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Contributions to the study of service characteristics of marine fuels

L Ali[1], P Somoiag[2] and B Ali[3]

[1]Ph.D. attendee Eng, Bureau Veritas Romania, [2]Professor Ph.D. Eng., Military Technical Academy, [3]Professor Ph.D. Eng.,"Mircea cel Batran" Naval Academy

[1] ali.beazit@yahoo.com [2] pamfils@yahoo.com [3]levent.ali86@gmail.com

Abstract: Since the beginning, development of marine diesel engines was turned towards obtaining a low fuel consumption and the result has reflected in engines construction: increased bore and cylinder liner diameter, higher working pressures and lower piston speeds. Similar improvements have taken place in the supercharging system, innovative fuel injection technologies and changes in combustion pressures. Nowadays, the trend of development has changed, the concept of reducing NOx and SOx emissions became a priority in order to meet the limits imposed by international organizations. As a consequence, a series of changes in operating mode of marine engines was noticed but also several innovations appeared in the construction and development of marine engines.

1. Introduction

Stricter environmental rules are conducting to big changes in the shipping industry. Many shipping companies are gradually looking abandoning the use of polluting fuels such as residual and distillate fuels in favor of cleaner and environmental friendly fuels. Due to lack of infrastructure of biodiesels and LNG, the transition to new types of engines and fuels will go through options of reducing emission poluants by converting or retrofitting the actual engines.

Main engine cylinder together with working fluid is representing a thermodynamical system which can be described by the first principle of thermodynamics. The energy provided inside the cylinder as fuel is processed through combustion in energy flow, thermal energy transferred to cylinder walls and exhaust gasses energy. The energy transferred to cylinder walls is absorbed by the workign medium contained in the cylinder coolign system, cylinder cover and injectors. The energy of exhaust gasses is transferred to turbocharger and used for steam production in exhaust gas boiler. Mechanical work of piston is transferred through crankshaft and stern tube to propeller, a percentage being lost due to friction, but also used for auxiliary systems of the main engine.

Energy balance of the cylinder can be written under following form:

$$\frac{dU}{d\tau} = \frac{dQ_f}{d\tau} - \frac{dQ_c}{d\tau} - \mathrm{p} \cdot \frac{dV}{d\tau} + \frac{dH_d}{d\tau} - \frac{dH_{ex}}{d\tau} \quad , \tag{1.1}$$

where:

$$\frac{dU}{d\tau} = \dot{U}(\tau) \text{ – cylinder internal energy,}$$

$$\frac{dQ_f}{d\tau} = \dot{Q}_f\,(\tau) \text{ – heat resulted by the injected fuel inside the cylinder,}$$

$$\frac{dQ_c}{d\tau} = \dot{Q}_c\,(\tau) \text{ – lost heat through cylinder walls,}$$

$$p \cdot \frac{dV}{d\tau} = N_i\ (\tau)$$ – mechanical work produced in cylinder,

$$\frac{dH_d}{d\tau} = \dot{H_d}\ (\tau)$$ – used entalpy,

$$\frac{dH_{ex}}{d\tau} = \dot{H_{ex}}(\tau)$$ – resulted entalpy.

Taking into consideration internal energy of the workign medium as a function of temperature T and chemical content of the fuel F:

$$\frac{dU}{d\tau} = \frac{\vartheta U}{\vartheta T} \cdot \frac{dT}{d\tau} + \frac{\vartheta U}{\vartheta F} \cdot \frac{dF}{d\tau}, \quad (1.2)$$

where:

F – ratio between mass of fuel m_{fb} and mass of air m_a:

$$F = \frac{m_{fb}}{m_a},\ m = m_a + m_{fb}$$

$C_V = \frac{\vartheta U}{\vartheta T}$ (specific heat of the fuel in J/Kg K).

The equation of energy balance will be re-written under following form:

$$\frac{dT}{d\tau} = \frac{1}{m\, C_V}\left(\frac{dQ_f}{d\tau} - \frac{dQ_c}{d\tau} - p\ \frac{dV}{d\tau} + h_d\ \frac{d\, m_d}{d\tau} - h_{ex}\ \frac{d\, m_{ex}}{d\tau} - u\frac{dm}{d\tau} - m\frac{\vartheta U}{\vartheta F}\ \frac{dF}{d\tau}\right) \quad (1.3)$$

During the admission of a mass of air ($\frac{dm_d}{d\tau}$) necessary for combustion, the gas is entering the cylinder with a specific entalpy h_d, resulting in change of the chemical content of the fuel and its internal energy:

$\frac{dQ_f}{d\tau} = 0$; $\frac{d\, m_{ex}}{d\tau} = 0$; $\frac{dF}{d\tau} = -\ \frac{(F+1)F}{M}\ \frac{dm}{d\tau}$, there by energy balance becomes:

$$\frac{dT}{d\tau} = \frac{1}{m\, C_V}\left(-\frac{dQ_c}{d\tau} - p\ \frac{dV}{d\tau} + h_d\ \frac{d\, m_d}{d\tau} - u\frac{dm}{d\tau} - m\frac{\vartheta U}{\vartheta F}\ \frac{dF}{d\tau}\right) \quad (1.4)$$

When the air is blown out from the cylinder, energy balance will be expressed as:

$$\frac{dT}{d\tau} = \frac{1}{m\, C_V}\left(-\frac{dQ_c}{d\tau} - p\ \frac{dV}{d\tau} - h\ \frac{d\, m_d}{d\tau} - u\frac{dm}{d\tau}\right) \quad (1.5)$$

Thereby energy balance of the engine will be:

$\dot{Q}_d = N_i + \dot{Q}_c + \dot{Q}_{ex} + \dot{U}$, where:

$\dot{Q}_d$ – internal energy of the cylinder;

N_i – internal mechanical work of the cylinder;

$\dot{Q}_c$ – heat flow transferred to cylinder walls;

$\dot{Q}_{ex}$ – exhaust gasses energy;

U – internal energy of working fluid.

2. Requirements for bunkering onboard vessels

Nowadays bunkering may take place alongside, at anchor by barge or even offshore and the posibilities are various as well: bunker barge, terminal, truck or ship to ship transfer, but the procedures are similar, this opeation being considered of high risk due to pollution, accidents, financial penalties.

Before starting the operation there are several items to be taken into consideration and to be prepared for a succesfull bunkering operation:

a. Bunker plan should be studied and made available to engine crew involved in bunkering operation. The bunker plan includes fuel system diagram on board and the bunker tanks sounding tables.

b. Communication has to be provided in an effective way between bunker provided and ship. Apart from VHF radios, a clear way of emergencu stop of bunkering operations is to be agreed between both parties and usually this is an emergency stop button or signal raised by officer in charge.

c. Pollution by risk of spill is highly expected during these operations. This can be caused by multiple reasons: failure in the bunker pipeline, damaged gaskets, accidental handling of bunker valves, overflow and even incorrect mooring. With this scope, each ship is fitted with a SOPEP plan with its relevant equipment which is always available to minimize the risk of oil spill during bunkering. SOPEP plan is approved by classification society and has a minimum items such as: absorbent rolls, pads and granules, brooms, mops, scoops, empty recipients, portable pumps, oil spill dispersants. This items are stowed in an easily and available place, clearly marked.

An important aspect of bunkering is sampling of fuel and constitutes an evidence in case an engine breakdown or damage occurs later on. This is achieved by a drip type sampler which is dripping continuously during the operation in order to ensure a good representative sample for laboratory analysis. There are necessary three samples which are handed to various authorities: laboratory, onboard retention, supplier records. MARPOL requires that sample as to be stored on board for at least 12 months.

Figure 1 – Drip type fuel bunker sampler [1]

The scope of further laboratory analysis is to confirm that fuel is meeting purchase specifications, but also to warn in case of high contamination levels in order for engineers to adopt counter-measures. Fuel analysis results will contain important information regarding:

- fuel density: used to confirm quality of fuel delivered and estimate combustion performance through CCAI (Calculated Carbon Aromaticity Index);
- compatibility: giving information regarding chemical stability of fuel and posibility of belnding with existent fuel on board or other types of fuels;
- water content: preventing any failure of machinery.
- aluminium and silicon contents: these are highly abrasive components which can conduct to wear of engine and are difficult to remove through separators onboard.

3. Fuel suppliers – standards, methodology

Different purposes and applications of fuels and environmental problems with regards to air pollution have led to different specifications of fuels. These are more stringent than first requirements ever launched for fuel "Bunker C no 6". The scope of standardization is to define the requirements of marine fuels used for engines and boilers before usage. This standards is also used as guide for engine designers, ship owners of class societies and is revised periodically due to continuous changes of maritime industry. General requirements of ISO 8217 are:

- Fuels must met the characteristics illustrated in standard and tested according with specified methods;
- Fuel must be a homogenous blend of hydrocarbons resulted from refining of petroleum. The fuel will not include inorganic acids or used lubricating oils;
- Components which are not acceptable for use in maritime applications will not be included;
- Any bio-derivated materials are not accepted unless it respects the minimum specified values from standard.

Table 1 – Extract from ISO 8217 regarding quality of marine fuels [14]

		Fuel type						
Limit	Parameter	DMX	DMA	DFA	DMZ	DFZ	DMB	DFB
Max	Viscosity at 40°C (mm^2/s)	5.500	6.000		6.000		11.00	
Min	Viscosity at 40°C (mm^2/s)	1.400	2.000		3.000		2.000	
Max	Residual carbon (% m/m)	0.3	0.3		0.3		-	
Max	Density at 15°C (kg/m^3)	-	890.0		890.0		900.0	
Max	Sulfur (% m/m)	1.00	1.00		1.00		1.50	
Max	Water content (% V/V)	-	-		-		0.3	
Max	Ash content (% m/m)	0.010	0.010		0.010		0.010	
Min	Ignition point (°C)	43	60		60		60	
Max	Pour point-winter (°C)	-	-6		-6		0	
Max	Pour point-summer(°C)	-	0		0		6	
Min	Cetanic index	45	40		40		35	
Max	Acid number (mgKOH/g)	0.5	0.5		0.5		0.5	
Max	Stability at oxidation (g/m3)	25	25		25		25	
Max	Methyl ester	-	-	7.0	-	7.0	-	7.0
Max	Lubricity	530	520		520		520	
Max	Hydrogen sulfate (mg/kg)	2.00	2.00		2.00		2.00	

As demand for natural gas as fuel for ships has increased dramatically, International Organization for Standardization released first version of ISO20519 – specification for bunkering of liquefied natural has fuelled ships in February 2017. This will help vessel operators to provide the safety standards but also contains information regarding fuel quality.

ISO 20519 is containing requirements not covered by International Gas Code and it is divided in following sections:

- Liquid and vapor transfer systems
- Operational procedures
- LNG bunkering notes
- Training and qualification for bunkering personnel
- Requirements for LNG facilities

Since the use of LNG as fuel is new, the standard will be updated continuously to include lessons learned during experience and according with technology updates, this standard being produced at request of IMO.

4. Regulations regarding utilization of fuels onboard vessels

Marine engines are very much depending on the attention given at treatment of fuel before entering the engine, especially to foreign particles or inorganic material which can have an abrasive effect on engine components. Settling tank is the first equipment used for separating through gravitation of the marine fuel. The separation is much more efficient when fuel remains longer or at least more than 24 hours. Before transferring of the product into service tank, water and sediments deposited on the bottom of the tank are drained. Classification societies requirements regarding design of settling tanks are listed below:

- heating capacity is to be sufficient to increase temperature of the fuel up to 70°C within 12 hours;
- as for any other tank on board vessels, shall be equipped with acceptable means for drainage, opening and ventilation;
- for safety reasons, suction outlets must be placed with 500 mm above bottom.

Fuel separators are usually of centrifugal type with the scope of separating components with high specific gravity such as water, foreign particles, sludge or bilge. Separators have automated cleaning intervals and their effective design and maintenance will be the key in providing correct protection against harmful substances contained in the fuel.

5. Products resulted after combustion

Emissions from marine diesel engines are composed mainly from nitrogen, oxygen, carbon dioxide and water vapors with small quantities of carbon monoxide, sulfur oxides and unreacted hydrocarbons. Nitrogen and oxygen constitutes principal components of exhaust gases from an engine. Nitrogen is also part of admission air in proportion of 78% and it stays unreacted on large scale in the combustion process. Oxygen representing 21% from the admission air will be partially converted in the combustion process, basically the oxygen as component of exhaust gasses is highly dependent on excess air of the engine.

Nitrogen oxides are the results of nitrogen oxidizing in the combustion air or oxidation of organic nitrogen in the fuel. Depending on the type of fuel, organic nitrogen can explain the proportion of total emissions of NO_x, particularly for engines operation on heavy fuel oil.

Carbon dioxide and water vapors are formed in all combustion processes, partial or complete, and its production is function of quantity of burned fuel, engine power, efficiency of installation and elementary composition of burned fuel.

Sulfur oxides are derived directly from quantity of sulfur contained in the fuel. In the combustion chamber sulfur is oxidized resulting sulfur dioxide and in small quantities sulfur trioxide. Also utilization of alkaline lubricating oils for protection of engine components from acid corrosion will convert an important proportion of SOx produced in the combustion process in calcium sulfate.

Carbon monoxide is a product of incomplete combustion of the fuel and it is highly dependent on the excess air, temperature of combustion and uniformity of the air/fuel mix in the combustion chamber.

Mechanical particles are of carbon compound and can be of two types: ash and particles containing sulfates and condensed hydrocarbons. Many studies showed that ash have an adverse effect on human health and it is an important factor contributing at global warming.

6. Procedures for reducing pollutant emissions

The method by which water is added in fuel, named water emulsion in fuel (WIF), before fuel injection into combustion chamber, is an efficient method of reduction combustion temperature, suppressing NOx formation. This method has been tested on two stroke propulsion engines using residual fuels which inherently emulsifies due to different physical properties. On the other hand, distilled fuels, which became more utilized in order to comply with new IMO regulations, require stable emulsions for this emulsify procedure to become efficient. In this emission reduction procedure, water is added in fuel system and through mechanical methods it is created a homogenous mixture. When this blend is injected, the heat necessary for heating the liquid at boiling point, the evaporation and overheating of water vapors are dropping significantly and as a results NOx formation is decreased.

In order to obtain an optimum spray in the combustion chamber it is recommended that water drops in the fuel, after emulsification, to be as small as possible. However if the engine operates using distilled fuel it is necessary to add additives in order to stabilize the emulsion. In the figure below it is represented a version of converted fuel system where a homogenizer was added which can be mechanical or ultrasonic.

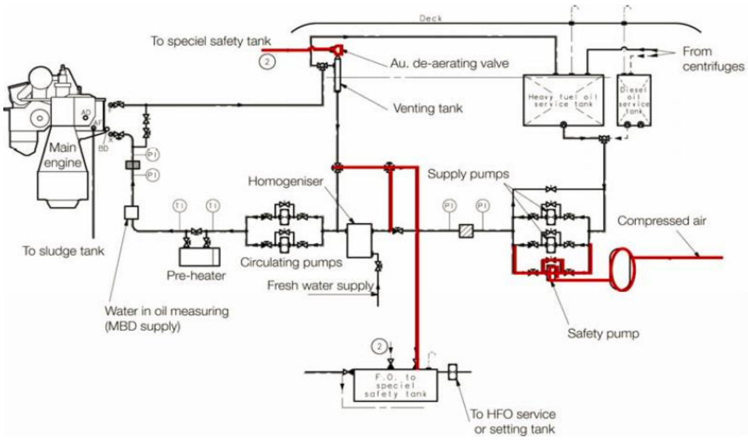

Figure 2 – Retrofit fuel installation with homogenizer for water in fuel emulsion [14]

Adding water in the residual fuel will raise viscosity but in order to maintain viscosity level between 10-15 cSt at at engine fuel admission will be necessary raising the temperature at more than 150°C which is standard today. The water used for emulsification must be de-mineralized in order to respect maximum levels of NaCl from combustible, because sodium can react chemically with vanadium from fuel and the deposits created are accumulating on the exhaust valve resulting in blockage or leaks of the valve. According to diagram above, a safety pump is installed with the scope of keeping the fuel feeding system pressurized in case of a black-out or malfunction of the system. The homogenizer was already tested on several MAN engines.

The effect of water content on NO_x emissions is presented in figure 3 below and it can be noticed that NO_x emission level is inversely proportional with the volume of added water, recent studies showing a reduction of 1% NO_x at 1% volume of added water.

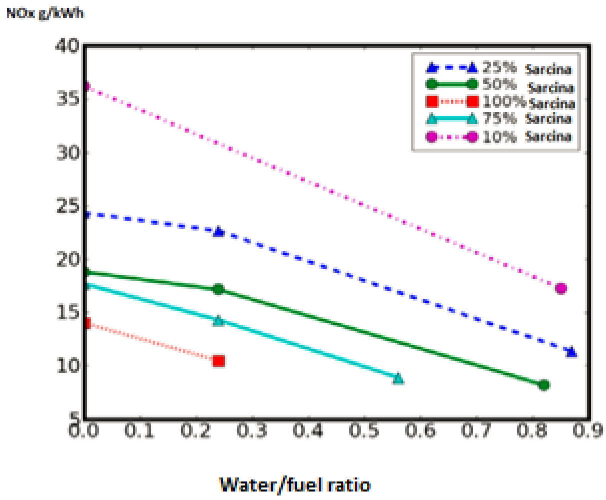

Figure 3 – Effect of water content added in fuel [2]

When it comes to CO2 emissions, these are decreasing rapidly when water is added in fuel, due to raising of air quantity in added water vapors, but also due to reduced burning temperature. (figure 4)

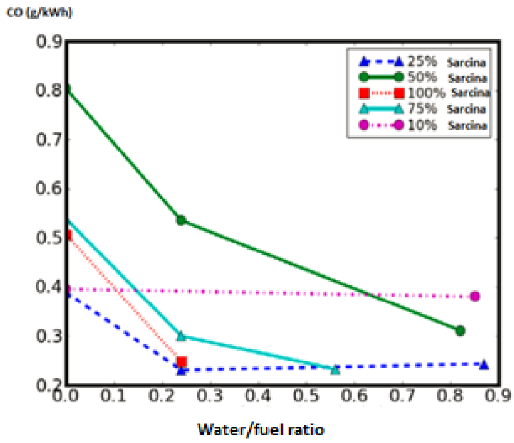

Figure 4 – Water in fuel reported to CO_2 emissions [2]

Conclusions

The impact of emissions coming from marine diesel engines on the environment is upraising every year. Different technological options are featured on the market with the scope of NO_x and SO_x emissions reduction. Nowadays, with the exception of SECA and ECA areas, which were regulated in 2005 and incorporated in MARPOL convention, regulations no 13 and 14, most of the ships are using marine heavy fuel oil with low sulfur content.

When it comes to sulfur emissions, the situation is quite clear, but the challenge is coming from international regulations imposed by IMO, this being the cause of chemical fog and acid rains which can be transported up to 20 kilometers on inland. NOx emissions are estimated at approximate 10millions tons per year, which is equivalent with 14% of NOx emissions worldwide. Sweden managed to develop its own tax system for emissions coming from ships, but also Sweden and Denmark established a new tax named "eco tax" based on quantity of emissions

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