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Chapter

Some Methods to Prevent the Wear of Piston-Cylinder When Using Low Sulphur Fuel Oil (LSFO) for All Ships Sailing on Emission Control Areas (ECAs)

Tien Anh Tran

Abstract

The IMO (International Maritime Organization) of MARPOL 73/78, Regulations for the Prevention of Air Pollution from Ships, has been adopted and took effect from May 2005 and had significantly to the present. The increases in a number of ships are leading to a large of number of exhaust gas emission into the environment. It is main reason that the Annex VI, MARPOL 73/78 is extremely necessary to require the ships need to comply. Furthermore, the marine fuel is used mainly for marine diesel engine nowadays, heavy fuel oil with high sulphur content. However, the IMO's regulations show that from January 1, 2020, fuel oil that is used on board should have no more than 0.50% sulphur content in order to protect the environment. Its benefit will have positive effect to the environment. On another side, the diesel engine operation especially the corrosion phenomenon for all piston-cylinder components will have negative effect due to the use of low sulphur fuel oil (LSFO). This chapter concentrates on researching the above phenomenon and gives some methods to restrict the negative influence on using the kind of low sulphur fuel oil. The results are fundamental knowledge for all vessels to comply the regulations of MARPOL 73/78 while sailing on ECAs.

Keywords: low sulphur fuel oil, corrosion, piston-cylinder, MARPOL 73/78, diesel engine

1. Introduction

Marine engines are generally compression ignited two- and four-stroke diesel engines. From the environmental and economic point of view, the Specific Fuel Oil Consumption (SFOC, measures unit in gram fuel oil/kWh) of engine is one of the important factors that contribute to the energy efficiency of ships [1]. On the other hand, the other important factors are the emissions of other gases such as NO_x, SO_x and PM (particulate matter). Some factors depend on the quality of fuel oil and some on the combustion process in the combustion chamber of the engines [2].

The sulphur content of heavy fuel oil is determined through the content of SO_x into the exhaust gas from diesel engine combustion process. In the combustion chamber, the sulphur content of heavy fuel oil is being oxidised into the primary SO_2. A much smaller portion, some 3–5% is further oxidised into SO_3. SO_2 and SO_3 together are called SO_x. The lubrication oil cylinder contains substances to neutralise the sulphur thus preventing the damage caused by sulphuric acid in the engine. Only a very small portion of SO_x is neutralised into calcium sulphate and is considered insignificant.

The exhaust gas emissions are often directly related to the impurities contained in fuels that are being used. The high level of sulphur oxides SO_x and nitrogen oxides NO_x is an inevitable result of using heavy fuel oil (HFO). Maximum emissions of these oxides are regulated by IMO (International Maritime Organization). The requirements for reducing SO_x emissions in certain areas of navigation have resulted in using low sulphur fuel oils in diesel engine operation. The use of HFO with high sulphur contents become unacceptable after adopting the regulations brought by Annex VI of International Convention for the Prevention of Pollution from Ships (MARPOL 73/78) at some sensitive areas (emission control areas—ECAs), and after introducing the monitoring of emissions from ships in ECAs. The maximum sulphur content in fuel oil is regulated in European ECAs that amounts to 0.10% for ships in ports and all inland waterways across the European Union.

Following the new requirements relate to sulphur content emissions that forced into all ships when sailing in emission control areas (ECAs) on January 2015, namely that ships trading have to use the heavy fuel oil and marine diesel oil with a low sulphur content of no more than 0.10%, do not, strictly speaking, alter the regulatory environment.

However, using low sulphur content fuel oil will cause some troubles for technical engine condition.

At the request of California Air Resources Board, following a series of problems that occurred on ship due to fuel switching after the introduction of regulations on using low sulphur fuel oils within 24 miles of the California coastline, a research was conducted from 2009 to 2010; according to the research findings indicated, the fuel switching causes [3]:

- Loss of propulsion and operation instability as the engine reduces speed to come to dead slow or slow astern, resulting in revolution per minute (rpm) fluctuations or stopping the engine, whereas the engine operation was stable at high rpm.

- Failures to start events, including difficulties in starting the engine or inability to start the engine due to low pressures in fuel systems, low viscosity of fuel, problems related to high-pressure fuel pump operation, fuel injection, leakage of oil in the fuel systems, and leakage of sealing rings.

- Inability to reach maximum speed, inability to reserve the engine Ahead/Astern, most commonly due to pressure of fuel injection.

This chapter is based on the effects of using low sulphur fuel oil to engine operation. It is significant to give the method to restrict the negative forces to the engine technique condition when operation.

2. Literature review

2.1 Marine diesel engine

The diesel engine is an internal combustion engine in which the fuel ignition has been conducted into the combustion chamber at high temperature.

The ignition process of diesel engine takes place in the combustion chamber. The operational principle of diesel engines is carried out throughout 4 cycles: suction—compression—ignition—exhaust.

The compression-ignition engine has the highest thermal efficiency (engine efficiency) of any practical internal or external combustion engine due to its high expansion ratio and inherent lean burn which enables heat dissipation by the excess air. The low-speed compression-ignition engines (as used in ships and other applications, where overall engine weight is relatively unimportant) can have a thermal efficiency that exceeds 50%.

The compression-ignition engines are manufactured in two-stroke and four-stroke versions. They were originally used as more efficient replacement for stationary steam engines. Since the 1910s, they have been used in submarines and ships. The use of locomotives, trucks, heavy equipment and electricity generation plants followed later. The structure of marine diesel engine is described in **Figure 1**. The main marine diesel engine is a two-stroke diesel engine type with large size, slow speed, high power engine that installed on large size ship.

In the true diesel engine, only air is initially introduced into the combustion chamber. The air is then compressed with a compression ratio typically between 15:1 and 23:1. The high compression causes the temperature of the air to rise. At about the top of the compression stroke, fuel is injected directly into the compressed air in the combustion chamber. This may be into a (typically toroidal) void in the top of the piston or a pre-chamber depending upon the design of the engine. The fuel injector ensures that the fuel is broken down into small droplets, and that the fuel is distributed evenly. The heat of the compressed air vaporises fuel from the surface of the droplets. The vapour is then ignited by the heat from the compressed

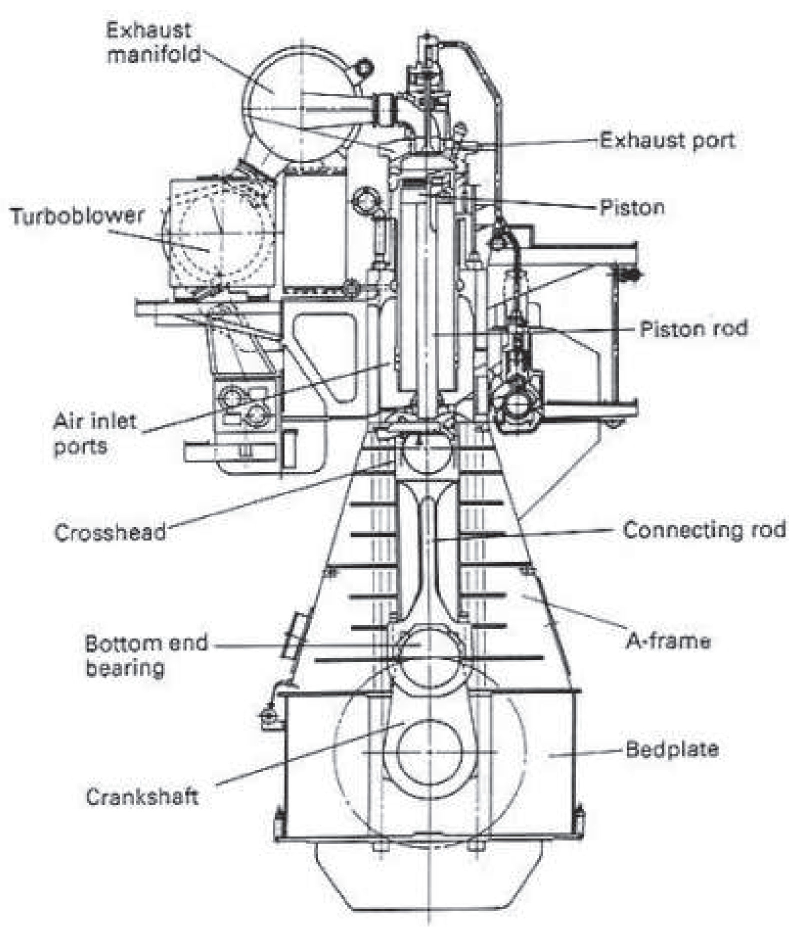

Figure 1.
The structure of diesel engine.

air in the combustion chamber, the droplets continue to vaporise from their surfaces and burn, getting smaller, until all the fuel in the droplets has been burnt. Combustion occurs at a substantially constant pressure during the initial part of the power stroke. The start of vaporisation causes a delay before ignition and the characteristics diesel knocking sound as the vapour reaches ignition temperature and causes an abrupt increase in pressure above the piston (not shown on the P-V indicator diagram).

When the combustion process is complete, the combustion gases expand as the piston descends further, the high pressure in the cylinder drives the piston downward, supplying power to the crankshaft. The working cycle of two-stroke diesel engine has been described on P-V (pressure-volume) diagram in **Figure 2**.

As well as the high level of compression allowing combustion to take place without a separate ignition system, a high compression ratio greatly increases the engine's efficiency. Increasing the compression ratio in a spark-ignition engine where fuel and air are mixed before entry to the cylinders is limited by the need to prevent damaging pre-ignition. Since only air is compressed in a diesel engine and fuel is not introduced into the cylinder until shortly before top dead center (TDC), premature detonation is not a problem and compression ratios are much higher.

2.2 Emission control areas

The International Maritime Organization (IMO) member states acknowledged the low quality of heavy fuel oil in the field of connection with the high sulphur content of fuel on boards. Since the low quality of fuel oil will bring to producing exhaust gas fumes such as SO_x that leads to acid rain phenomenon. So, it is main reason that the most straightway form of reducing acid rain effects is to life creatures due to change-over high sulphur content fuel oil to low sulphur content fuel oil at present.

MARPOL 73/78, Annex VI entered into force on May 19, 2005. Regulations 14 and 18 define the method of controlling sulphur oxide (SO_x) emissions on a global basis and in defined protected areas called sulphur emission control areas (SECAs or ECAs).

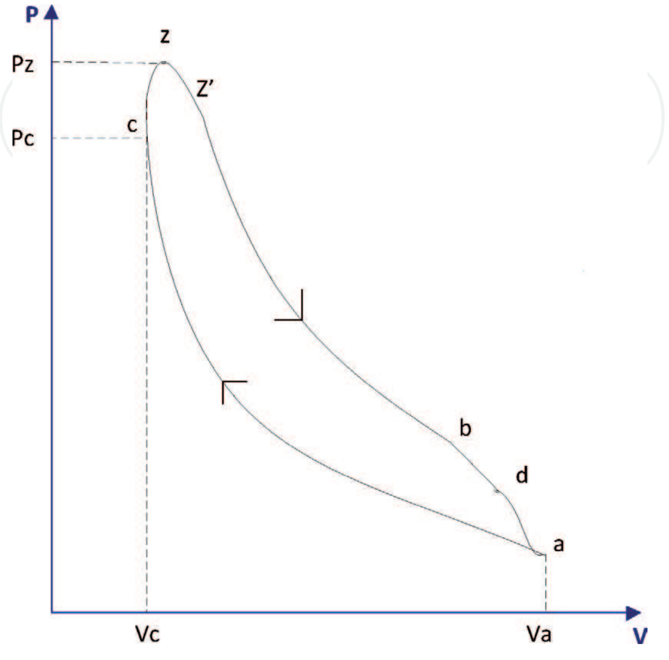

Figure 2.
P-V diagram of 2-stroke diesel engine.

The aim of the legislation is to reduce SO_x emissions from ships to reduce the acidification of the atmosphere and the resulting acid rain. This is to be achieved by setting a limit on the sulphur content in marine fuels.

Marpol Annex VI, Regulation 14 requires the following:

- A limit on the sulphur content on any fuel used onboard ship, this must not exceed 4.5% m/m until January 1, 2012 (currently 3.5% max sulphur).

- The sulphur content on any fuel used onboard a ship operating in a SECA must not exceed 1.5% m/m.

- Alternatively, an exhaust gas cleaning system or other approved technological method of reducing total SO_x emissions from main and auxiliary engines and boilers to a maximum of 6.0 g SO_x/kWh when operating in a SECA. Controls are also set on effluent discharges from such cleaning systems.

- Details of the change-over operation from high sulphur fuel to low sulphur fuel when entering a SECA are to be recorded in a log book and also when changing over to high sulphur fuel when leaving a SECA for an uncontrolled area. The procedure is to ensure that all fuels exceeding the 1.5% sulphur limit are flushed out of the fuel system prior to entering a SECA.

Marpol Annex VI, Regulation 18 establishes requirements for the quality, sampling and delivery of fuel oil and the keeping of bunker deliver note records.

On the other hand, Annex VI regulations include caps on sulphur content of fuel oil when ships sail on ECAs with the SO_x emissions and indirectly, PM emissions. Special fuel quality provisions exist for SO_x emission control areas (SO_x ECA or SECA). The sulphur limits and implementation dates are listed in **Table 1** and illustrated in **Figure 3**.

Heavy fuel oil (HFO) is used popularly but this fuel needs to meet the requirements of MARPOL 83/78 when sailing on ECAs. In addition, the alternative measures are also allowed (in the SO_x ECAs and global) to reduce sulphur emissions, such as through the use of scrubbers.

Especially, the Marine Environment Protection Committee, session 69th (MEPC 69) on April 18–22, 2016 has adopted the limit of low sulphur content fuel oil used for marine engines through **Table 1** and **Figure 3**. The MEPC 69 has supplied some contents such as mandatory system for collecting ships' fuel consumption data, reduction of Greenhouse Gas (GHG) emissions from ships, the establishment of effective dates for the Baltic Sea Special Area, the implementation of the BWM (Ballast Water Management) Convention, the energy efficiency of international

<table>
<tr><th rowspan="2">Date</th><th colspan="2">Sulphur limit in fuel (% m/m)</th></tr>
<tr><th>SO_x ECA (%)</th><th>Global (%)</th></tr>
<tr><td>2000</td><td>1.5</td><td rowspan="2">4.5</td></tr>
<tr><td>2010.07</td><td rowspan="2">1.0</td></tr>
<tr><td>2012</td><td rowspan="2">3.5</td></tr>
<tr><td>2015</td><td rowspan="2">0.1</td></tr>
<tr><td>2020</td><td>0.5</td></tr>
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Table 1.
Marpol annex VI fuel sulphur limits [4].

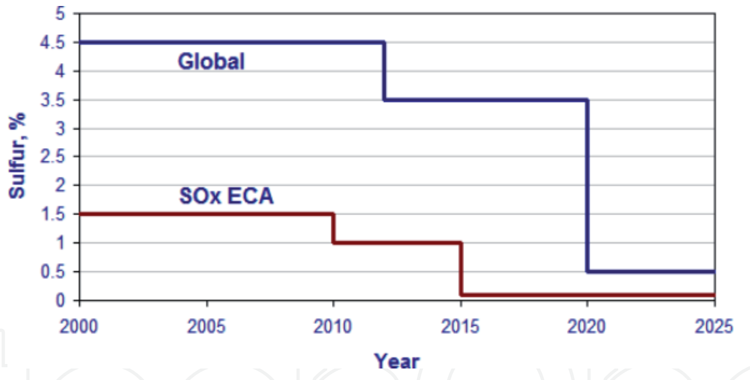

Figure 3.
Marpol annex VI sulphur content limit [4].

shipping, etc. [5]. In where, the fuel oil quality was concerned more since the cost of ship operation will be increased due to the requirement of high quality fuel oil. The low sulphur content fuel oil will be regulated detail in MEPC 69. Following that, to 2020 global sulphur cap implementation date decided in aims with sea environmental protection and human health. Due to, January 1st 2020 was confirmed as the implementation data for a significant reduction in the sulphur content fuel oil used on ships. In addition, the decision about limit of a global sulphur cap of 0.50% m/m (mass/mass) in 2020 will be applied to all ships. Following discussion, the Committee encouraged the fuel oil supply industry to develop the draft best practice for fuel oil providers and submit this best practice to the Committee for consideration at a future session.

The date of 2020 was agreed in amendments adopted in 2008. In then, those amendments were adopted. If it was also agreed that a review should be carried out by 2018 in order to assess whether the sufficient compliant fuel oil would be available to meet the 2020. On the other hand, the review completed in 2016 and submitted to the Marine Environment Protection Committee, session 70th (MEPC 70) organised in London. So, the new global limit about sulphur content in fuel oil of no more than 0.50% m/m in 2020. It is contrasting the current limit of 3.50% applied from January 1, 2012 [6].

2.3 MARPOL 73/78, Annex VI (Regulation 14)

The following IMO's regulations about the International Convention for the Prevention of Pollution from Ships, 1974 as modified by the Protocol of 1978 (MARPOL 73/78) is one of the most important international marine environmental conventions. This convention was developed by the International Maritime Organization (IMO) with a lot of delegates from different country where the diversity of ships and nation's border lies on the sea.

SO_x and particular matter (PM) emission controls are applied to all fuel oil, combustion equipment and devices due to both of main engine and auxiliary engine together generate the harmful gas emission in where contain a lot of other elements not only above ones but also carbon dioxide, nitrogen oxide, etc.

Among the SO_x controls, the level of sulphur content must be controlled in fuel oil varies for designated emission control area (ECA). The existing controls are in **Table 2**.

Under the provisions of MARPOL 73/78, Annex VI, Regulation 14, the availability of fuel oil to meet the global 0.50% sulphur content in fuel oil used. It is determined by the Committee in 2018. Moreover, a Steering Committee (regionally represented by Member States) began reviewing of the availability of 0.50%

sulphur fuel oil under terms of reference agreed at MEPC 68 with a report submitted to MEPC 70 held in October 2016 [7].

During the period of session time of MEPC 60 has been held from March 22 to 26, 2010, a lot of views were given out by delegates, a proposal has been adopted to amend the MARPOL Convention by designating the areas within 200 nautical miles from the coasts of North America and Canada (excluding a part of the areas such as the West Coast of Alaska) as the North American Emission Control Area for controlling the emissions of NO_x, SO_x and PM (particulate matter) from August 1, 2012 (see **Figure 4**).

Besides that, IMO (International Maritime Organization) also has given out the latest emission control regulations about the limit of SO_x content exhaust gas emission next time. Annex VI, MARPOL 73/78, Regulations for the Prevention of Air Pollution from Ships, has been applied since May 2005.

The emission control areas (ECAs) are the Baltic Sea, North Sea and English Channel, possibly Mediterranean in August 2007, 200 nautical mile zone at the US coast; Californian Air Resources Board (CARB), it is 24 nautical miles of the Californian baseline.

Thus, the sulphur oxides (SO_x) limit applies to all vessels in the category of ships with an engine power output of more than 130 kW. In the regulation 13 of Annex VI, MARPOL 73/78 has indicated that NO_x emission control requirements for all ships installed 130 kW engine. So, the SO_x emission control must be complied.

The international general limit on sulphur is reduced from 5% to 4.5% through the ISO 8217 fuel standard. International Maritime Organization has specified that in the future, this limitation will be imposed on SO_x as well as the other components into exhaust gas.

Effective date	Area other than designated emission control area	Designated emission control area
Before 1 July 2010	4.50%	1.50%
On and after 1 July 2010	↓	1.00%
On and after 1 January 2012	3.50%	↓
On and after 1 January 2015	↓	0.10%
On and after 1 January 2020	0.50%	↓

Table 2.
Controls on the concentration of sulphur content in fuel oil.

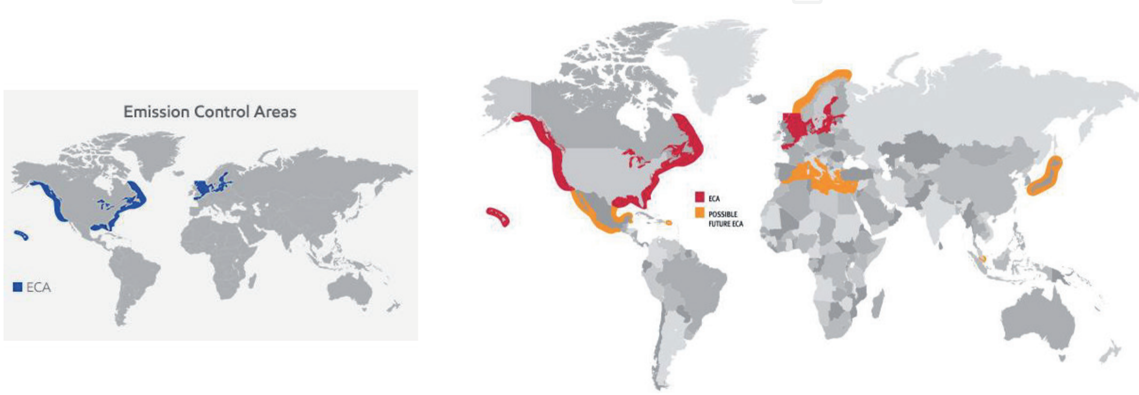

Figure 4.
The emission control area (ECA).

Today, ECAs comprise the Baltic Sea, the English Channel and the North Sea, however, more areas will be added to these in the future.

California Air Resources Board (CARB) has introduced limits on the use of sulphur for distillates [8].

Ports in the European Union Area (European Union—EU) includes EU member states, Norway, the Faroe Islands and Iceland applied the regulations about using the low sulphur content in shipping transportation industries.

In addition, Ports in Turkey include Istanbul & Marmara, Aegean, Mediterranean and Black Sea Regions also admit the limit of sulphur content fuel oil in the emission control areas (ECAs).

2.4 Low sulphur fuel oil

The sulphur content of marine fuel depends on the crude oil fuel and the refining process. In the combustion process of the engine, sulphur contains into the fuel, mixed with oxide after that converted into the sulphur oxides. These oxides are corrosive to engine piston liner and must be neutralised by the cylinder lubricant. If the correct lubricant is used, the sulphur content of marine fuels is technically not important, but sulphur oxides do have environmental implications. Fuel is the specification of ISO 8217:2010 that is not necessary for compliance with the regulations in force at the vessel's location. IMO sets the limitation regarding the sulphur content of any fuel oil used on board ships. However, the low sulphur content fuel oil may have a negative impact on different fuel properties depending on the fuel type. **Table 3** shows the relation between fuel properties and fuel types.

The types of marine fuel are being used on vessels in order to meet the requirements of MARPOL 73/78 Annex VI about low sulphur content fuel oil limit including marine gas oil (MGO) and marine diesel oil (MDO). In where, the MGO includes DMA, DMX, and DMZ grade. The MDO has DMB grade according to ISO 8217. Especially, the ultralow sulphur fuel oil (ULSFO) is a new fuel type with sulphur content of no more 0.10% (m/m). It is not traditional distillates, but blended products are from refinery streams that have not previously been utilised extensively in marine fuel oils [9]. These main properties of fuels above are introduced in **Table 4**.

The characteristics of ultralow sulphur fuel oil (ULSFO) differ completely compared with types of fuel MGO and MDO [11]. There are some other characteristics of fuel oil but in **Table 4** only uses the main characteristics include the sulphur content, viscosity at 40°C, and flash point of fuel oil. In reality, the ultralow sulphur fuel oil is suitable to use low sulphur fuel oil for vessels with advantageous characteristics.

2.5 Procedures of change-over HSFO to LSFO for main engine

Emission control areas (ECAs) are designed at sea in order to follow the MARPOL 73/78 regulations about reducing of SO_x and NO_x emissions. In this researching, the article is referred to SO_x emission into the environment by ships due to using the high sulphur content of heavy fuel oil for equipment.

Some local laws regarding air pollution are more stringent than those laid down by the IMO. For example, in Europe while the ship is at the port, all the running of machinery consumes the type of fuel oil must be less than 0.10% sulphur content.

As the SO_x emission is purely dependent on the quality and sulphur content of the fuel, while entering emission control areas. It is required to change-over for a

Fuel properties	Fuel types
Low viscosity	MDO
Lubricity	MGO/MDO
Acidity	MGO/MDO/HFO
Flash point	HGO/MDO/HFO
Ignition and combustion quality	HFO
Increased catalytic fines	HFO

Table 3.
Relation between the fuel properties and fuel types.

Grade	MGO			MDO	ULSFO
	DMX	DMA	DMZ	DMB	
Sulphur content % (m/m)	max. 1.00	max. 1.50	max. 1.50	max. 2.00	max. 0.10
Viscosity at 40°C (cSt)	min. 1.40 max. 5.50	min. 1.50 max. 6.00	min. 3.00 max. 6.00	max. 11.0	min. 40 max. 75
Flash point (°C)	min. 43	min. 60	min. 60	min. 60	min.70

Table 4.
Main properties of fuel oil defined in ISO 8217 (2010) [10].

low sulphur content fuel oil including flushing of fuel from the system with sulphur content more than 1.0% sulphur before entering the emission control areas (ECAs).

For the changing-over to low sulphur fuel oil for main engine is carried out under supervising of Chief Engineer. To consider that most of the ships today run at high sulphur fuel oil, changing over of fuel at the appropriate time is very important. Moreover, looking at today's economic condition of the industry, it s imperative to change over the fuel from high to low sulphur at the correct time as an early change-over will lead to loss of low sulphur oil, which is quite expensive, whereas a delay in the changeover procedure will lead to violation of MARPOL Annex VI. This is to be done along with using other technologies to reduce SO_x and NO_x from ships.

Almost all ships are usually installed one service tank and more setting tanks. The changing-over of fuel is conducted between tanks each other on ships. So, the mixture of two different grades of fuel oils will be happened in order to decrease the low sulphur content of fuel oil on ships nowadays [12].

On the other hand, it is provided with changing-over to low sulphur fuel oil calculator which tells the correct changing-over time at a certain case that before entering an emission control areas (ECAs). This system requires some important factors [3]:

- The sulphur content of high sulphur fuel currently in the system;
- The sulphur content of low sulphur fuel;
- The fuel capacities of the main engine system including setting tank, service tank, main engine piping and transfer piping from service tank to main engine;
- The capacity of transfer equipment—fuel oil transfers pump and fuel oil separators.

Once the change-over time is computed which also accounts for the time of intermixing of two different sulphur grades oil (let us suppose 48 h) following action are to be taken 48 h prior.

- Ensure that no transfer of high sulphur fuel is carried out any further to settling tank;
- Ensure that the low sulphur bunker tank steam is open for transfer and purification of fuel should not have any problem;
- If two separate settling tanks are present, once can be dedicated to low sulphur oil which will reduce the changeover period;
- Keep running the separator till the settling tank level reaches minimum;
- If filling of service tank with HSFO increases the calculated time period of changeover then stop the separator and drain the settling tank;
- Settling tank can be first drained into fuel oil overflow tank, and then the oil drained can be transferred to bunkers tanks containing same grade of oil;
- Once the settling tank is drained from heavy sulphur oil, fill the settling tank with low sulphur fuel oil via transfer pump;
- As the separator are stopped, service tank oil will be consumed by main engine system;
- Remember not to lower the level of service tank below which the fuel pumps cannot take suction;
- Start separators from settling to service tank which be now filling low sulphur fuel oil;
- Fill the low sulphur fuel oil into settling tank and service tank as per quantity required to cross the ECA calculated by the Chief Engineer as per the voyage plan.

3. Impacts on piston-cylinder of main engine using LSFO

3.1 Impact of high sulphur content fuel oil on ship operation

Firstly, to understand the effects of using low sulphur fuel oil to piston-cylinder liner component, need to regime of high sulphur content of fuel oil on ship operations [9].

The greatest environmental problem of maritime transport is heavy fuel oil (HFO) with high value of sulphur content and used popularly for diesel engine. Merchant vessels consume the heavy fuel for the marine engines and auxiliary engines in order to generate the energy for ship propulsion and electricity, respectively, on board. On the other hand, the unwanted properties elements like as incombustible transition metals, polycyclic aromatic hydrocarbons and sulphur also exist in heavy fuel oil which are residual oil from petroleum refining process to produce the marine diesel oil (MDO), marine gas oil (MGO) and other distillate oil.

The unwanted properties make HFO price cheaper than distillate fuel oil. Intermediate Fuel Oil (IFO) 380 is the most commonly used for ocean-going vessels. Nowadays, some ships usually carry out bunkering oil in Singapore, China, Netherland, etc. In reality, the price of fuel oil at some places is different. For example, the price of IFO 380 is $311.50/tonne in then the price of DO is $487.00/tonne in port of Singapore in the year 2017. Port of Rotterdam, the price of IFO 380 is $282.00/tonne, DO is $460.00/tonne in the year 2017 [13]. The cheaper price of HFO is an advantage for ship operators to lower fuel costs considering incremental fuel costs if the engine consumes distilled products. It is the main reason why HFO is used by most ocean going ships. In fact, fuel costs are a dominant proportion of voyage costs accounting for 47%, while voyage costs contribute roughly 40% of the total operational costs [14]. Consequently, the fuel costs is the most important factor in the voyage costs which should be maintained as low as possible, otherwise it will bring negative effects on the total operational costs.

Nevertheless, HFO entails several drawbacks in shipping operation. For example, the heavy fuel oil must be heated before injected into the engine combustion chamber with the temperature approximately 140°C because of its viscous. Besides that it is necessary to equip the sludge tanks to accommodate the sludge of HFO which cannot be burnt during combustion process of engine and it must be moved on shore. The methods which are treated include as burning into an incinerator on ship or transferred to the reception facilities. So, the exhaust fumes are released from the combustion process using HFO in diesel engines which is vastly more harmful to human health and life environment.

Until now, marine low speed engines and their lubricants have been optimised for operation on heavy fuel oil (HFO) with a high sulphur S content. During the combustion process is happening, the sulphur S is converted to the sulphur trioxide (SO_3). In combination with water from the combustion and the scavenge air, SO_3 forms sulphuric acid (H_2SO_4) is be generated.

When the liner temperature drops below the dew point of sulphuric acid and water, a corrosive on the liner wall. The high alkaline lubricants (high-BN oils) neutralise the acid and prevent corrosion of piston rings and cylinder liner surfaces.

3.2 Impact of low sulphur content on engine operation

Secondly, when operating on fuels with less than 0.10% S, such as distillates, ultra-low sulphur fuel oil (ULSFO) with less than 0.10% S, LNG, methanol, ethane and LPG, only small amounts of sulphuric acid are formed in the combustion chamber. The cylinder lube oil additives are then not used for the designed purpose and they tend to build up as deposits. These deposits may disturb the lube oil film and obstruct the piston ring movement, which could lead to micro-seizures on the piston rings and liner and increase the risk of scuffing. Deposit formation and the total lack of corrosion increase the risk of bore-polishing, which could also lead to increased wear and scuffing. For engines operating continuously on fuels with less than 0.10% S.

3.3 Impact of emission control area (ECA) on the ship operation

Emission control area (ECA) has been adopted by IMO members, the countries need follow the IMO's regulations about using low sulphur content fuel oil from now until 2020.

The availability of low sulphur fuel oil is a major issue in ECA implementation. For this purpose, EPA (Environmental Protection Agency) confirms LSFO under 1% available within the US ECA [15]. Therefore, Canada should also be able to provide adequate LSFO in the ports in its territorial waters. Since the scheme requires more stringent control of sulphur content in fuel to 0.10% from 2015, due to the fuel consumption is the greatest problem for all ships and ship owners under pressure of high fuel price nowadays (**Figure 5**). **Table 5** describes the cost of SO_x and NO_x emission regulation.

Table 5 shows that operating costs will attribute to the total costs to comply with ECA standard. For the existing ships, the changeable prices will be varied around $2.07 billions in 2020. In then, the new building ships will spend at least $3.2 billions to install appropriate hardware and to use distillate fuel and urea in 2020.

3.4 Impact of low sulphur fuel oil on diesel engine

3.4.1 Lack of lubricity

Lubricity is the ability to generate a hydrodynamic lubrication film (oil wedge). To ensure that a given low sulphur marine gas oil, the significant value of the lubrication oil needs to provide enough. Following the fuel is tested under the ISO 12156-1 (EN 590) High Frequency Reciprocating Rig (HFRR) protocol. This standard is required at a maximum wear scare rate if 460 μm. However, the refineries add a lubricity additive in case of EN 590 requirements are not completed. The higher value of HFRR is showed in **Figure 6**.

The reduction of the lubricity in low sulphur fuel oil will be risked to the marine fuel oil pump system. Its result will be caused the excessive wear and premature failure. So, the special lubrication oil must be used to add lubricity and prevent carbon deposition that is called lacquering. On the other hand, the largest contribution to diesel engine lubricity system comes from the trace amounts of surface-active polar compounds forming a protective layer on the metal surface, thus enhancement of the boundary lubrication. The most active polar materials naturally occurring in diesel fuel are hetero-compounds containing nitrogen and oxygen. The hydro-desulphurization (HDS) process which removes sulphur content also removes these polar compounds, resulting in very poor lubricity characteristics and exposing pumping systems to damage and potential catastrophic failure. It is main reason that the lower fuel lubricity can be seen as abrasive wear of fuel system components. It is not sufficient fuel to supply to the plungers, barrels and injectors.

The proper lubrication in a marine plunger/barrel fuel pump depends on a balance between both hydrodynamic lubrication (**Figure 7**) and boundary lubrication (**Figure 8**). Hydrodynamic lubrication occurs when two surfaces are in motion to each other and are separated by a liquid film that carries the applied load. The result is collected to make a low friction and minimal wear between two surfaces (**Figure 7**).

Type of cost	Compliance strategy	Cost in 2020 (billions USD)
Operating costs (apply to all ships)	Fuel switching	$ 1.9
	Urea consumption (for SCR-equipped engines)	$ 0.17
Hardware costs (apply to ships built in 2020)	Fuel switching	$ 0.03
	SCR	$ 1.1
Total costs		$ 3.2

Table 5.
The total of compliant SO_x and NO_x emission regulation.

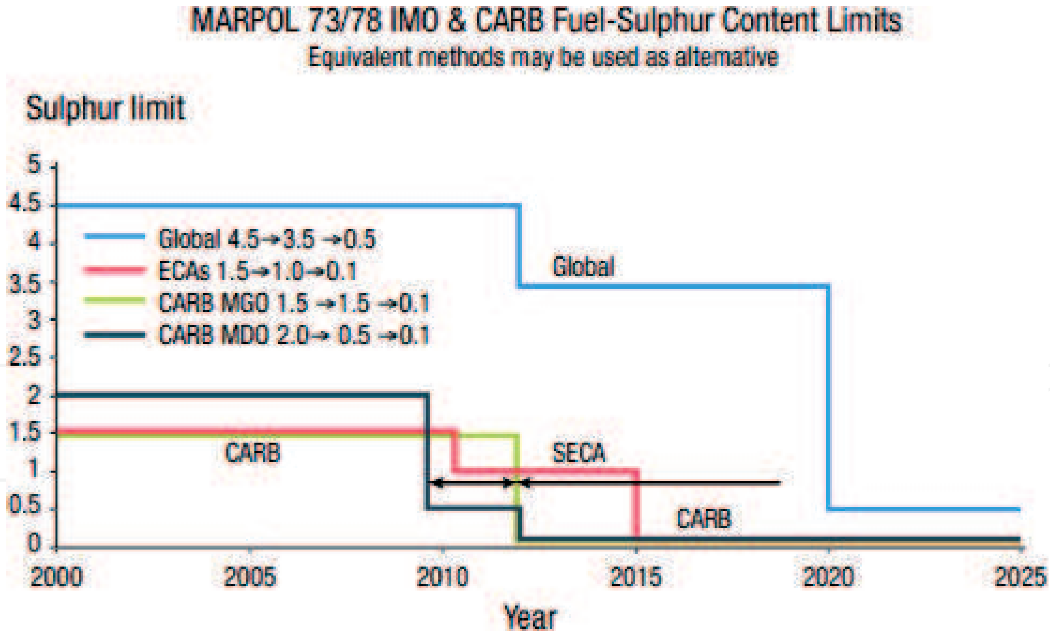

Figure 5.
The diagram of sulphur content limit in ECAs.

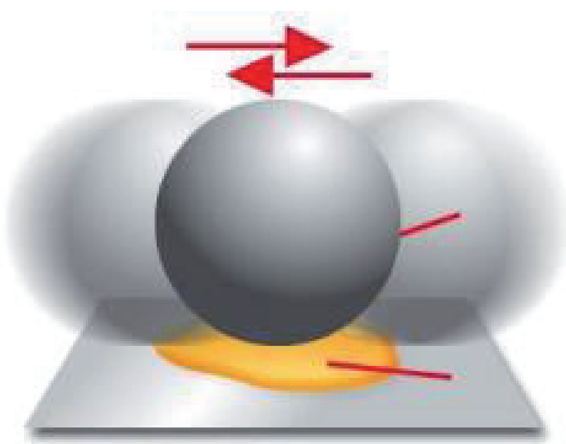

Figure 6.
HFRR test.

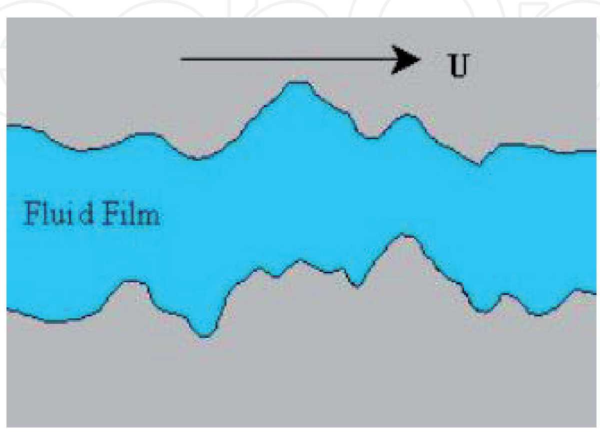

Figure 7.
Hydrodynamic lubrication.

In contrast, the boundary lubrication happens when the liquid film becomes thin to the point that it attains the same thickness as the surface roughness of the high points of the two interfacing solid surface contact, the fuel must have sufficient

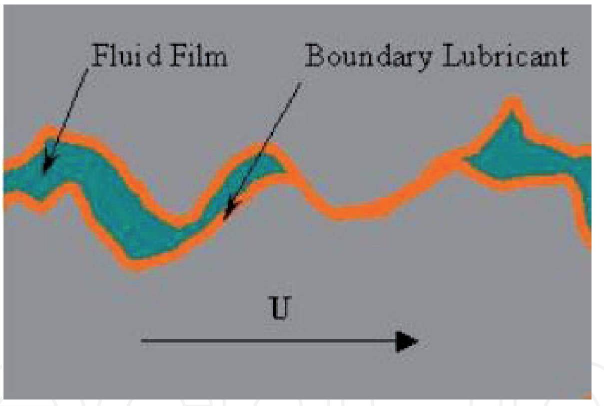

Figure 8.
Boundary lubrication.

lubricity to prevent increased friction and wear. The boundary lubrication is critical in three different situations, namely on initial start-up with insufficient liquid film, at low speed operations when not enough fuel is pumped to provide a satisfactory film and at very high speed operation when high pressure within the pump diminishes the film thickness (**Figure 8**).

A viscosity range 12–16 centistokes is sufficient to provide adequate hydrodynamic lubrication. Viscosity of low sulphur MGO varies from 1.5 to 3.0 cSt. In that case the protective fuel film between the surfaces of the barrel and plunger becomes dangerously thinner resulting is increased metal to metal contact even if fuel viscosity is increased through chilling or cooling. The difference between boundary and hydrodynamic lubrication is depicted.

Unfortunately the IMO regulation only regulates the sulphur content and no other fuel specifications are addressed. Low sulphur fuel with good lubricity characteristics is expected to be more expensive. Owners should not opt for less expensive fuel quantities, which will result in wear of fuel pump and injection components, bad combustion and engine wear and damages.

3.4.2 Fuel stability

The hydro-desulphurization (HDS) removes a large measure of aromatic content, resulting in reduced ignition quality. It also removes naturally occurring anti-oxidants that provide both physical and thermal stability of the fuel. Absence of natural anti-oxidants leads to the formation of hyper-peroxides, which can result in acid corrosion attach of fuel pump systems and pump seal failure. Especially, the formation of hyper-peroxide in fuel oil happens quickly at high temperature and it causes the negative influence on the fuel oil system. Oxidation process also produces gums, polymers and other insolubles. Standards to detect hyper-peroxide contamination are available.

The inherent instability of low sulphur fuel poses four critical threats to safe marine engine operation, namely degraded ignition quality, excessive engine deposits, an increase in visible particular emissions and excessive sludge production and fuel system fouling. Reduced stability of the fuel can also result increased emissions. Low sulphur marine fuels often produce excessive unburned hydrocarbon and visible particulate emissions (smoke opacity). Poor stability may result in the formation of gum and sludge during storage as well as deposit formation on injection nozzles and gumming of valves.

Poor physical stability can result in problems with fuel compatibility, particular when transitioning from operation on heavy fuel to low sulphur marine gas oil. Since some marine gas oils will be stored aboard the vessel for prolonged time

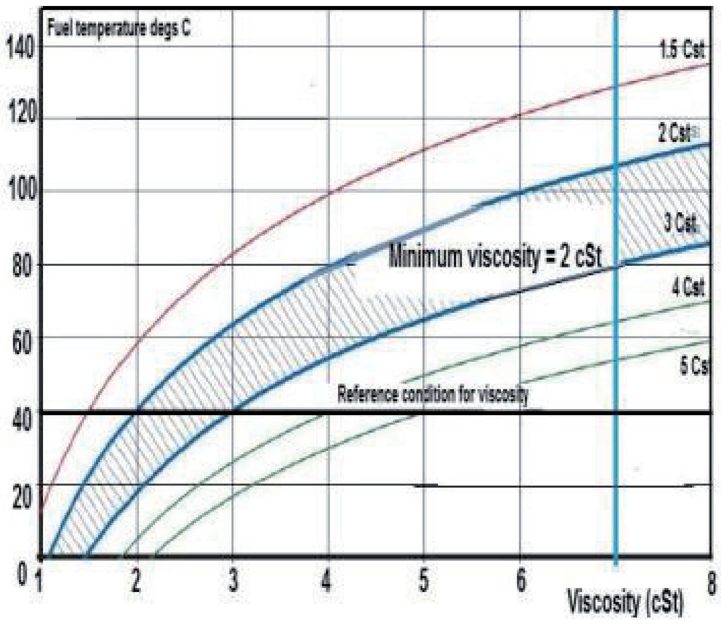

Figure 9.
Viscosity versus temperature [16].

periods, fuels of poor stability characteristics will suffer accelerated degradation, resulting in reduced ignition quality and degraded engine operation.

3.4.3 Low fuel viscosity

Low sulphur distillates have relatively low viscosity, ranging from 1.5 to 3.0 cSt. Fuel pumps depend upon an appropriate viscosity to meet required volumetric capacity, an especially important consideration in maintaining proper feed rates. ISO 8217 states minimum viscosities for DMX, Distillate Marine Oil of Class X, of 1.4 cSt at 40°C and DMA, Distillate Marine Oil of Class A, of 1.5 cSt at 40°C. A rule of thumb value advised by the makers is 2 cSt at engine inlet [10]. Ambient temperature in an engine room easily reaches 40°C and sometimes even higher—in some cases as much as 55°C. Adding excessive heat from pipes and engines will raise the temperature even further and as consequence viscosity will fall, causing a significant change of operating conditions in the system. Mercifully, the lower the viscosity at 40°C the more gradual the fall of viscosity with temperature rise as depicted in **Figure 9**.

The lower viscosity will reduce the film thickness between the fuel pump plunger and casing and in the fuel valves leading to excessive wear and possible sticking, causing failure of the fuel pump. Special fuel injection pumps may be available that are more suitable for this type of fuel, such as tungsten carbide coated pumps, or a fuel pump lubrication system could be installed. Any new types of fuel injection equipment installed to address lubrication issues shall be certified by the engine maker to maintain engine compliance with emission standards and may require re-certification of engines.

4. Methods to restrict from affectation of using low sulphur fuel oil (LSFO)

Following the operation experience associates with the properties of the low sulphur fuel oil. The use of low sulphur fuel oil for marine diesel engine has caused the corrosion between piston-cylinder liner components due to the cylinder liner lubrication oil with low BN (Base Number). It is primarily obtained from stationary engines, operating at 100% load and 100% rpm in high ambient conditions.

4.1 To provide the appropriate lubrication oil quality

Using of low sulphur fuel oil for marine diesel engine will be momentum for causing the sulphuric acid (H_2SO_4) in the combustion chamber. This process is made from the progress chain in **Figure 10**.

To neutralise the acid generated, the cylinder liner lubrication oil must contain alkaline components by mean of using *calcium salts*. Normally, the Base Number (BN or TBN) is a measure of the cylinder liner lubrication oil's ability to neutralise acid because the higher BN, the more acid can be neutralised.

So the Base Number (BN) is very important parameter in controlling the corrosion on the cylinder liner surface. To control corrosion is not avoiding corrosion so it is important to ensure the proper tribology needed for creation of the lubrication oil film. It the neutralisation of the acid is too efficient, the cylinder liner surface has a risk of being polished. It is leading to the lubrication oil film damaged and the risk of the scuffing increases.

On the other hand, the operation of engine with an unmatched BN/fuel sulphur content could increase the risk of either scuffing or excessive corrosive wear.

To make a comparison between using of the different BN lubrication oil for the cylinder line with the same type of low sulphur fuel oil.

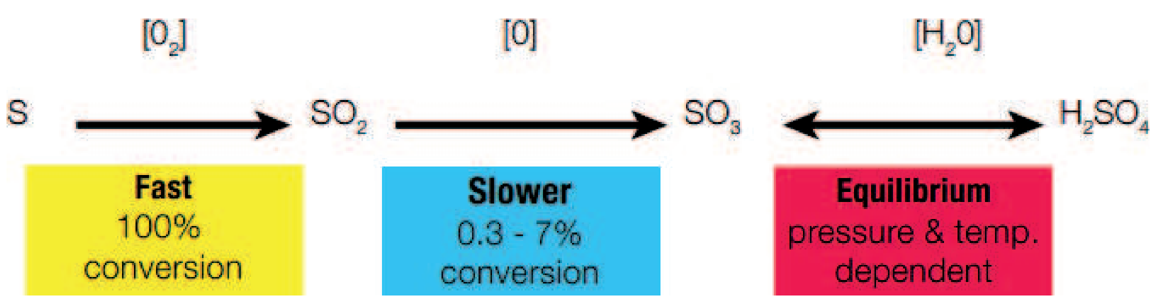

Figure 10.
Chemical conversion of sulphur to sulphuric acid.

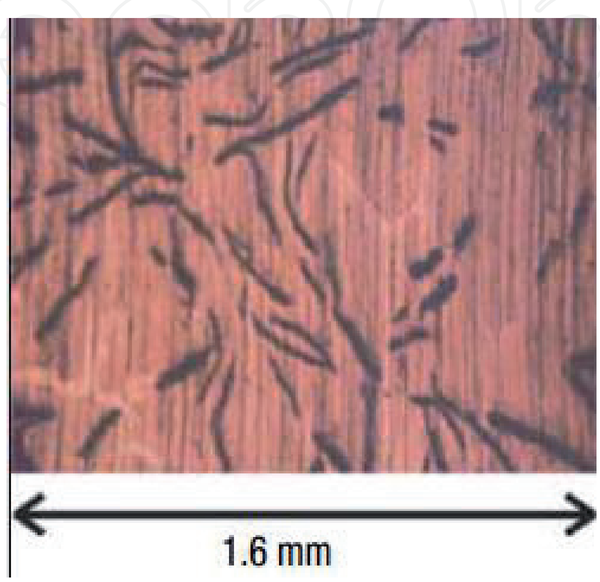

Figure 11.
Cylinder liner surface with BN40. 'Open' graphite structure with good tribological abilities.

Like as **Figures 11** and **12**, it is used the different BN lubrication oil will make the changeable graphite structure on the cylinder liner surface. By using of BN40 lubrication oil will create the 'open' graphite structure with good tribological abilities in contrast to using BN70 lubrication oil has the 'closed' graphite structure with reduced tribological abilities.

It is essential for a good cylinder condition and performance that keeps an 'open' graphic structure on the cylinder liner surface so that a hydro-dynamic oil film is always kept between the piston-rings and cylinder walls at all times.

Therefore, it runs on low sulphur fuel oil that is considered more complex due to the relationship between liner corrosion and scuffing resistance, dry lubrication properties from elements in the fuel (or lack of same), the interaction between the BN in the cylinder oil and the detergency level, possible sulphur of alkaline additives, the piston ring pack, etc.

The appropriate operation of diesel engine is very important especially when it operate at the low sulphur fuel oil. Due to the selection of the low BN cylinder liner

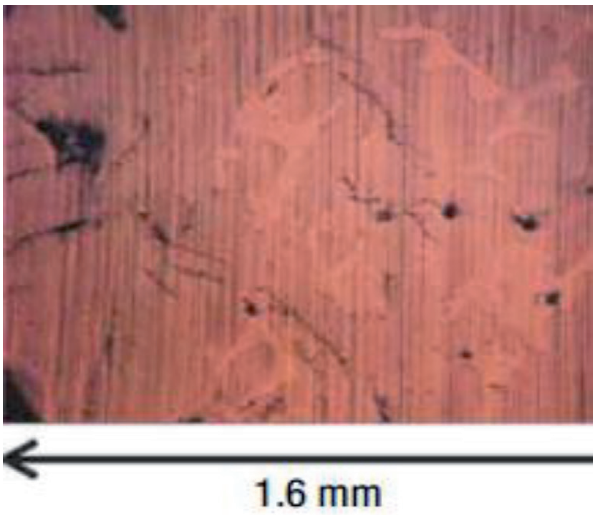

Figure 12.
Cylinder liner surface with BN70. 'Closed' graphite structure with reduced tribological abilities.

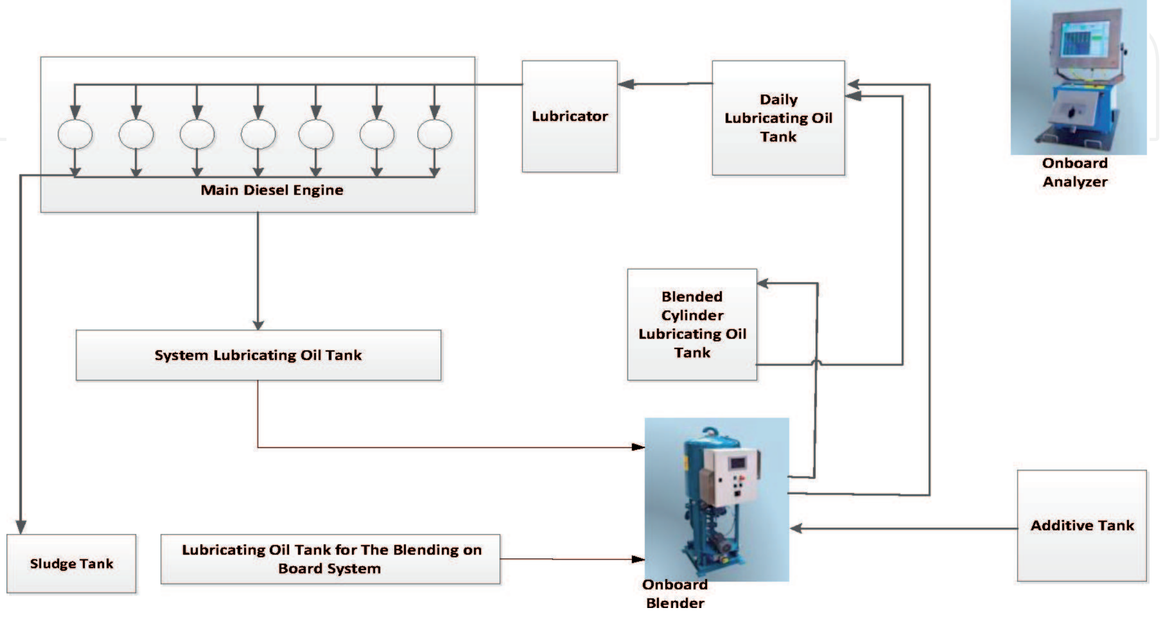

Figure 13.
The blend on board (BOB) system for main diesel engine lubricating oil.

lubrication oil is carried out carefully. In this research, OEMs (Original Equipment Manufactures) recommend the regular testing of scrape down oil for residual BN and Fe content and adjustments to BN of cylinder oil and feed rate to suit. They provide the charts showing the safe zones for the results of the testing and adjustments. In **Figure 13**, the blending on board system is given out in aim with regulating the lubricating oil quality for main diesel engines according to the use of low sulphur content fuel oil nowadays.

The lubricating oil for main diesel engine is regulated through onboard blender from using the system lubricating oil and additives. This task will meet the BN characteristics of lubricating oil in process of using low sulphur content fuel oil for main diesel engines. The scheme of blend on board system is represented in **Figure 13**.

The use of BOB system will get benefit to obtain the lubricating oil feed rate depending on variable BN characteristic. And then, it will increase the lubricity of lubricating oil for main diesel engines in case of using low sulphur content fuel oil onboards.

In a result, it is recommended for using the BN40-BN70 for cylinder liner lubrication oil at feed rate of large bore (**Figure 14**). The selection of appropriate lubrication oil depends on the low sulphur content in marine fuel.

4.2 To equip the cooler in the fuel oil system

The fuel oil viscosity is very important because it decides the ignition quality of fuel oil in diesel engine combustion chamber. Since the main engine must change-over to low sulphur fuel oil when the ship sails into the emission control areas (ECAs) with low viscosity. So, the best method that has solved this problem is the cooler in the fuel oil system.

It is necessary to instant cooler in the fuel oil system in order to maintain the required viscosity at the engine inlet fuel oil (**Figure 15**).

On the other hand, the hydrodynamic characteristics of fuel oil are completely dependent on the fuel oil temperature and fuel oil viscosity. The fuel oil system contains supporting equipment such as pumps (transfer pump, supply pump, booter pump, fuel oil pump, etc.), filters, heaters and coolers. So it is necessary to concern

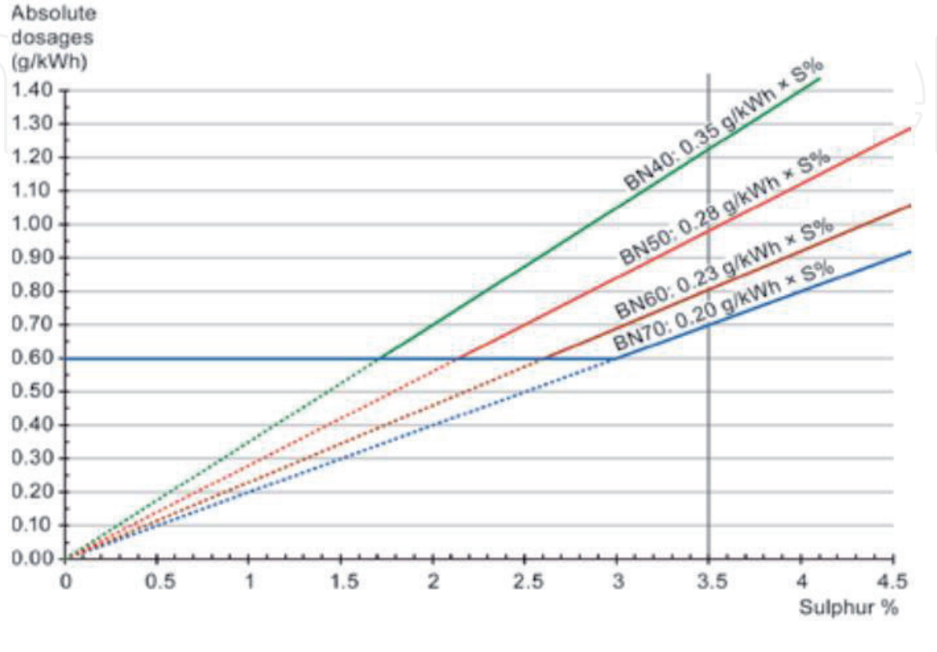

Figure 14.
Use of BN40, BN50, BN60 and BN70 for cylinder liner lubrication oil.

about the fuel oil viscosity. In this chapter, it describes the depend between the fuel oil viscosity and temperature in **Figure 16**. It is useful to ensure the appropriate temperature of fuel oil flows in the system.

The horizontal axis shows the fuel viscosity in cSt. Its value is taken from the bunker analysis report. In the case if the temperature of the MGO (marine gas oil) is below the lower blue curve at engine inlet, the viscosity must be above 3 cSt.

Furthermore, the black thick line shows the viscosity at reference condition at 40°C according to ISO 8217. Minimum viscosity for marine distillate DMX, DMA, DMB and DMZ are indicated.

Moreover, there are a lot of factors that influence the viscosity tolerance during the engine operation during of the time from the start point to the normal operation. These include engine condition and maintenance, fuel pump wear, engine

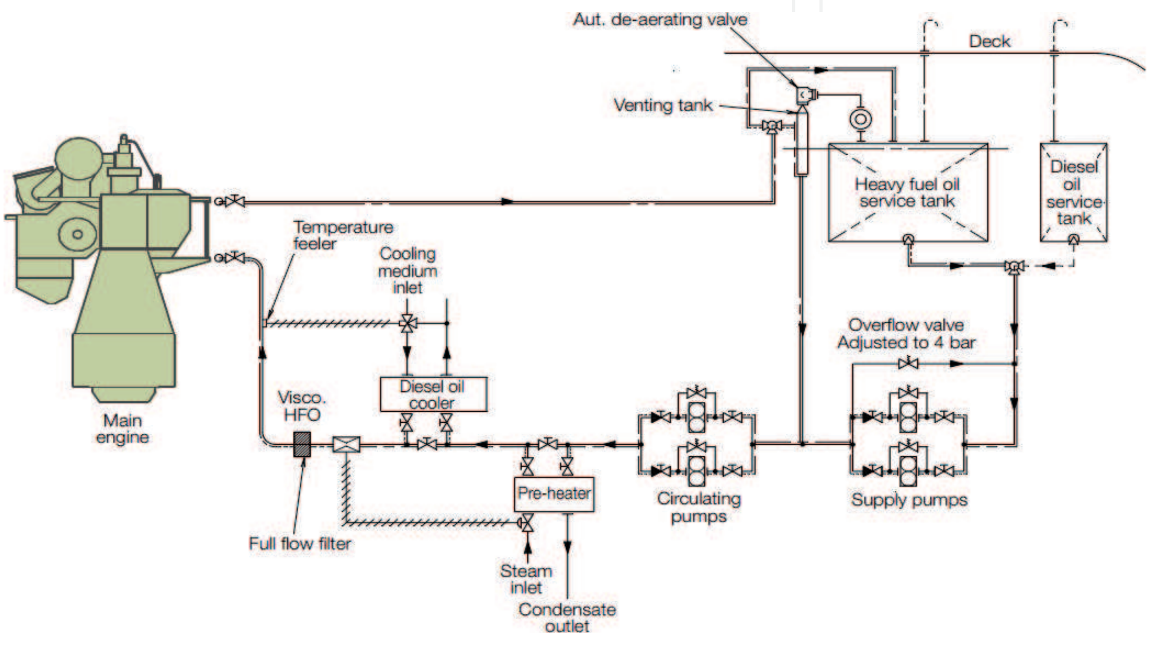

Figure 15.
Fuel oil system with fuel oil cooler.

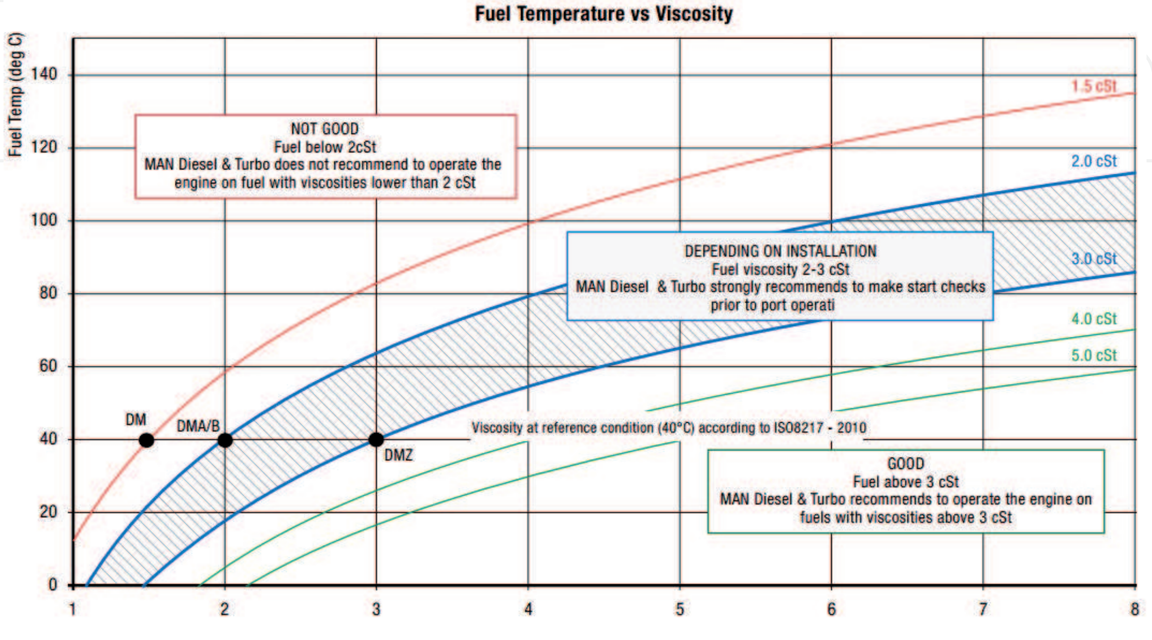

Figure 16.
Fuel oil temperature and viscosity [9].

pump wear, engine adjustment, actual fuel temperature in the fuel system, human factor, etc.

The effective operation plays an important role to maintain in good condition for devices and equipment in the fuel oil system. The makers of marine diesel engine (MAN B&W) recommend to operate the engine with viscosity of fuel oil above 3 cSt when using the low sulphur content fuel oil.

4.3 Lubricity-improvement additive for low sulphur diesel oil

The use of low sulphur content fuel oil will be applied widely for all ships operate outside the emission control areas (ECAs) from 2020 with no more of 0.50% m/m. This regulation will impact positively on the environment due to the reduction of sulphur dioxide (SO_2) emissions from engine exhaust gas. However, there will be a lack of lubrication oil. Its effect includes abnormal friction and operational defects, crucial parts of engines such as the fuel-supply pumps and fuel-injection pumps. As a result, the additives for low sulphur diesel oil are used in order to improve the lubricity of low sulphur marine gas oils with aims in keeping the safe vessel operations as well as protecting the environment.

Yunic 700LS is used in order to improve the lubricity for low sulphur marine gas oil (LSMGO) and low sulphur marine diesel oil (LSMDO) with standard dosing rate of 1/2500 (**Figure 17**). Its effect is addressed to prevent the abnormal wear and stick the fuel injection pump and fuel pump of marine diesel engine by the low lubricity of fuel oil. There are lots of other similar products which are used for increasing the lubricity ability of low sulphur diesel oil. The comparison between other products is showed in **Table 6**.

In addition, the blending Yunic 700LS into the low sulphur, the low lubricity ability of marine gas oils (MGO) was verified through an HFRR (High Frequency Reciprocating Rig) test (**Figure 18**). The HFRR is currently approved and then it is a standard index for evaluating lubricative ability of low sulphur fuel oil.

Figure 17.
Yunic 700LS.

Products	Advantages	Inconvenients
Yunic 700LS	• Improve the lubricity of low sulphur fuel oil • Prevent the stick phenomenon of fuel oil injection pumps	• Disable to prevent the emulsion phenomenon • Disable to prevent the sludge dispersion of low sulphur heavy fuel oil • Lower price than Yunic 750 LS-F
Yunic 300	Separate the water out of oil from emulsion phenomenon	Disable to increase the lubricity ability of low sulphur fuel oil
Yunic 555D	• Increase the sludge dispersion of low sulphur heavy fuel oil • Improve the combustion process of diesel engine when using low sulphur fuel oil	Disable to increase the lubricity ability of low sulphur fuel oil
Yunic 650-II	• Increase the sludge dispersion of low suphur fuel oil • Increase the melting point of ash factor of low sulphur fuel oil	Disable to increase the lubricity ability of low sulphur fuel oil
Yunic 600S-II	• Increase the melting point of ash factor of low sulphur fuel oil • Decrease the gas leakage phenomenon from exhaust valve of diesel engine	Disable to increase the lubricity ability of low sulphur fuel oil
Yunic 600SX	Prevent the slag formation with high content of vanadium of low sulphur fuel oil	• Disable to increase the lubricity ability of low sulphur fuel oil • Normally used for marine boiler
Yunic 750LS-F	• Increase the lubricity ability of low sulphur fuel oil • Prevent the mould sludge of fuel oil	• Disable to prevent the emulsion phenomenon • Disable to prevent the sludge dispersion of low sulphur heavy fuel oil

Table 6.
The comparison between same other products.

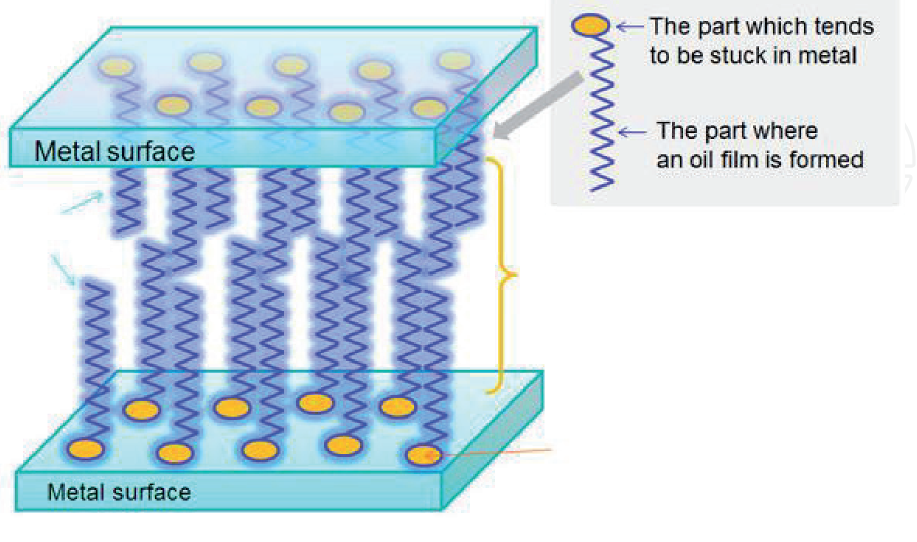

Figure 18.
High Frequency Reciprocating Rig (HFRR) test method.

In particular, the HFRR uses a ball in which a load is applied. Then, the ball will reciprocate on a metal surface immersed in the test of fuel oil. Finally, the size of the scars created on the ball is used to assess the lubricative ability of fuel oil.

In HFRR test, the lubricity indexes of light fuel oil are tested, the wear scar diameter of low sulphur fuel oil is about 600 μm. Addition of 200 pm with 1/5000 is standard addition rate of Yunic 700LS, the wear scar diameter is reduced to 460 μm or less, which is the specification recommended by engine manufacturers (**Figure 19**).

So, the engine manufacturers suggest using with HFRR wear scar diameter of 460–520 μm or less. In reality, the use of fuel oil has a lower lubricity that will lead to the corrosion of fuel injection pump and fuel pump of main diesel engine on ships.

4.4 Alpha adaptive cylinder-oil control (alpha ACC)

The Alpha Lubricator System is available for all MAN B&W MC/MC-C two-stroke diesel engines (**Figure 20**) [16].

The Alpha Lubricator System has an algorithm controlling cylinder oil dosage proportional to the sulphur content in the fuel. And, this algorithm is considered as Alpha Adaptive Cylinder-oil Control (Alpha ACC).

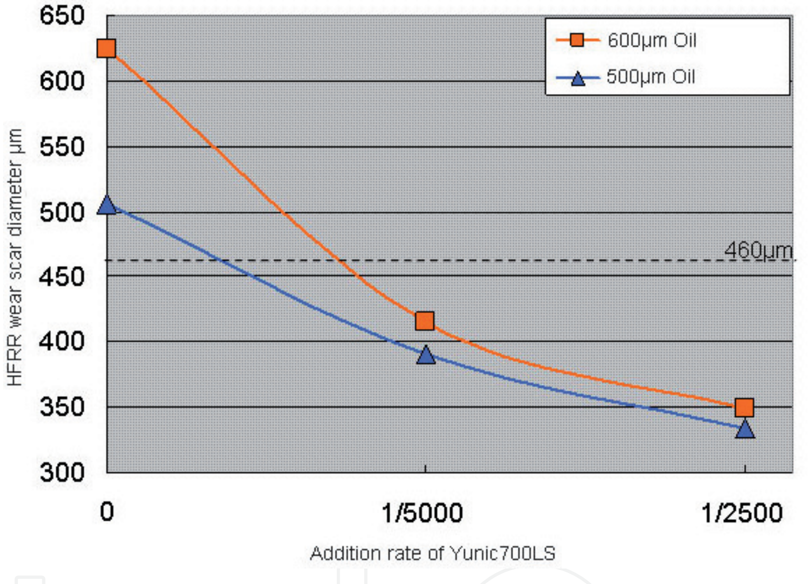

Figure 19.
Relationship of addition rate of Yunic 700LS and HFRR.

Figure 20.
Alpha lubricator system.

The advantage of Alpha Adaptive Cylinder-oil Control (Alpha ACC) in field of saving cylinder oil then a large scale testing programme is in progress on MAN B&W MC/MC-C type engines in service for a number of owners. In addition, to save the cylinder oil consumption will protect the environment from impacting on ship operation by Alpha Lubricator System.

The testing programme includes large bore engines for both container ships (K-MC/MC-C) and for VLCC propulsion (S-MC/MC-C), as well as small and medium bore MC/MC-C engines [16].

The cylinder oil dosage is proposed to an amount of sulphur content percentage in fuel oil. The cylinder oil dosage shall be proportional to the sulphur percentage in the fuel oil in **Figure 21**. On the other hand, the cylinder oil dosage shall be

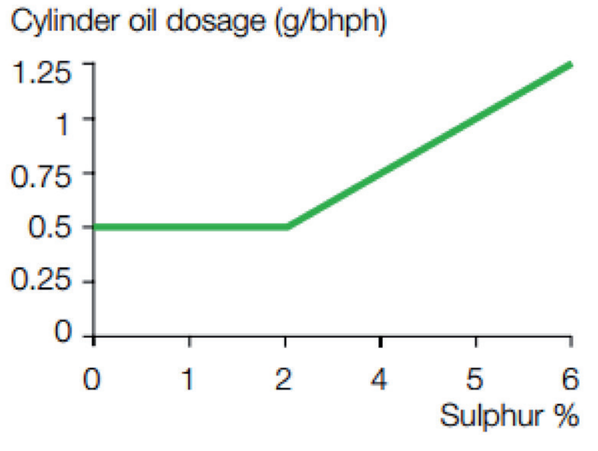

Figure 21.
Cylinder oil dosage versus sulphur percentage in the fuel oil.

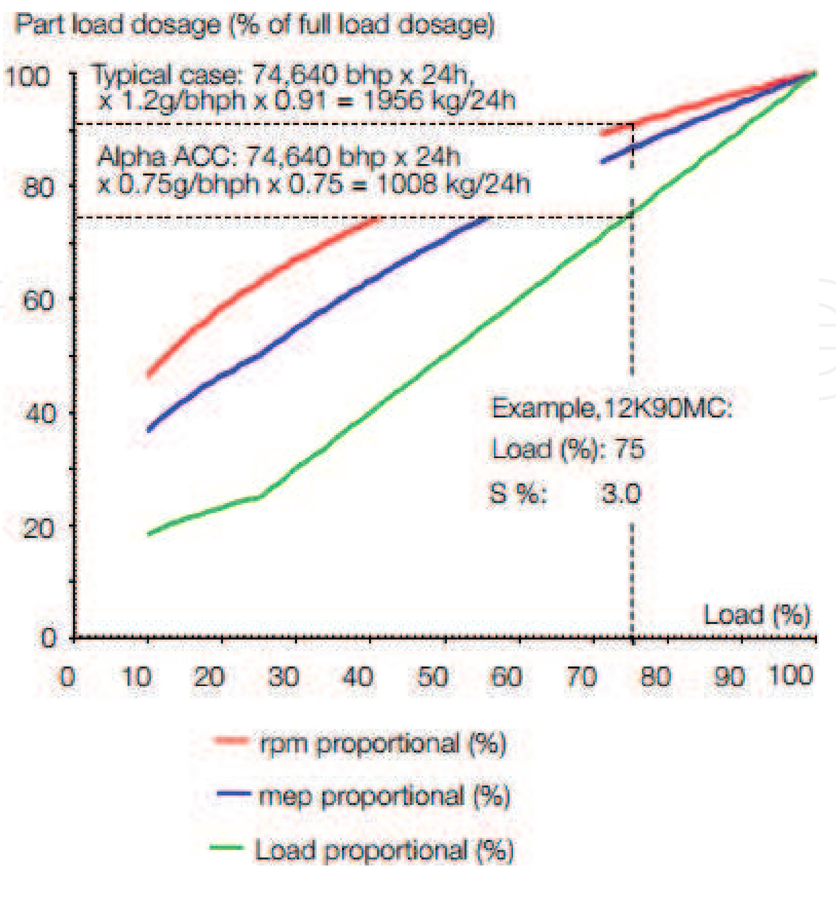

Figure 22.
Load-proportional cylinder oil dosage is used by alpha ACC.

proportional to the engine load like this amount of fuel admitted into the cylinders. This one will decide an optimal cylinder oil dosage with sulphur content in the fuel oil admitted into the cylinders.

Furthermore, it is very important to determine the cylinder oil dosage admitted into the cylinder line in aims with saving amount of cylinder oil following the sulphur content percentage in fuel oil used.

In **Figure 22**, the control of cylinder oil dosage proportional to the engine load together with revolution per minute (rpm)-proportional and mep-proportional lubrication. In case of part load, load-proportional cylinder oil dosage will provide large cost saving and reduce environmental pollution due to excessive lubrication. Additionally, if it is below 25% load, the load-proportional lubrication will stop and rpm-proportional lubrication will take over.

5. Conclusion

In this chapter, the new regulations for sea environment protection have been introduced through IMO and MARPOL 73/78 for all vessels that operate on special areas (ECAs). Especially, the IMO decision of 0.50% m/m sulphur content limit in marine fuel oil after 2020 is definite and no further decision till the date has happened. So, some methods have been represented including the use of an appropriate lubrication oil quality for diesel engine on ships, installing the cooler in fuel oil system, improving the additive for low sulphur fuel oil and using the alpha adaptive cylinder oil control (Alpha ACC). This research will be meaningful solutions for all ships to comply with the new regulations when sailing on ECAs.

Acknowledgements

The author wants to thank Chief Engineer, MSc, Thuy.H.V of M/V NSU JUSTICE, who gave meaningful suggestion to complete this study. Furthermore, I acknowledge all colleagues at Reliability Engineering Institute and Key Laboratory of Marine Power Engineering & Technology (Ministry of Transportation), School of Energy and Power Engineering, Wuhan University of Technology, 430063 Wuhan, P.R. China. Finally, I would like to thank reviewers for valuable comments for revised manuscript.

Nomenclature

Alpha ACC	alpha adaptive cylinder oil control
BMW	Ballast Water Management
BN/TBN	Base Number/Total Base Number
CARB	California Air Resources Board
ECAs	emission control areas
EPA	Environmental Protection Agency
HSFO	high sulphur fuel oil
HFO	heavy fuel oil
HFRR	High Frequency Reciprocating Rig
HDS	hydro-desulphurization
IMO	International Maritime Organisation
ISO	International Standard Organisation
IFO	Intermediate Fuel Oil

GHG	Greenhouse Gas
LSFO	low sulphur fuel oil
LPG	liquefied petroleum gas
LNG	liquefied natural gas
MEPC	Marine Environment Protection Committee
MGO	marine gas oil
MDO	marine diesel oil
MARPOL 73/78	International Convention for the Prevention of Pollution from Ships
PM	particulate matter
RPM	revolution per minute
SFOC	specific fuel oil consumption
ULSFO	ultra low sulphur fuel oil

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