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OPERATIONAL PROBLEMS IN MARINE DIESEL ENGINES SWITCHING ON LOW SULFUR FUELS BEFORE ENTERING THE EMISSION CONTROLLED AREAS

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Abstract

Introduction of rules connected with implementation of Sulfur Emission Control Areas and changes in MARPOL Convention Annex VI not only increased the operation costs or forced ship owners to comply with convention but first of all put pressure and provided influence on ship's operation. In this article there are presented operational problems in Marine Diesel Engines switching from the residual fuels HFO to low sulfur residual LSFO and distillate LSGO fuels before entering Emission Control Areas (ECAs). There are defined ECA Zones in Europe and North America. There are introduced changes in limits with regards to Sulfur content in fuel oils during last years, planed trends and changes. There are characterized the changing over process, the applied procedures and methods of time calculation in changing over from HFO into LSFO/ LSGO. Besides, there are described the method of sulfur calculation in fuel during blending both grades of fuel. To conclude authors have characterized technical and legislative demands that the ship-owners have to face up to adopt the operated vessels to meet ECAs requirements.

Keywords: *Emission Control Areas, SOx reduction, marine diesel engine, low sulfur fuels, fuel change over operation*

1. Introduction

In response to the desire of some countries to reduce the harmful effects of ship emissions on air quality with a focus mostly on the release of sulfur oxide (SOx) and presently on nitrogen oxide (NOx) compounds and particulate matter (PM), the International Maritime Organization (IMO) Regulation 14 of Annex VI to the International Convention on the Prevention of Pollution from Ships (MARPOL) permits the establishment of SOx Emission Control Areas (SECAs), 19 May 2005 [11]. The IMO has approved two such areas: the Baltic Sea 19 May 2006 and the North Sea with English Channel 21 Nov 2007, fig. 1a. The United States and Canadian Government have requested that the IMO designate an area off their coastal waters to 200NM, fig. 1b. The US Environmental Protection Agency (EPA) is currently preparing documents for approval process and is expected to enter into force as early as August 2012 [6, 14].
In October 2008, IMO adopted stringent new standards found in Revised MARPOL Annex VI – Resolution MEPC.176 (58) to control emissions from ships [12]. The revised Regulation 14, effective 1 July 2010, adopted progressive reduction in SOx included other harmful exhaust

emissions from the engines that power ships as NOx and PM, and revised geographic-based standards for former SECA that was renamed as the Emission Control Area (ECA).
Ships operating in designated ECAs since 1 July 2010 are required to use fuel with a sulfur content not exceeding 1.0% and from January 2015, this would be reduced to 0.1% [1, 9, 12, 14].

a) *b)*

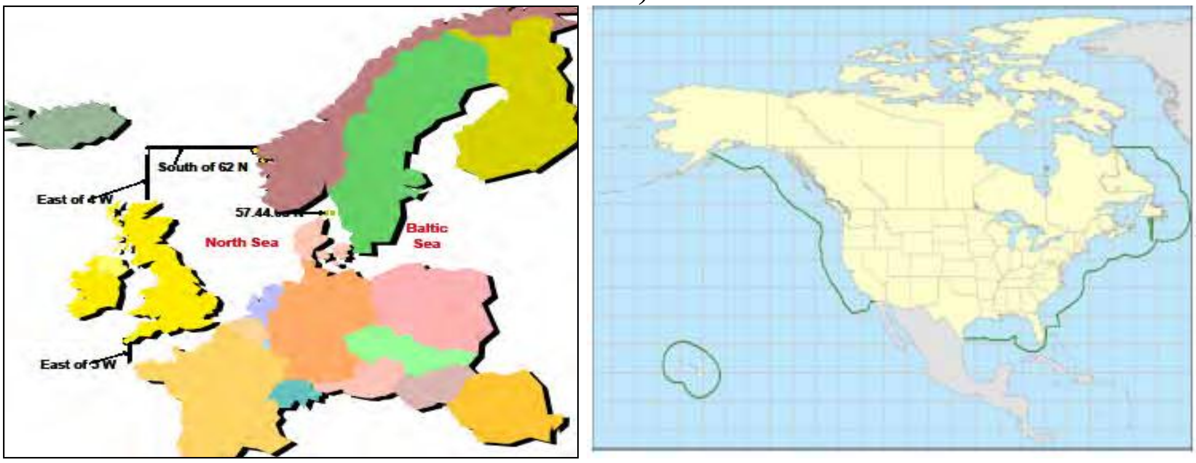

Fig. 1 MARPOL Annex-VI Emission Control Area (ECA) [1, 14]
a – Baltic and North Sea, b – US and Canada

European Union countries has implemented regulation relating the sulfur content of fuel used in its port under Article 4b of EU Council Directive 2005/33/EC with effective date 1 January 2010 is limited to 0.1% (replaced limits 1.5% from 11 August 2006) that applies to all types of marine fuels unless an approved emission abatement technology is employed or shore power is available. It applies to both main and auxiliary boilers [1, 9, 12, and 14].
The California Air Resources Board (CARB) under its authority within the state has implemented regulations pertaining to the sulfur content limits and types of fuels can be used in Californian waters within 24NM of coastal baseline in two phases with effective date 1 July 2009, limit 0.5% and with 1 January 2012 - 0.1%. It applies to auxiliary boilers too, excluding main propulsion boilers, however low sulfur residuals fuels are not permitted only distillate fuels [1, 9, and 14].

	Operating Area	Regulatory Authority	Product Type	Current Requirements	July 1 2010	Jan 1 2012	Aug 1 2012	Jan 1 2015	Jan 1 2020 or Jan 1 2025 (decision to be made by 2018)
A	Global Limit	IMO MARPOL Annex VI	FO	4.50%		3.50%			0.50%
			DO	2.00%	Follow the revised ISO 8217 standards which will be issued around July 2010.				
			GO	1.50%					
B	ECA-SOx (Emission Control Area) Baltic & North Sea	IMO MARPOL Annex VI	FO	1.50%	1.00%			0.10%	
			DO						
			GO						
C	EU Territory (At berth* in E.U. Ports unless published timetables give 'at berth' less than 2 hours)	EU Directive 2005/33/EC	FO	0.1%					
			DO						
			GO						
D	Within 24 nautical miles of Californian coastline	CARB (CARB Regulation)	FO	Vessels are NOT allowed to use Marine Residual Fuel in this area					
			DO	1.5% for MGO DMA or 0.5% for MDO DMB		0.1% for all distillate fuel grades			
			GO						
E	Emission Controls for waters within 200 nautical miles of the United States & Canadian coastlines	IMO MARPOL Annex VI	FO	Areas excluding CARB follows Global Limit 'A'. CARB area (within 24 NM of California) follows 'D'			1.00%	0.10%	
			DO						
			GO						

*Fig. 2 Sulfur reduction "road map" - current and future sulfur requirements for Marine Fuel Products; * - the regulation is applicable for inland waterways and at berth [14]*

Current and future requirements for Marine Fuel Products used by ships in ECAs including US and Canadian countries, EU territory and CARB are presented in table, fig 2.

To meet the sulfur emission legislation rules is to reduce the SOx either by switching fuel supply to engine/ boiler from the Marine Residual Fuels known as HFO (Heavy Fuel Oil) into Low Sulfur: Marine Residual Fuels LSFO (Low Sulfur Fuel Oil)/ the Marine Distillate Fuels LSGO (Low Sulfur Gas Oil, ISO 8217, DMA Grade [1]) or by cleaning the exhaust gases what can be obtained in special scrubber constructions.

2. Effects of Low Sulfur Fuels on Operation of Marine Diesel Engines

Operational concerns of switching between HFO and LSFO or LSGO have the potential for several harmful effects on diesel engines as discussed in the following paragraphs.

Low Sulfur (Heavy) Fuel Oils:

Sulfur levels are required to be less than 1%. If LSHFO is created by a desulphurization unit, fuel aromaticity may be decreased which can result in lower fuel stability [1, 7, 9]. A consequence of this happening is increased fuel incompatibility problems when mixing with regular HFO during fuel changeover. The low sulfur processing can also lead to additional quality problems such as ignition and combustion difficulties and increased catalytic fines levels. In addition, when LSFO is carried on board for use in an ECA, it is required by MARPOL Annex VI be stored and purified separately from regular HFO. This can require piping changes to the fuel transfer and purification system. As LSFO are not applicable in some ECAs – CARB, EU Territories and after 1 Jan 2015 the sulfur limit will be 0.1% in all ECAs and if production of such an Ultra LSFO will be too expensive that they will be replaced completely by LSGO.

Low Sulfur Diesel/ Gas Oils:

1. Lubricity and Low Viscosity [1, 7, 9]:

- Reduced (effectiveness as a lubricant) the film thickness between the high pressure fuel pump plunger and casing in the fuel valves leading to excessive wear and possible sticking and seizing, causing failure of these elements. This can be minimized by purchasing distillate fuels with lubricity enhancing additives and higher vis. 3 mm^2/s (cSt) at 40˚C.
- Loss of capacity in fuel supply (booster) and circulation pumps due to low viscosity, fuel leaking around pump rotors, preventing the ship from achieving full power.
- Leakage of fuel through the high pressure fuel pump barrel, plunger, suction and spill valve push rods on slow speed engines. This leakage may result in a higher load indication position of the fuel rack and may require adjustment of the governor for sustained operation on low viscosity fuel or may results in worn pump’s elements (enlarged clearances). As an internal leak is part of design and is used in part to lubricate the pumping elements, it can cause too high leak rate and in consequences lead to smaller than optimal injection pressures resulting in difficulties during start and low load operation.
- Maintaining viscosity above the minimum value of 2 mm^2/s (cSt) at 40˚C, fig. 3. One of the solutions is to install a fuel cooler (for tropical conditions equipped with chiller unit) that will keep the fuel temperature below 40˚C.

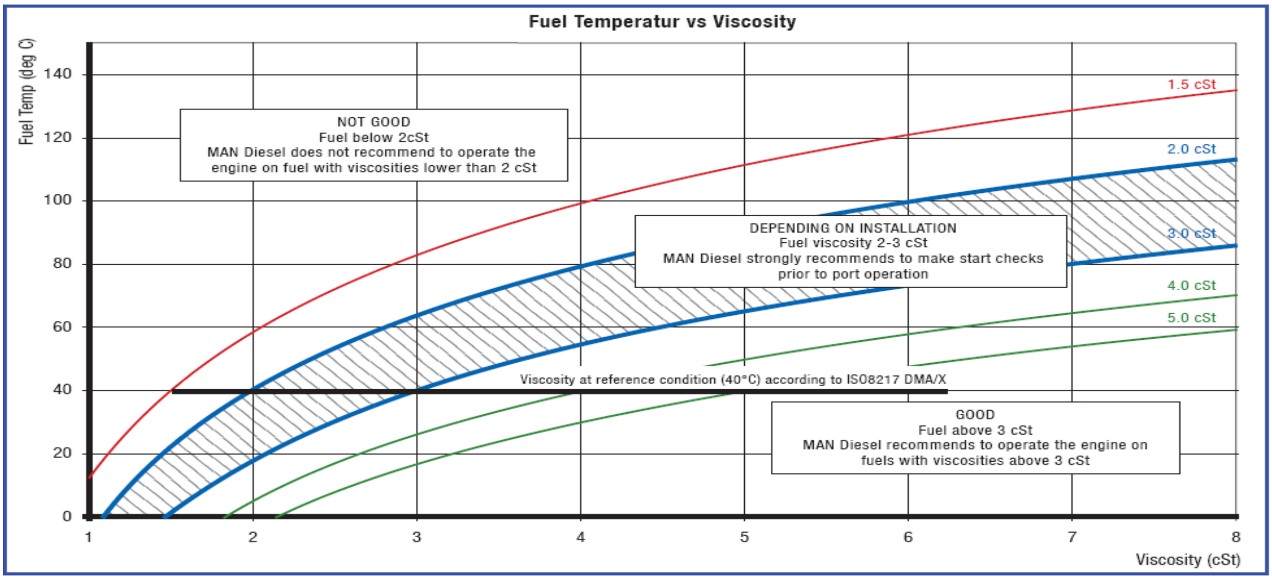

Fig. 3 Fuel temperature relation to viscosity [8]

2. Low Density: Low sulfur, low viscosity fuels typically have low density when compared to heavy fuel oils. This will result in less energy per volume of fuel (volumetric energy content) and thus will require more fuel volume to be supplied to the engine to maintain equivalent power. Engine governors and automation need to be able to adjust to the changes in fuel rack position and governor settings [1].

3. Incompatibility of Fuels: Mixing two types of fuels can lead to risk of incompatibility between them, particularly when mixing heavy fuel and low sulfur distillate fuels. If incompatibility does occur, it may result in clogging of fuel filters and separators and sticking of fuel injection pumps, all of which can lead to loss of power or even shut down of the propulsion plant, putting the ship at risk. Compatibility problems can be caused by differences in the mixed fuels' stability reserves. If the stability level of the HFO is low there can be difficulties when mixing with more paraffinic, low sulfur fuels and as a consequence the asphaltenes can precipitate of the blend as heavy sludge, causing clogging [1, 3]. This can be minimized through on board compatibility test kits used when bunkering both HFO and low sulfur fuel called Spot Test Method for Assessing Fuel Cleanliness and Compatibility (ASTM D 4740-4) [14], by DNV Program for fuel samples send to laboratory Onboard Blending Optimization Program - BOP and Fuel Quality Test - FQS [4] or by purchasing distillate and residual fuels from the same refinery [3, 4]. If incompatibility is indicated by presence of suspended solids when equal volumes of a sample and a blend stock are mixed together there is necessity to avoid mixing these grades of fuel by discharging one grade to port facilities or more preferable to treat them by chemicals with mixing reduced to minimum in proportion maximum 80:20 [3]. The examples of the mentioned chemicals are Amergize deposit modifier/ combustion improver and Amergy222 fuel oil conditioner minimizing the effect of fuel instability and incompatibility by Drew Marine Division – Ashland's Chemicals [5].

3. Impact of Low Sulfur Fuel on lubrication of Marine Diesel Engines

Diesel engines require lubrication in order to operate efficiently and these lubricating oils need to be compatible with fuel used in the engine. Therefore, if lube oil BN (Base Number) does not match the acidity of the fuel it will have an effect on maintaining a compatible lubricant between the fuel and the oil. Too high BN70 can develop calcium and other deposits on the liner's surfaces. Too small BN30-50 can increase the fuel's acidity causing additional wear on parts as well as creating problems combusting the fuel. Lube oils are used to neutralize acids formed in combustion, mostly commonly sulfuric acids created from sulfur in the fuel. The quantity of acid neutralizing additives in lube oil should match the total sulfur content of the fuel. It has been established that a certain level of controlled corrosion enhances lubrication, in that the corrosion generates small “pockets” in the cylinder liner running surface from which hydrodynamic lubrication from oil in the pocket is created. In other words, controlled corrosion is important to ensure the proper tribology needed for creation of lubricating oil film, fig. 4.

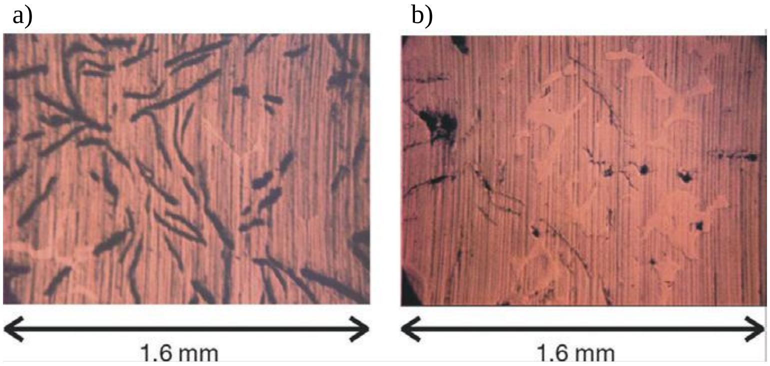

Fig. 4 Cylinder liner surface: a - ‘Open’ graphite structure with good tribological abilities from where the cylinder oil can spread, b - ‘Closed’ graphite structure with reduced tribological ability [8]

If the neutralization of the acid is too efficient (the alternative no corrosion) it can lead to bore-polishing, liner lacquering and subsequently hamper the creation of the necessary oil film resulting in increase of scuffing and accelerated wear of liner [1, 2, 8, 13]. This especially applies to slow speed engines which have cylinder lubrication and are operated continuously at high load having less need for SOx neutralizing on the liner surface due to high temperature but it can occur on trunk piston engines, too where a bore-polished liner surface hampers the functioning of oil scraper rings and leads to accelerated lube oil consumption due to access to crankcase [9].

It should be considered that irrespective of sulfur content (high or low) the fuels used in low speed engines are usually low quality heavy fuels. Therefore, the cylinder oils must have full capacity in respect of detergency and dispersancy, irrespective of the BN specified. In consequence of the above, the cylinder oil feed rate is very important factor as from one hand its consumption represents a large expenditure for engine operators but from the other hand a satisfactory piston rings/ liner wear rate and maintaining the time between overhauls is a must. To achieve these requirements engine’s producers developed high pressure electronically controlled lubricators that inject the cylinder oil into the liner at the exact position and time where the effect is optimal (MAN B&W Diesel the Alpha Lubricator System or Wärtsila RPLS Retrofit Pulse Lubrication System). Therefore, cylinder oil feed rate is readjusted depending on the actual fuel sulfur content (fig. 5) and the actual condition of piston rings and liners evaluated during inspection through scavenge ports.

The practical approach for the correlation between fuel sulfur and cylinder oil can be shown as follows:

- Fuel sulfur level <1%: BN40/50 is recommended;
- Fuel sulfur level 1-1.5%: BN40/50 is recommended, however BN70 can be used only when operating for less than 2 weeks;
- Fuel sulfur level >1.5%: BN70 is recommended, however BN40/50 can be used with higher feed rate.

Some ship owners supply vessels with low speed engines with cylinder oil BN50 and HFO bunker up to 3.5% of sulfur limit as company policy [4].

At present, additional researches have been conducted by several oil companies to create lubricating oil that would be compatible with different type of fuel [15].

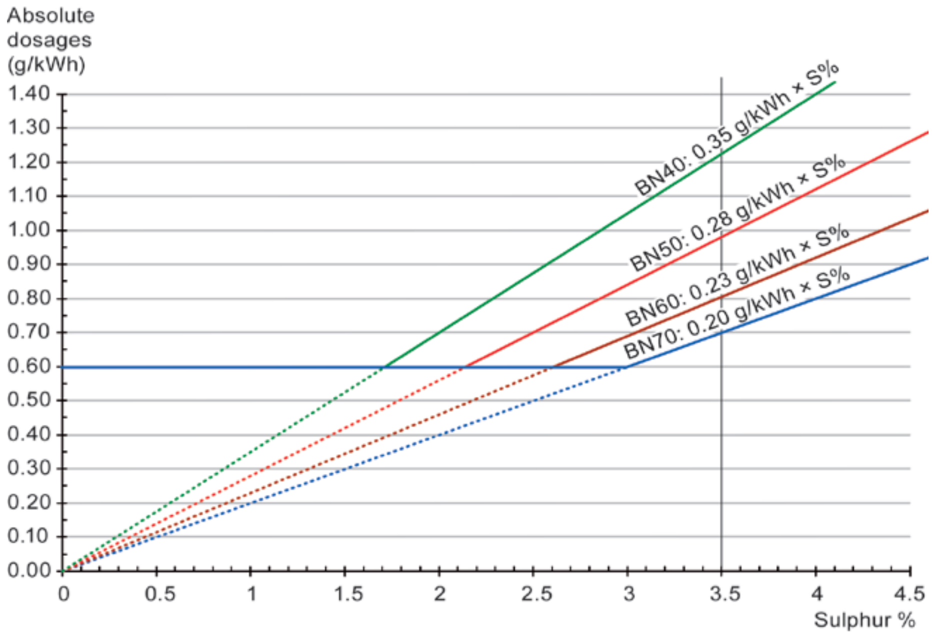

Fig. 5 Cylinder oil feed rate dependent on BN40 vs. BN70 cylinder oil use [8]

4. Procedures of Changing over from HFO to LSFO/ LSGO and Methods to Assume Sulfur Content of Fuel Oil in a Mixed State

It is the responsibility of the ship-owner to ensure that it can be demonstrated, to the satisfaction of any relevant administrative body (for example Port State Control - PSC), that the fuel oil being burned within ECA complies with MARPOL Annex VI, Regulation 14 [12]. Details of fuel oil change-over procedures from HFO to LSFO/LSGO and vice versa have to be recorded in suitable log books as the Engine Room Log Book, the Oil Record Book Part 1 and a dedicated MARPOL Annex VI log book. Log Book entries could be as follows:

Arrival at/ Departure from ECA on completion/ commencement of fuel change-over.

1. Date and time of completion/ commencement of fuel change-over.
2. Position, latitude and longitude at completion/ commencement of fuel change-over.
3. Volume of LSFO/ LSGO in each tank on completion of fuel change-over.
4. Signature of responsible Officer (Chief Engineer and confirmed by Captain).

Besides, the records and history of BDNs (Bunker Delivery Note) for 3 years and MARPOL Samples for 1 year have to be maintained in ship's custody to immediate access [4].

In addition to the mentioned above obligatory documents, as a service to ship-owners wanting documentary proof they operate in compliance with the regulations the following are available:

1. Classification Societies (CS) as ABS are prepared to issue Statement of Fact (SOF) Certificate. These will require survey by CS Surveyor to verify that vessel has dedicated low sulfur fuel storage tank, fuel piping systems suitable for its use that maintain segregation from other fuels and has operational procedures in hand for its use [1].
2. DNV Petroleum Services has developed a service where in-system samples before and upon completion of change-over can be taken and submitted for testing to determine whether complete change-over has been achieved [4].
3. Next DNVPS invention is the Blend Optimization Program (BOP) which by submitting a representative sample of each blend component will undertake fuel quality and compatibility check of the blends, calculation of the resultant blend viscosity or recommendation on optimum blend composition to meet engine fuel specification and correct injection temperature [4].

Fuel change-over operation should be carried out in safe navigation area and followed with ship-owner's On Board Procedure (OBP) approved checklist. After completion Main Engine (M/E) start should be confirmed on LSGO as the increased start index might be required what can be combined with regular M/E test astern.
Suggested routine for change-over from HFO to LSFO could be as follows:

- Switch off auto-start of fuel oil transfer pump.
- Allow settling tank to reduce to minimum level by normal purification. Stop fuel oil purifier. The remaining HFO quantity should allow obtaining mixing ratio below 20:80 but if the system permits it can be dropped to the overflow tank to speed the process.
- Transfer HFO from overflow tank to HFO bunker tank.
- Change-over fuel oil transfer pump suction to LSFO bunker tank and refill settling tank.
- Allow service tank to reduce to a minimum acceptable level by normal main and auxiliary engine consumptions including boiler. Preferable mixing ratio 20:80. Care should be taken to allow for any vessel movement that might affect suction.
- Start fuel oil purifier.
- Switch on auto-start of fuel oil transfer pump.

Suggested routine for change-over from HFO to LSGO during sailing could be as follows:

- Stop FO Purifier and steam to HFO Service tank to reduce temperature to 80˚C (it will be required in reverse process as mixing hot HFO into relatively cold LSGO can be difficult due to the mixed fuel is not homogeneous immediately and some temperature/ viscosity fluctuations are expected).
- Reduce the engine load to 25-40% to ensure a slow reduction of the temperature gradient (35-45 minutes) - The load can be changed to a higher level based on experience.
- Stop steam tracing and steam to pre-heater.
- Carry out change-over of fuel by swinging 3-way valve when the fuel temperature starts to drop not exceeding viscosity 20 mm^2/s (cSt).
- As a complete change-over may take several hours depending on the engine load, volume of fuel in the circulating circuit and the system layout, observations of the temperature/viscosity must be the factor for manually taking over the control of the steam valve to protect the fuel components although in general the viscosimeter should control the steam valve for the fuel oil heater. The viscosity must not drop below 2 mm^2/s (cSt) and the rate of temperature change of the fuel inlet to the fuel pumps must not exceed 2°C/minute.

The sulfur content in fuel oil is expressed in terms of analysis value at the Laboratories are generally indicated in weight percent. When other 2 fuel oils are mixed, the assumed sulfur content can be determined by the formula below or graphs on fig.6:

$$X_w = \frac{X_1 \times W_1}{W_1 + W_2} + \frac{X_2 \times W_2}{W_1 + W_2}$$

where:

- X_w: Assumed sulfur content of the mixed fuel oil (%)
- X_1, X_2: Sulfur content of each fuel oil (%)
- W_1, W_2: Weight percent of each fuel oil (%)

If it is assumed that a reduced amount of total of 90 tons of HFO with a sulfur content of 3.5% is remained in the engine room FO Settling and Service Tanks then min 180 tons of LSFO/LSGO with a sulfur content of 1.0% is required before the ship enters ECAs to the assumed sulfur content of the mixed fuel oil in respective tanks reaches Xw = **1.5%**:

$$X_w = \frac{3.5\% \times 90 \text{ tons}}{90 + 180 \text{ tons}} + \frac{1.0\% \times 180 \text{ tons}}{90 + 180 \text{ tons}}$$

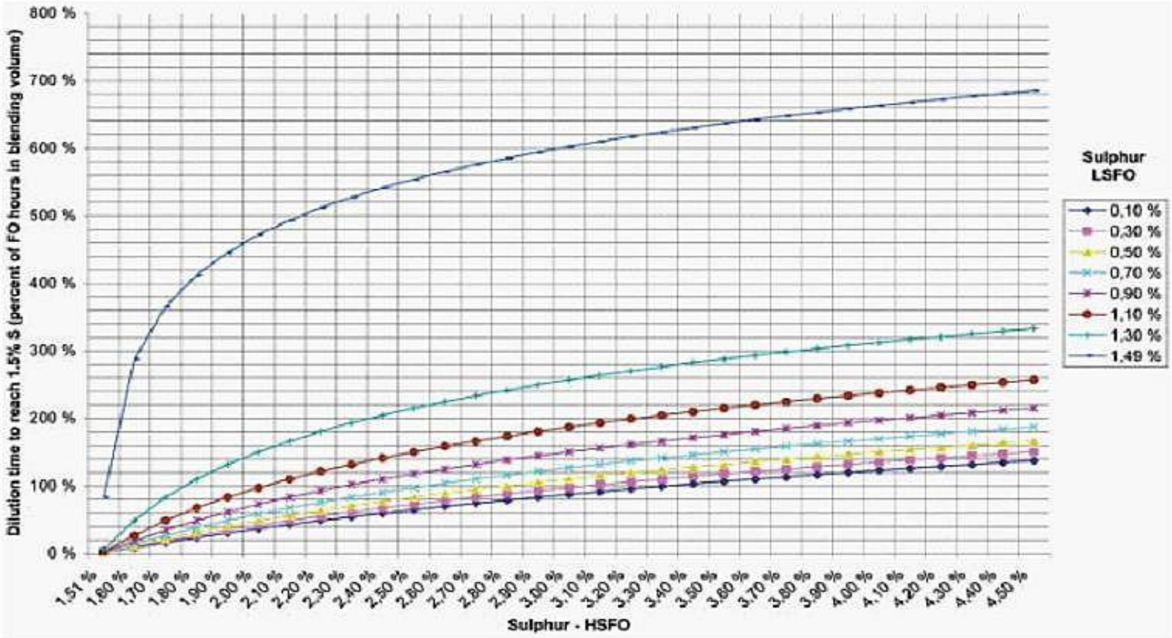

Fig. 6 Dilution time to reach 1.5% Sulphur in percent of the fuel oil hours contained in the blending volume [14]

If we assume further that fuel oil consumption is 90 tons per day then changing should be commenced minimum 3 days before the ship enters ECAs giving a larger margin against the controlled value that depends on the sulfur content of each component fuel oil, mixing ratio and consumption of the mixed fuel oil. For the above example from the fig. 6 graph as published by DNVPS which shows the sulfur dilution time would be 200% of the fuel oil consumption time for the quantity of HFO remaining in the settling and service tanks, plus the system pipelines at the commencement of the change-over to LSFO.
It can be seen that, because of the infinite number of possible values for the sulfur contents of both HFO and LSFO/LSGO, it is not feasible to dictate a definite time for the minimum duration of the change-over period. Therefore, timing for changing over cannot be assumed by any fixed figure and it is necessary to have precise calculations and to establish an enough allowance, assuming that re-bunkering has taken place since the previous change-over. Moreover, each vessel will require to have own procedures depending on bunker condition and fuel oil system.

5. Conclusions

To meet requirements of IMO Regulation 14 of Annex VI to the International Convention on the Prevention of Pollution from Ships (MARPOL) the ship-owners have to face up the problems in operation and adaptation of fuel piping/ tank systems connected with switching of fuel supply to marine diesel engines from HFO to LSFO/ LSGO and/ or to install additional equipment as wet/ dry scrubbers to clean exhaust gases [10].

The presented in this article consideration regarding operational problems in marine diesel engines switching on low sulfur fuels before entering and operating in the emission controlled areas, allows the following conclusions and expressions to be constructed:

1. LSFO combustion doesn’t give rise to any difficulties except compatibility which can be reduced to minimum if proper rules are followed as fuel testing and mixing of two different grades in maximum 80:20 proportion. However, certain amount of chemicals (10% of bunker being mixed) should be maintained on board all the time to suspend heavy fuel particles and disperse sludge, to dissolve existing sludge, to enable the fuel to become a more stable and

homogeneous fluid and finally to improve combustion in case the effect of fuel instability and incompatibility occurred. Besides, one HFO bunker tank has to be separated to store only LSFO what in the most ship's constructions and available tanks is not a problem.

2. Use of LSGO that is obligatory presently in CARB and in at internal EU waters and at berth but soon since 1 January 2015 it will cover all ECAs, causes not only compatibility problems but lubricity, low viscosity and density difficulties as well. Besides, process of switching to/ from LSGO is technically more complicated and requires marine diesel engines to be adapted to combust this fuel. As resulting from the engines producers' analysis modern and low speed engines are well adapted to combust LSGO and with suitable protective and preventive measures and application of appropriate and the adjusted cylinder oil there is no reported problems with operation on LSGO [1, 8]. However, fuel systems will need the closer individual analysis because of quantities of LSGO required to operate in ECAs can cause that some vessels may need to be modified for additional distillate fuel storage capacity and reconstructed fuel piping including bunker lines. This condition may create some problems in transition stage and needs to be taken into consideration in advance. Next, cylinder oil can cause that some vessels may need to store two grade of oil BN70 and BN40/50 or use one grade of more universal oil BN50 considering electronically controlled feed rate and bunkering HFO with sulfur content to 3.5%. That condition mostly can be easily accomplished due to global tendency of HFO bunker deliveries and common fitting electronically controlled cylinder oil feed rate systems on low speed engines (MAN Alpha Lubrication System or Wärtsila RPLS). Even if systems are not fitted during ship's delivery most of the ship-owners decide to install them on already operated vessels as modification during dry docking due to significantly reduced quantity of consumed cylinder oil.
3. As an alternative to using low sulfur fuel or additional supporting equipment, ship-owners may choose to equip their vessels with exhaust gas cleaning devices "scrubbers" that are bringing positive results. However, they require modifying construction already operated vessels what can be difficult especially with vessels equipped with exhaust gas economizer used for turbogenerator at sea and most of present application has testing character and require to be optimized for marine use [8, 9, and 12]. Next, considerable financial outlays to benefits in relation to use of low sulfur fuels haven't been evaluated yet.
4. Apart of the above mentioned technical problems and difficulties with operation of marine diesel engines in ECAs, legislation demands have to be considered. It means custody of relevant documents (BDN, DNV results and sampling records), checklists, and specific manuals for each vessel, logbooks entries and crew members' trainings.

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