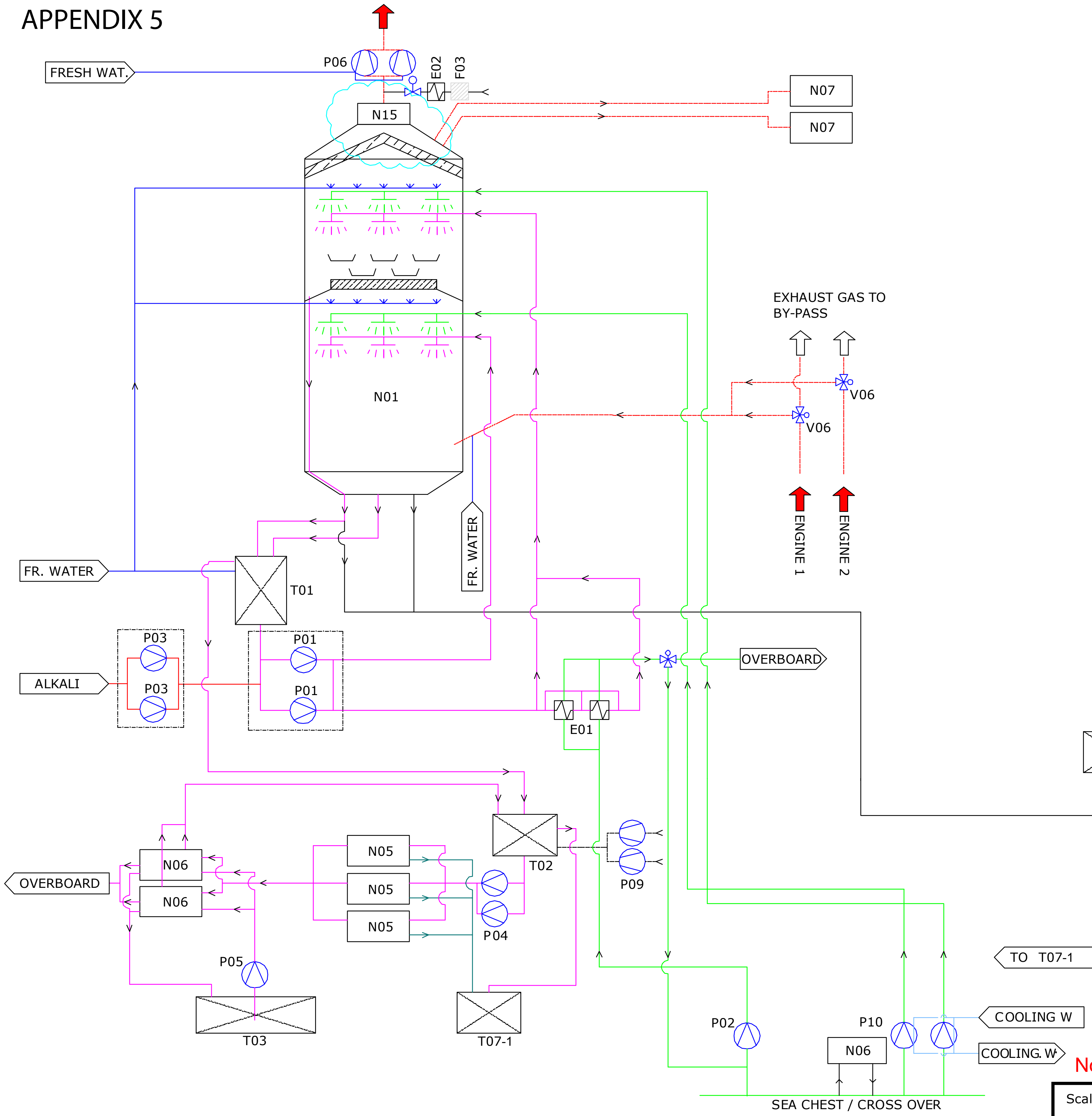
(Bunkerworld 2012a)

Global Ship Emissions Allocation Factors



Global Ship Emissions Allocation Factors (SEAF) from EDGAR (2006), AMVER (2003) and ICOAD (2007). SEAF in each grid cell is defined as the fraction of ship emissions in that grid cell of the global total which are expressed in millionth of the global total (Eyring & all 2009, 8).

APPENDIX 5



Symbol	Designation
	EXHAUST GAS
	SCRUBBING WATER
	SEA WATER
	TECHNICAL FRESH WATER
	ALKALI
	SERVICE AIR (not shown)
	CONTROL AIR (not shown)
	SEA WATER EFFLUENT
	SLUDGE

Code	Denomination
E01	HEAT EXCHANGER
E02	DE-PLUME AIR HEATER
F03	DE-PLUME AIR FILTER
F04	UV-FILTER
N01	SCRUBBER UNIT
N04	ALKALI FEED MODULE
N05	BLEED-OFF TREATMENT UNIT
N06	EFFLUENT MONITORING MODULE (CLOSED LOOP)
N06	WATER MONITORING MODULE (OPEN LOOP)
N07	CONTINUOUS EMISSION MONITORING SYSTEM
N11	SCRUBBING WATER PUMP MODULE
N14	WASH WATER TREATMENT UNIT
N15	DE-PLUME UNIT
P01	SCRUBBING WATER PUMP
P02	SEA WATER COOLING PUMP
P03	ALKALI FEED PUMP
P04	BLEED-OFF TRANSFER PUMP
P05	EFFLUENT TRANSFER PUMP
P06	EXHAUST GAS FAN
P08	ALKALI TRANSFER PUMP
P09	AERATION BLOWER
P10	SEA WATER SCRUBBING PUMP INVERTER DRIVEN
P11	WASH WATER PUMP
P12	SLUDGE TRANSFER PUMP
P13	DE-AERATION TANK FAN
P14	SETTLING WATER TRANSFER PUMP
P16	SEA WATER TRANSFFER PUMP
P17	ALKALI DOSING PUMP
P18	ALKALI TOPPING UP PUMP
T01	PROCESS TANK
T02	BLEED-OFF BUFFER TANK
T03	EFFLUENT HOLDING TANK
T04	ALKALI STORAGE TANK
T07	SLUDGE TANK
T08	DE-AERATION TANK
T09	SETTLING TANK
V06	EXHAUST GAS DAMPER
V10	DE-PLUME AIR DAMPER
V11	EXHAUST GAS FAN DAMPER

Note: The quantity of the equipment is installation specific.

Scale: -

WÄRTSILÄ

Designed: 19.04.2012 AKi

Checked: - -

Metric

INTEGRATED DUAL WATER HYBRID EXHAUST GAS SCRUBBER SYSTEM DIAGRAM

Project : EFFICIENT DUAL WATER HYBRID SCRUBBER DESIGN PARAMETERS -thesis

Drawing number:

Page 1(1)

Revision: -

Paper Size: A3

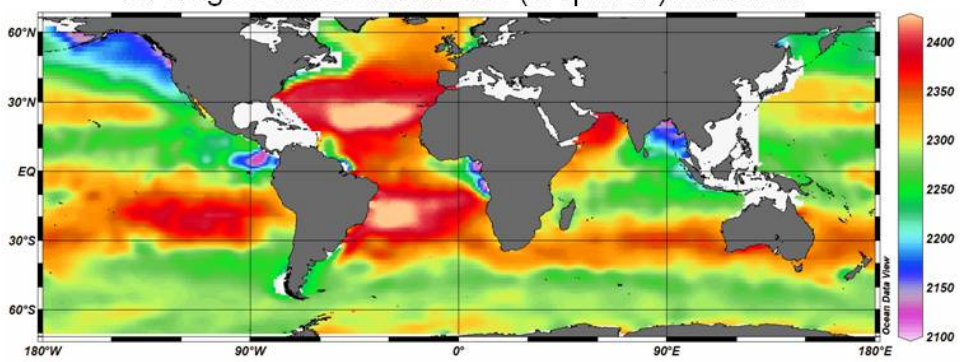
Appendix 6 **Engine types and machinery configurations for different ship types**

Vessel segment	Vessel type	Vessel size	2-str %	4-str %	Average speed	Machinery Concepts
Cruise Vessels	Cruise Vessel	Post-Panamax Cruise Vessels	0%	100%	21,7	K
Cruise Vessels	Cruise Vessel		0%	100%	22,5	K
Cruise Vessels	Cruise Vessel		0%	100%	20,2	K
Cruise Vessels	Cruise Vessel		0%	100%	14,6	C
Pax & Cargo Vessels	RoPax	Large Pax & Cargo Vessels	3%	97%	23,4	C/O
Pax & Cargo Vessels	RoPax		3%	97%	20,2	C/O
Bulk Carriers	Bulk Carrier	VLOC			14,4	N
Bulk Carriers	Bulk Carrier	Capesize Bulk Carriers	100%	0%	14,5	N
Bulk Carriers	Bulk Carrier	Panamax Bulk Carriers	100%	0%	14,4	N
Bulk Carriers	Bulk Carrier	Handymax Bulk Carriers	100%	0%	14,5	N
Bulk Carriers	Bulk Carrier	Handysize Bulk Carriers	96%	4%	14,1	N
Bulk Carriers	Bulk Carrier	Small Bulk Carriers	32%	68%	11,9	C
Bulk Carriers	Bulk Carrier	Very Small Bulk Carriers	0%	100%	11,5	C
Cargo Vessels	General Cargo Vessel		62%	38%	15,2	N
Cargo Vessels	General Cargo Vessel		15%	85%	13,0	C
Cargo Vessels	General Cargo Vessel		1%	99%	11,7	C
Cargo Vessels	MPC		100%	0%	17,5	N
Cargo Vessels	MPC				14,5	N
Cargo Vessels	MPC				12,5	N
Cargo Vessels	Reefer Vessel		79%	21%	17,9	C
Container Vessels	Container Vessel	Ultra Large Container Vessels	100%	0%	24,9	N
Container Vessels	Container Vessel	Very Large Container Vessels	100%	0%	25,2	N
Container Vessels	Container Vessel	Post-Panamax Container Vesse	100%	0%	24,6	N
Container Vessels	Container Vessel	Panamax Container Vessels	94%	6%	22,8	N
Container Vessels	Container Vessel	Sub-Panamax Container Vesse	99%	1%	22,0	N
Container Vessels	Container Vessel	Handysize Container Vessels	78%	22%	19,5	N
Container Vessels	Container Vessel	Feedermax	29%	71%	17,5	C
Container Vessels	Container Vessel	Feeder			12,3	C
LNG Tankers	LNG Tanker	Very Large LNG	18%	23%	19,4	L
LNG Tankers	LNG Tanker	Large LNG			19,6	L
LNG Tankers	LNG Tanker	Medium LNG			17,0	K
LNG Tankers	LNG Tanker	Small LNG			14,0	C
LPG Tankers	LPG Tanker		97%	3%	16,8	N
LPG Tankers	LPG Tanker		100%	0%	16,7	N
LPG Tankers	LPG Tanker	Medium LPG	79%	21%	15,3	C
LPG Tankers	LPG Tanker	Small LPG	35%	65%	13,5	C
RoRo Vessels	RoRo Vessel		36%	64%	20,0	C
RoRo Vessels	RoRo Vessel		24%	76%	18,4	C
RoRo Vessels	RoRo Vessel		37%	63%	17,1	C
RoRo Vessels	Car and Truck Carrier		96%	4%	20,1	N
RoRo Vessels	Car and Truck Carrier		60%	40%	19,2	C
Tankers	Oil/Chemical Tanker	Handy Tankers	86%	14%	14,5	C
Tankers	Oil/Chemical Tanker	Small Tankers	27%	73%	13,2	N
Tankers	Oil/Chemical Tanker	Very Small Tankers	9%	91%	12,5	N
Tankers	Crude Oil Tanker	ULCC	100%	0%	15,8	N
Tankers	Crude Oil Tanker	VLCC	100%	0%	15,9	N
Tankers	Crude Oil Tanker	Suezmax Tankers	99%	1%	15,3	N
Tankers	Crude Oil Tanker	Aframax Tankers	100%	0%	14,9	N
Tankers	Crude Oil Tanker	Panamax Tankers	100%	0%	15,1	N
Tankers	Crude Oil Tanker	Handy Tankers	100%	0%	14,5	N
Tankers	Crude Oil Tanker	Small Tankers	40%	60%	13,9	C
Tankers	Crude Oil Tanker	Very Small Tankers	11%	89%	10,8	C
Tankers	Product Tanker	Handy Tankers	87%	13%	14,5	C
Tankers	Product Tanker	Small Tankers	8%	92%	11,7	C
Tankers	Product Tanker	Very Small Tankers	6%	94%	11,3	C
Offshore Vessels	Jack-Up Rig		0%	100%	0,0	K
Offshore Vessels	Drillship		0%	100%	11,8	K
Offshore Vessels	Semi-Submersible Rig		0%	100%	0,0	K
Offshore Vessels	FPSO		19%	81%	13,9	K
Offshore Vessels	AHTS		2%	98%	13,6	C
Offshore Vessels	Offshore Supply Vessel				13,5	C
Offshore Vessels	AHTS		1%	99%	10,7	K
Offshore Vessels	Offshore Supply Vessel				21,8	K
Offshore Vessels	Other offshore vessels		4%	96%	13,5	K
Offshore Vessels	Other offshore vessels		0%	100%	21,6	K
Service Vessels	Fishing Vessels		0%	100%	12,1	C
Service Vessels	Inland Vessels		0%	100%	10,9	C
Service Vessels	Dredgers		0%	100%	13,1	C
Service Vessels	Dredgers		0%	100%	9,0	C
Service Vessels	Other Service vessels		0%	100%	16,0	C
Service Vessels	Other Service vessels		6%	94%	15,9	C
Service Vessels	Other Service vessels		0%	100%	14,8	C
Service Vessels	Tugs		0%	100%	12,5	C
Service Vessels	Tugs		3%	97%	11,6	A

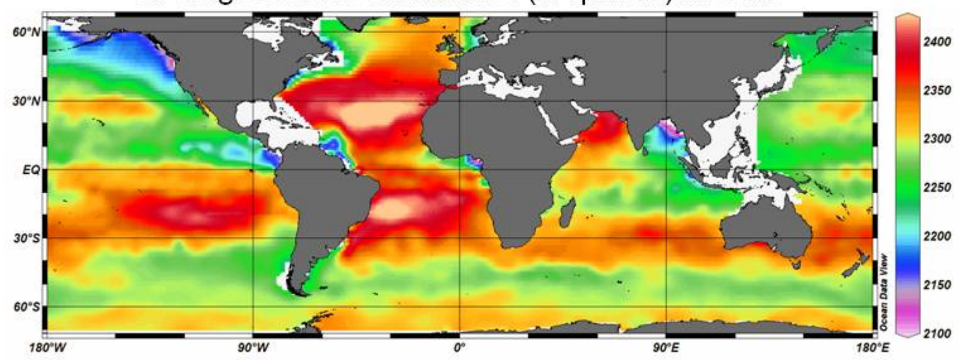
- A = Propac ST Diesel Mechanical
- B = Propac STh Diesel Hybrid
- C = Propac CP Diesel Mechanical (1)
- D = Propac CPh Diesel Hybrid (2)
- E = Propac CPhCRP Diesel Hybrid (2)
- F = Propac CP4h Diesel Hybrid (3)
- G = Propac LSh Diesel Mechanical
- H = Propac LSCRP Diesel Hybrid (4)
- K = Propac STIIc Diesel Electric
- L = Propac LLC Diesel Electric (5)
- M = Quattro LLC Diesel Electric
- N = Propac LS Diesel Mechanical
- O = Propac CP2-1 Diesel Mechanical (6)

Global ocean surface alkalinity

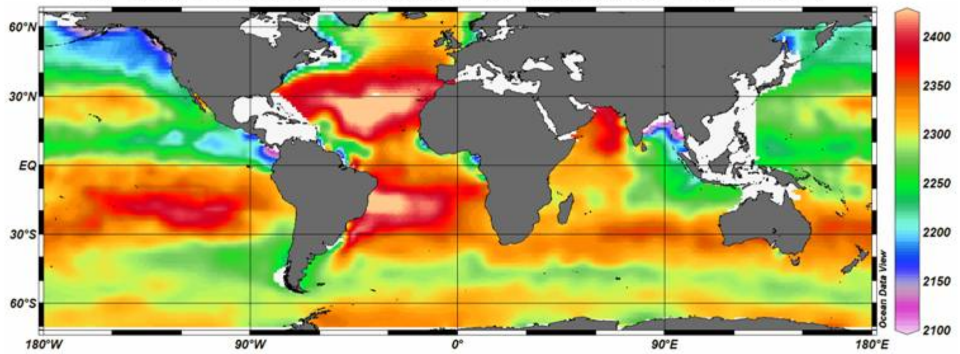
Average surface alkalinities (TA µmol/l) in March



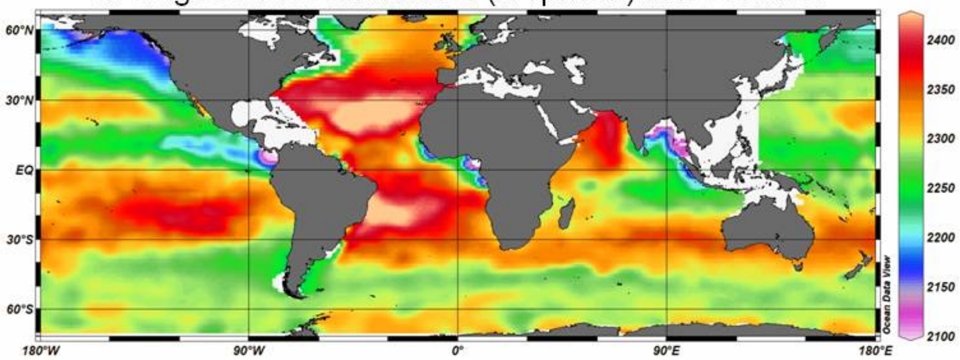
Average surface alkalinities (TA µmol/l) in June



Average surface alkalinities (TA µmol/l) in September

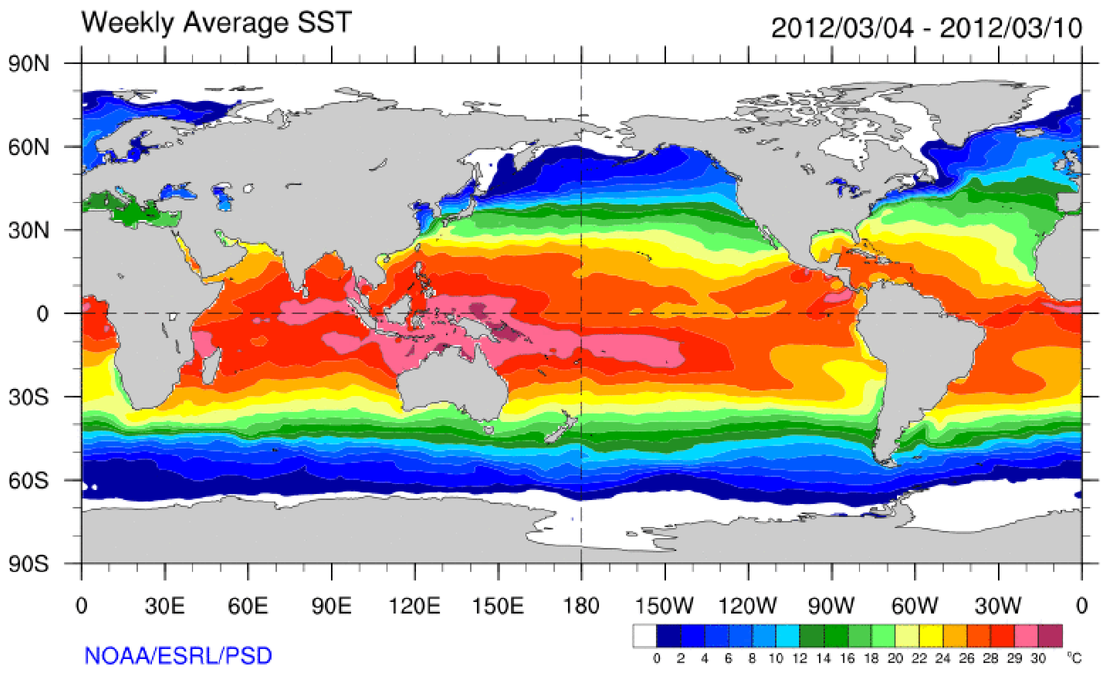


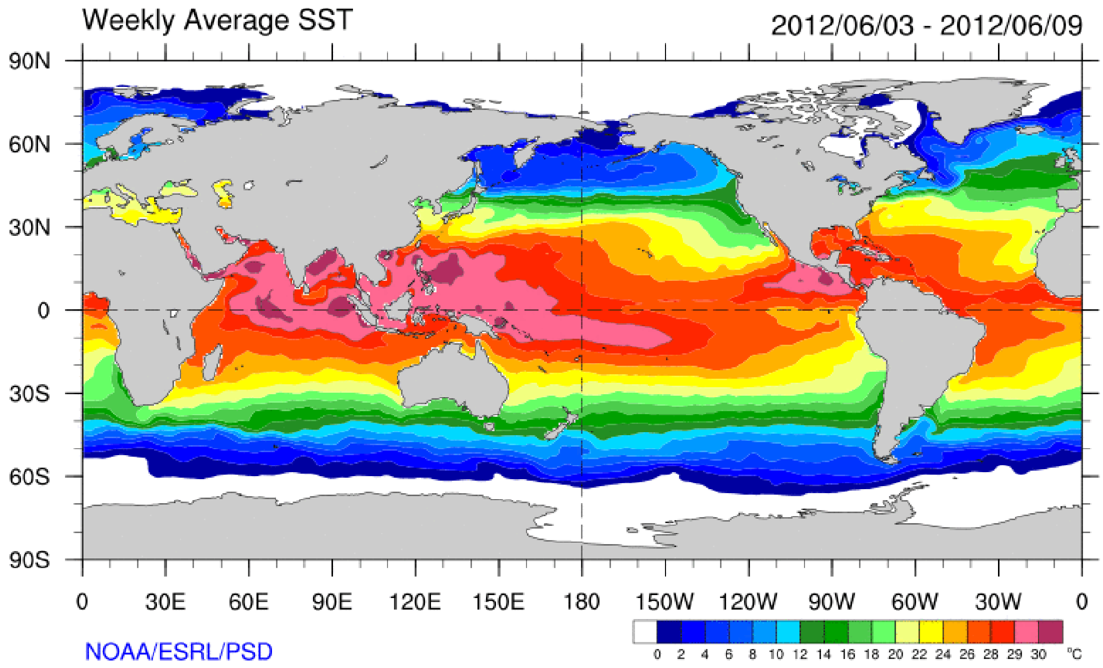
Average surface alkalinities (TA µmol/l) in December



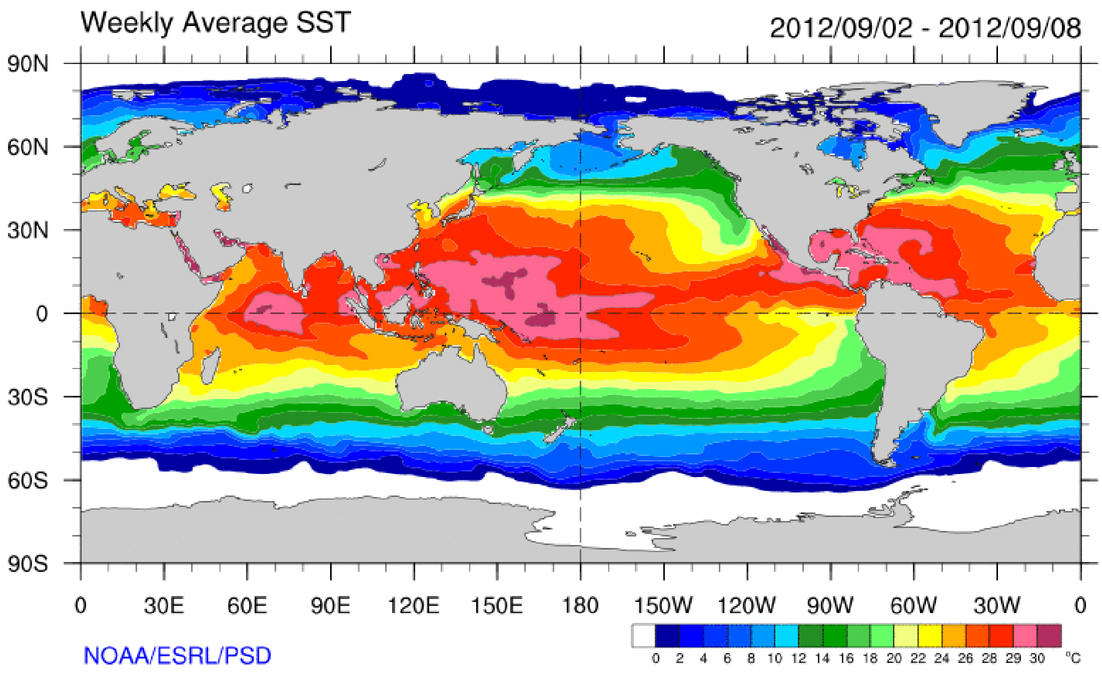
(Lee 2006)

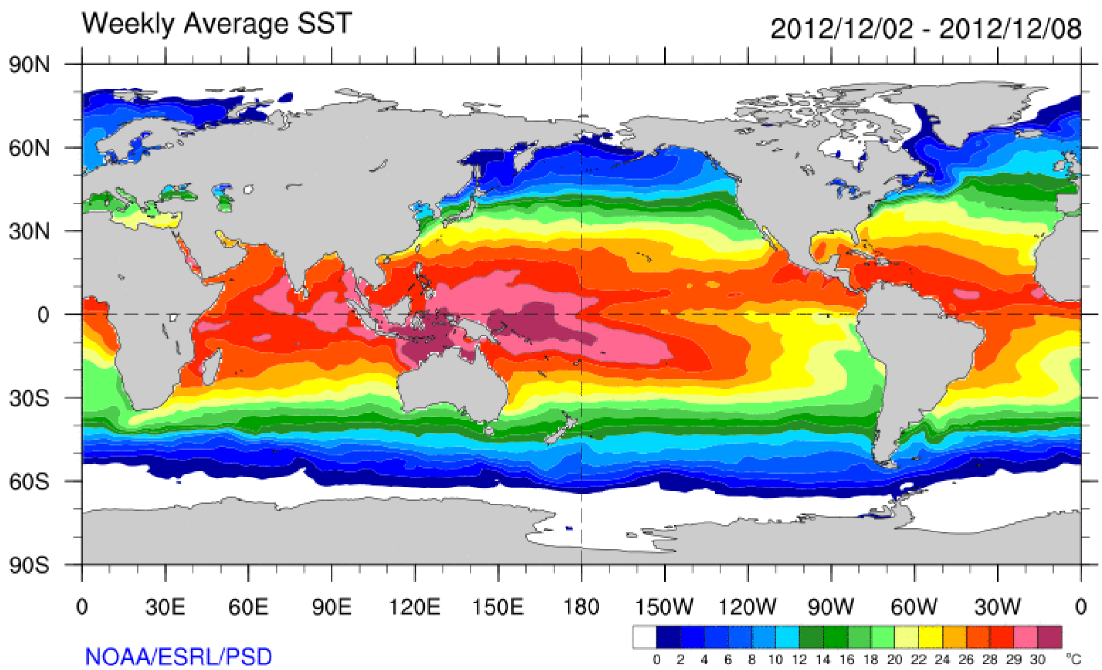
Sea water surface temperatures





Appendix 8





(NOAA 2013)

Appendix 9

Engine performance data

5RT-flex50-D							
Performance			Design conditions				
Power [%]	Power [kW]	Speed [rpm]	BSFC [g/kWh]	BSFC [kg/s]	BSEF [kg/kWh	BSEF [kg/s]	tEaT [°C]
110.0	9597.5	128.0	175.0	0.467	6.72	17.92	299.1
100.0	**8725.0**	**124.0**	**174.0**	**0.422**	**7.05**	**17.09**	**281.1**
95.0	8288.8	121.9	172.6	0.397	7.16	16.49	272.5
90.0	7852.5	119.7	171.3	0.374	7.25	15.81	264.6
85.0	**7416.3**	**117.5**	**170.4**	**0.351**	**7.39**	**15.22**	**259.1**
80.0	6980.0	115.1	170.1	0.330	7.63	14.79	256.9
75.0	6543.8	112.7	170.0	0.309	7.87	14.31	256.1
70.0	6107.5	110.1	170.0	0.288	8.02	13.61	254.5
60.0	5235.0	104.6	170.7	0.248	8.21	11.94	255.6
50.0	4362.5	98.4	172.4	0.209	8.31	10.07	265.1
40.0	3490.0	91.4	174.8	0.169	8.33	8.08	286.1
30.0	2617.5	83.0	175.9	0.128	8.97	6.52	282.1
25.0	2181.3	78.1	177.0	0.107	8.93	5.41	**295.1**

7RT-flex82T							
Performance			Design conditions				
Power [%]	Power [kW]	Speed [rpm]	BSFC [g/kWh]	BSFC [kg/s]	BSEF [kg/kWh	BSEF [kg/s]	tEaT [°C]
110.0	34804.0	82.6	170.0	1.644	7.13	68.93	315.1
100.0	**31640.0**	**80.0**	**169.0**	**1.485**	**7.38**	**64.86**	**290.1**
95.0	30058.0	78.6	167.6	1.399	7.44	62.12	280.1
90.0	28476.0	77.2	166.3	1.315	7.47	59.09	271.9
85.0	**26894.0**	**75.8**	**165.4**	**1.236**	**7.57**	**56.55**	**266.1**
80.0	25312.0	74.3	165.1	1.161	7.80	54.84	263.2
75.0	23730.0	72.7	165.0	1.088	8.02	52.87	262.1
70.0	22148.0	71.0	165.0	1.015	8.19	50.39	261.3
60.0	18984.0	67.5	165.7	0.874	8.22	43.35	264.4
50.0	15820.0	63.5	167.4	0.736	8.21	36.08	276.1
40.0	12656.0	58.9	169.8	0.597	8.13	28.58	**302.1**
30.0	9492.0	53.6	170.9	0.451	8.92	23.52	291.6
25.0	7910.0	50.4	172.0	0.378	9.01	19.80	298.1

14RT-FLEX96C-B							
Performance			Design conditions				
Power [%]	Power [kW]	Speed [rpm]	BSFC [g/kWh]	BSFC [kg/s]	BSEF [kg/kWh	BSEF [kg/s]	tEaT [°C]
110.0	88088.0	105.3	177.0	4.331	7.36	180.09	331.1
100.0	**80080.0**	**102.0**	**176.0**	**3.915**	**7.43**	**165.28**	**308.1**
95.0	76076.0	100.3	174.6	3.690	7.50	158.49	299.7
90.0	72072.0	98.5	173.3	3.469	7.59	151.95	293.4
85.0	**68068.0**	**96.6**	**172.4**	**3.260**	**7.69**	**145.40**	**289.1**
80.0	64064.0	94.7	172.1	3.063	7.80	138.81	286.6
75.0	60060.0	92.7	172.0	2.870	7.90	131.80	286.1
70.0	56056.0	90.6	172.0	2.678	7.97	124.10	287.1
60.0	48048.0	86.0	172.7	2.305	8.05	107.44	294.5
50.0	40040.0	81.0	174.4	1.940	8.01	89.09	312.1
40.0	32032.0	75.2	176.8	1.573	7.71	68.60	**349.1**
30.0	24024.0	68.3	177.9	1.187	8.29	55.32	339.6
25.0	20020.0	64.3	179.0	0.995	8.17	45.43	347.1

BSFC = Brake specific fuel consumption
BSEF = Brake specific exhaust gas flow
tEaT = Temperature of exhaust gas after turbine

Open loop scrubbing performance calculation results

Design scenario results

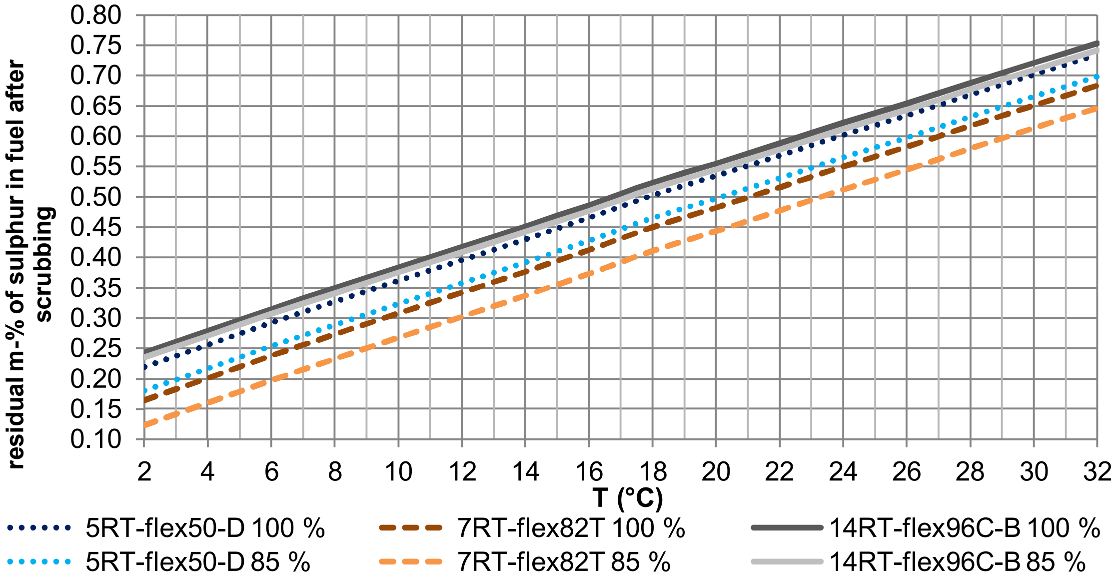


Figure 10.1. The corresponding fuel sulphur content after scrubbing when using sea water with a 3.5 m-% fuel sulphur content, TA = 2300 µmol/l, S = 35 PSU and sea water flow of 30 l/kWh as set by Operating scenario (Wärtsilä 2013a).

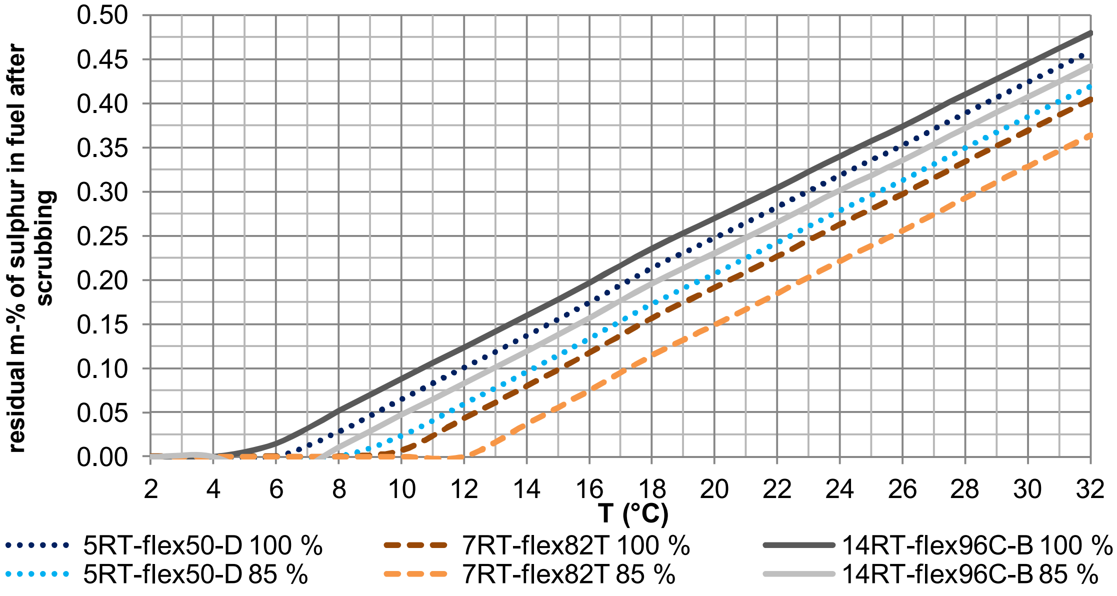


Figure 10.2. The corresponding fuel sulphur content after scrubbing when using sea water with a 3.5 m-% fuel sulphur content, TA = 2300 µmol/l, S = 35 PSU and sea water flow of 35 l/kWh as set by Operating scenario (Wärtsilä 2013a).

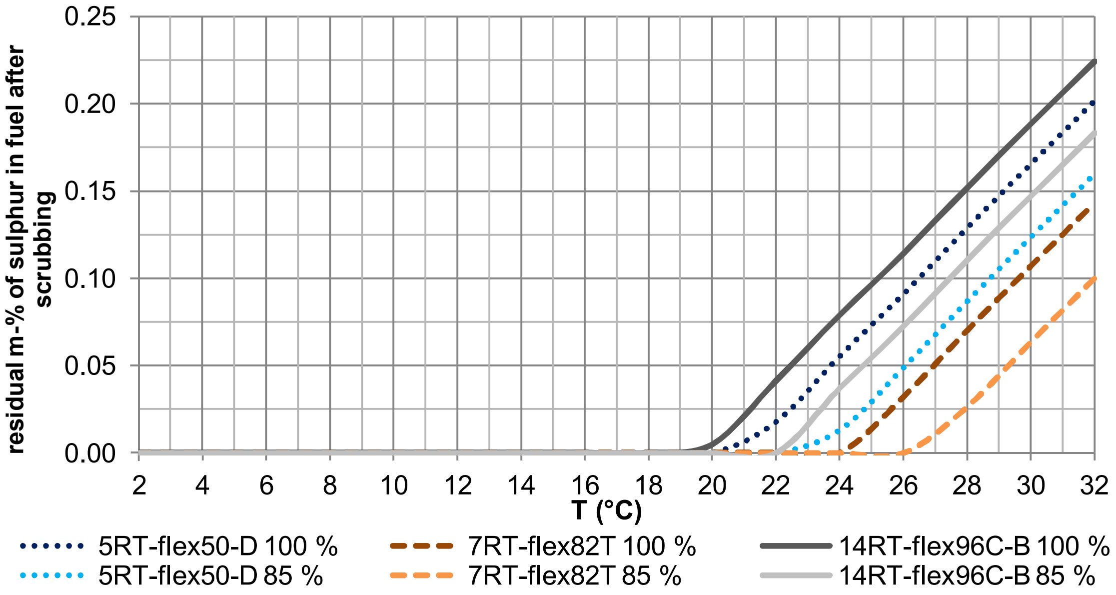


Figure 10.3. The corresponding fuel sulphur content after scrubbing when using sea water with a 3.5 m-% fuel sulphur content, TA = 2300 µmol/l, S = 35 PSU and sea water flow of 40 l/kWh as set by Operating scenario (Wärtsilä 2013a).

Operating scenario results

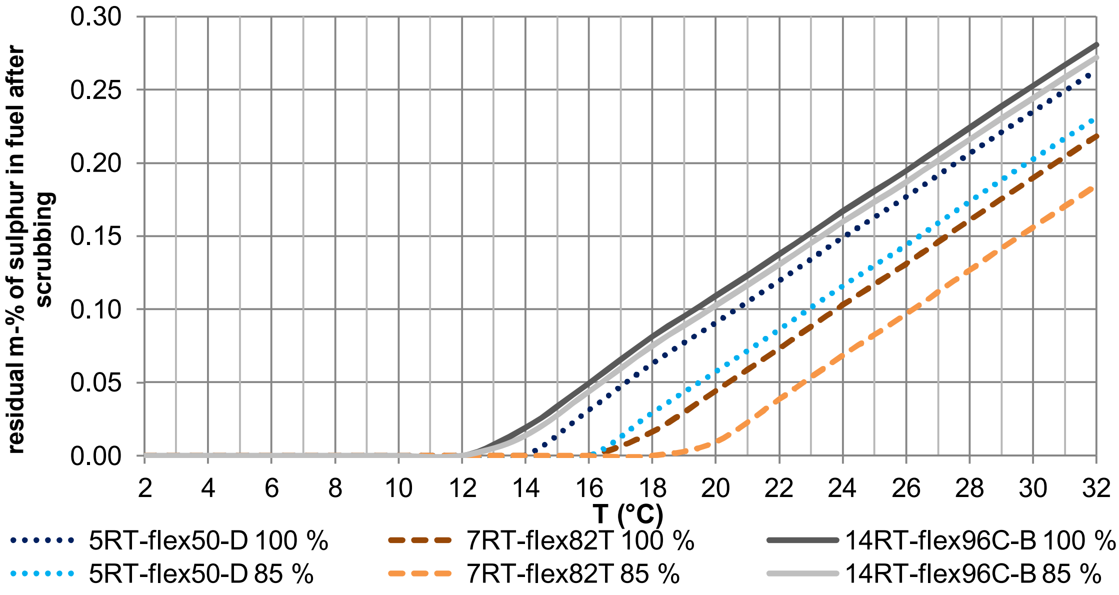


Figure 10.4. The corresponding fuel sulphur content after scrubbing when using sea water with a 2.8 m-% fuel sulphur content, TA = 2300 µmol/l, S = 35 PSU and sea water flow of 30 l/kWh as set by Operating scenario (Wärtsilä 2013a).

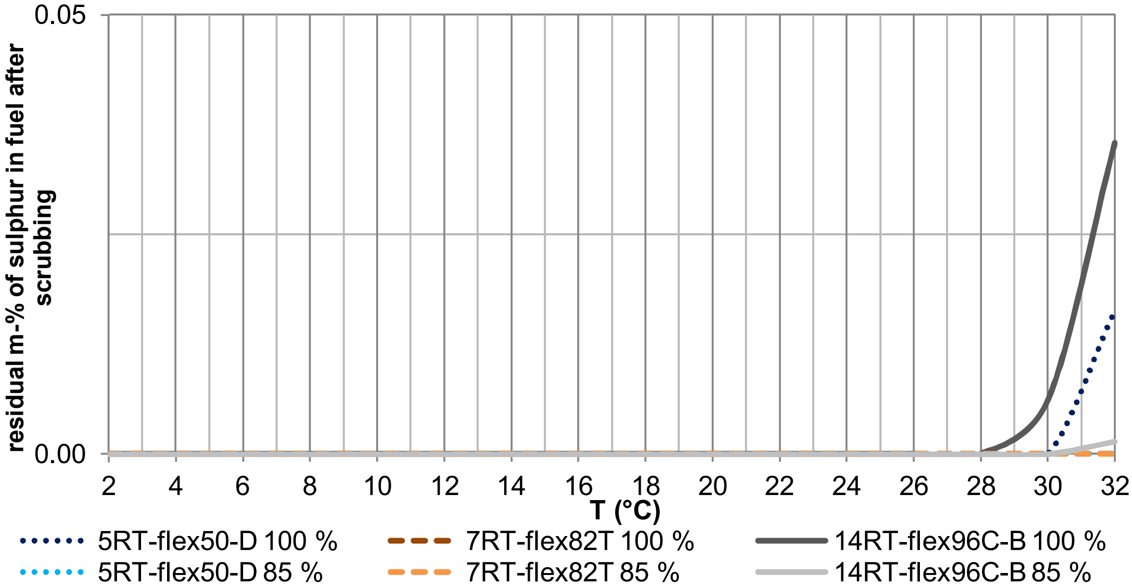


Figure 10.5. The corresponding fuel sulphur content after scrubbing when using sea water with a 2.8 m-% fuel sulphur content, TA = 2300 µmol/l, S = 35 PSU and sea water flow of 35 l/kWh as set by Operating scenario (Wärtsilä 2013a).