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ScienceDirect

Procedia Engineering 134 (2016) 157 – 164

Procedia Engineering

www.elsevier.com/locate/procedia

9th International Scientific Conference Transbaltica 2015

Comparative Overview of Marine Fuel Quality on Diesel Engine Operation

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Abstract

Publication devoted to the problem of translation of ship propulsion plant to low-sulfur fuel grades regulated by new International Maritime Organization (IMO) standards. Study and optimization of the physicochemical properties of marine fuels are important components in the work in order to improve energy efficiency and reduce toxic emissions from marine diesel engines. In the article gives the comparative analysis of standards of marine fuels. Using mathematical modeling, established variational indicated process characteristics of the diesel engine by simulating engine work in a wide range of fuels. As the object of the study was used diesel fuel, residual fuel, ethanol, RME and LNG. The aim of this work is to assess the impact of a number of properties of the fuel, in particular elemental chemical composition and calorific value to the energy performance of the working process of the diesel engine. Assessment carried out for the two cases of the diesel engine: the same cycle fuel delivery and implementations of the same indicated work, which is estimated at indicated pressure. The simulation results show that under the conditions of equal cyclic fuel supply differences indicated efficiency for different fuel are in the range 0.04–5%.

Keywords: marine fuel; fuel properties; standards; mathematical model; diesel engine.

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1. Introduction

Currently as a prime mover the most widely used diesel internal combustion engines (ICE) because they are the most economical. Marine engine is a part of ships power plant. Distinguish the main ship engine (allows movement

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doi:10.1016/j.proeng.2016.01.055

of the vessel) and auxiliary (to drive electric generators, pumps, fans and so on). A wide range of exploited marine diesel engine requires appropriate justification and difference types investigated fuels.

On the vessels are applied a slow, medium and high speed diesel engines. Slow speed ICE is used as the main engines of various types of vessels; their specific fuel consumption 170 g/(kWh), frequency of rotational 60–350 rev/min. Medium speed engine is used primarily as the main engines of ships of medium size; their specific fuel consumption 190 g/(kWh), speed 350–750 rev/min. High speed internal combustion engines are mainly used as the main engines for small vessels, as well as auxiliary engines on ships of all types; their specific fuel consumption 200 g/(kWh) frequency of rotation in excess of 750 rev/min (Winter 2007; Stenin 2014).

There is a definite pattern: the higher the frequency of rotation of the crankshaft of engine, the higher the requirements for fuels. This is explained by the fact that with increasing of frequency of rotation, decreases the time during which must occurs mixture formation and fuel combustion processes (Pahomov et al. 2004).

For slow and medium speed diesel engines mainly used heavy fuels, with decreased quality requirements of viscosity and contamination compared with fuels used for high rotational speed diesel engine. Therefore, when applied heavy fuels, necessary to use additional fuel processing system, which provides cleaning and heating fuel before being fed into the feed tank (Corbett et al. 2003; Pahomov et al. 2004).

Marine oil fuels are divided into two classes:

- distillate fuels, composed of the light fractions, they are characterized by low values of viscosity in the range 2.5–14.0 cSt;
- heavy fuels, consisting of mixtures of heavy residual fractions, their viscosity lies in a wide range 30–700 cSt (Voznickij and Punda 2008).

Due to limited resources and the high cost of distillate fuels (it is 1.5–2 times exceed the cost of heavy fuels), diesel fuel is used mainly in cases where the engine and additional fuel system not adapted to run on heavy fuel oil. In the total of fuel consumption on ships diesel expenditure is 6–12% (Voznickij 2005).

Recently, proposed instead of oil fuel using alternative fuels. Options for alternative fuel mostly consist of liquefied natural gas (LNG) and, to a lesser extent, bio-fuels (EMSA, 2010). FAME (fatty acid methyl ester) known as biodiesel can be blended with fossil fuels. In “Bio-fuel trial on seagoing container vessel” project was testing FAME onboard the container vessel Maersk Kalmar, hence ascertaining the impact of biofuel in terms of storage, handling, health, impact on engine. It was found that biofuels showed promising results for further use (Andersen K. L. et al. 2011). Other related projects have demonstrated that existing engines can be modified to operate on biofuels (EMSA, 2010). But according to International Standards ISO 8217:2010 under the paragraph 5.4 the requirement for the first time for marine fuels imposes that “the fuel shall be free from bio-derived materials other than “de minimis” level of FAME (FAME shall be in accordance with the requirements of EN 14214)” (Kalligeros et al. 2011).

The considerable work accomplished in establishing marine fuel standards, which has been going on worldwide since 1978 is by now. ISO 8217 (Specifications of marine fuels) standard 1th edition were published in 1987. Each new edition brings new changes. For example, ISO 8217:2005 – max water content 0.5% from 1%, max sulfur content 4.5% from 5.0%, restriction of used lubrication oil (ULO) by setting max. limit for Zn, Ca and P, max ash level 0.15% from 0.2% (for some highly viscous grades) (1985 marine fuel Jones).

Changing of standards primarily related with more stringent environmental requirements. In the context of the article assesses the impact of changes in operating, economic and environmental performance of a diesel engine depending on fuel, for example, the transition to ISO 8217:2010.

ISO 8217:2010 has been significantly amended: it specifies 4 categories of distillate fuel, one of which is for diesel engines for emergency purposes, and 6 categories of residual fuel; RMA 10 grade was added (previous DMC grade), RMG and RMK grades were expanded to include additional viscosity grades, RMF and RMH grades were removed, sulfur limits were excluded from residual fuel limits, as these are controlled by statutory requirements, sulfur limits for distillate fuels were retained, ash limit values for residual fuels were reduced for many of the categories, vanadium limit for RMG 380 was increased from 300 ppm to 350 ppm, vanadium limits for other grades were reduced, but for RMB 30 where limit remained unchanged, aluminum and silicone (Al + Si) limits were reduced from 80 ppm to 60 ppm; the introduction of new characteristics: acid number, hydrogen sulfide, oxidation stability, lubricity (for samples with S < 0.05%), sodium, CCAI, level of FAME.

ISO 8217:2012 became available on 15th August 2012, in response to concerns for measuring H_2S content. Introduced test method, IP 570 (with Vapor Phase Processor) as the reference test method (Giannakouros 2012).

Other than the international standard, many countries have their own national standards. Mainly national standards differ little from ISO, for example, by GOST P 54299-2010 flash point should be ≥ 61 °C, when by ISO 8217 it is 60 °C.

Therefore, in terms of energy and environmental requirements at the international level (EPA, ES, MARPOL) and at the regional there is an important issue of toxic emissions and improvement of quality of fuels.

The first task of the research generated is to assess the impact of these changes on the performance of diesel engine indications.

2. MARPOL – International Convention for the Prevention of Pollution from Ships

The MARPOL Convention is the main international convention covering prevention of pollution of the marine environment by ships from operational or accidental causes. It is a combination of two treaties adopted in 1973 and 1978 respectively and updated by amendments through the years.

The International Convention for the Prevention of Pollution from Ships (MARPOL) was adopted on 2 November 1973 at IMO and covered pollution by oil, chemicals, harmful substances in packaged form, sewage and garbage. Annex VI, covering air pollution, was adopted in September 1997 (Peet 1992).

The regulations in this annex set limits on sulfur oxide and nitrogen oxide emissions from ship exhausts and prohibit deliberate emissions of ozone depleting substances.

Annex VI contains provisions allowing for special "SO_x Emission Control Areas" to be established with more stringent requirements for control on sulfur emissions. In these areas on year 2000, the sulfur content in fuel oil, used on board ships, was allowed to 1.5% m/m (MARPOL 2009).

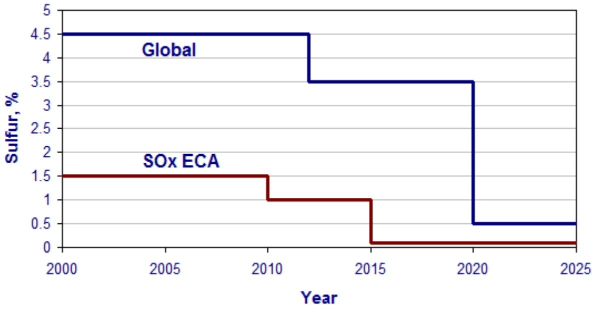

Fig. 1. MARPOL Annex VI sulfur content in fuel limits.

In October 2008 the International Maritime Organization (IMO) adopted a set of amendments to Annex VI of the MARPOL Convention, which among other things strengthened the requirements on the permitted sulfur levels in ships fuels. The amendments provide for a progressive reduction of the sulfur content of marine fuels. From 1 January 2012 the global sulfur cap was reduced, first to 3.50% (from 4.50%) and then, subject to a feasibility review to be completed no later than 2018, progressively to 0.50% from 1 January 2020 (or in 2025 at the latest). In "Sulfur Emission Control Areas" (SECAs) as from 1 July 2010, the maximum sulfur limit has been reduced to 1.00%, (from 1.50%), now (from 1 January 2015) the limit reduced to 0.10% (Vermeire M. 2012). The Baltic Sea is designated as a SO_x Emission Control area in the Protocol. MARPOL sulfur limits and dates show in figure 1 (Pedersen 2015).

3. Methodology of research

Fuel combustion in diesel engines – a complex set of processes that depend on the kinetic and diffusion phases, exactly: chemical reactions, internal energy, heat capacity, rheology, evaporation rate and others (Kavtaranze 2008). Factors affecting the combustion of fuel, determined mostly experimentally, in the planning of complex experiments, combining motor and laboratory researches. Another direction is computational research, but here it is necessary to use multi-zone mathematical models, which solved complex tasks: injection evaporation, combustion, heat transfer and other processes. On the first phase of this study solved the task of assessing the impact of elemental chemical composition of the fuel in the energy performance of indicated process. For this purpose it is sufficient to use a one-zone mathematical model, in which the modeling of the combustion of the fuel is carried out using heat release according I. I. Vibe law (Mollenhauer, Tschoeke 2010).

The model is based on a step by step solution of a of three equations system by angle of the crankshaft: conservation of mass, of energy and the state of the working fluid (Kavtaradze 2008; Merker et al. 2006).

The mass balance equation:

$$\frac{dm}{d\tau}=\frac{dm_{\mathrm{int}}}{d\tau}+\frac{dm_{inj}}{d\tau}-\frac{dm_{ex}}{d\tau}\ , \tag{1}$$

where: m – total mass, kg; m_{int} – air intake mass, kg; m_{inj} – fuel injection mass, kg; m_{ex} – exhaust gas mass, kg; τ – time, s.

The energy balance equation:

$$\frac{dU}{d\tau}=\frac{dQ_f}{d\tau}-\frac{dQ_w}{dt}-p\frac{dV}{d\tau}+h_{\mathrm{int}}\frac{dm_{\mathrm{int}}}{d\tau}-h_{ex}\frac{dm_{ex}}{d\tau}\ , \tag{2}$$

where: U – internal energy, J; Q_f, Q_w – heat release and heat exchange, J; p – pressure, Pa; V – volume, m^3; h – specific enthalpy, J/kg.

State equation:

$$\frac{dp}{d\tau}=\frac{mR}{V}\frac{dT}{d\tau}+\frac{mT}{V}\frac{dR}{d\tau}+\frac{RT}{V}\frac{dm}{d\tau}-\frac{p}{V}\frac{dV}{d\tau}\ , \tag{3}$$

where: R – gas constant, J/(kgK); T – temperature, K.

The principle of the I. I. Vibe mathematical model is described in detail in the Vibe I. I. publication: “The new operating cycle of the engine. Combustion rate and duty cycle of the motion engines”. Based on this model the characteristic of heat release set by duration of combustion φ_{CD}, form factor m (Merker et al. 2006):

$$\frac{dQ_f}{d\varphi}=Q_{f,total}\,a(m+1)\left(\frac{\varphi-\varphi_{SOC}}{\varphi_{CD}}\right)^{m}\times e^{-a\left(\frac{\varphi-\varphi_{SOC}}{\varphi_{CD}}\right)^{m+1}}\ , \tag{4}$$

where: Q_f – heat release, J; a – Vibe heat release rate constant, equal 6.908; m – form factor; φ – current crank angle, °c.a.; φ_{SOC} – start of combustion crank angle, °c.a.; φ_{CD} – combustion duration, °c.a.

Use of the Vibe model allows estimating the impact of the elemental chemical composition in various forms of indicator process: fast combustion in the first kinetic phase, typical of obsolete old diesels, which still in service by now; in the case of intense heat release in the main diffuse phase, typical of modern transport diesel (Klein 2004).

Duration of combustion and form factor established experimentally. It should be emphasized that, in the presence of the experimental results is almost always possible to choose the values of m and φ_{CD}, can adequately simulate the combustion process on the basis of the Vibe law (Kavtaradze 2008).

Use in the work software system is the possibility of the set of elemental chemical composition of the fuel, thus, for fixed values of the Vibe parameters m and φ_{CD}. Model allows us to investigate the effect on the performance of the process, the change in internal energy, enthalpy and specific heat of the combustion products of various fuels.

CO_2 emissions are calculated according to the equation:

$$m_i(CO_2) = \frac{G_i \cdot C \cdot M(CO_2)}{M(C)} \text{ g/(kWh)}, \tag{5}$$

where: G_i – fuel consumption for obtaining useful work, g/(kWh); C – the carbon content in the fuel; M – molar mass of component, g/mol.

Table 1. Fuel elemental composition and net calorific value.

Fuel	Elemental composition					H_{Net}, kcal/kg
	C	H	O	S	N	
Diesel	0.870	0.128	0.00	0.001	0.0	10198.4
Residual fuel	0.860	0.105	0.00	0.035	0.0	9640
Ethanol	0.520	0.130	0.35	0.000	0.0	6500
RME	0.775	0.120	0.11	0.000	0.0	8956.5
LNG	0.751	0.250	0.00	0.000	0.0	12216.8

As the object of the study was used diesel fuel, residual fuel, ethanol, RME and become especially topical in recent years, including Lithuania, LNG. Elemental composition and calorific value of the fuels listed above are shown in Table 1.

4. Results of mathematical modelling

Assessment carried out for the two cases of the diesel engine: the same cycle fuel delivery and implementations of the same indicated work, which is estimated at indicated pressure.

For comparing the effects of different fuels on the workflow engine, at the same kinetics of combustion and engine characteristic, when the fuel cyclic portion is 0.18 g indicated combustion parameters was calculated (Table 2).

Table 2. Indicated combustion parameters, when $m = 0.1$; $\varphi = 50$.

Fuel	$m = 0.1$; $\varphi_{CD} = 50$				
	P_z, bar	T_z, K	p_{mi}, bar	η_i	G_i, g/(kWh)
Diesel	150.47	1946.8	10.22	0.5192	162.7
Residual fuel	147.34	1904.9	9.75	0.5239	170.5
Ethanol	124.06	1590.5	6.61	0.5269	251.5
RME	141.93	1831.8	9.05	0.5234	183.7
LNG	161.07	2088.1	11.84	0.5018	140.5

The table shows that the different elemental composition of fuels affect the characteristics of heat, this is due to the calorific value of fuel. With an increase in calorific value, decreases the amount of fuel required for useful work. Increase in the proportion of oxygen in the fuel leads to a reduction in calorific value, but also to reduce theoretically necessary amount of air. Hydrogen during combustion provides more heat than carbon, respectively, when a greater proportion of hydrogen in the fuel, the higher it's calorific value. However, parts of the engine are experiencing great tension due to the higher temperature and pressure. By increasing the heating value at 20% maximum pressure is increased by 7% and the temperature at 7.25%.

Different organizations work process from variations m and φ are shown in Table 3–5.

Seen from these tables that the m variation has greater influence on the maximum pressure and temperature, when φ_{CD} – on indicated pressure, efficiency and fuel consumption. When duration of combustion shorter, the efficiency is higher and when parameters of forms are getting higher the workflow become softer.

Table 3. Indicated combustion parameters, when $m = 0.1$; $\varphi = 110$.

Fuel	$m = 0.1$; $\varphi_{CD} = 110$				
	P_z, bar	T_z, K	p_{mi}, bar	η_i	G_i, g/(kWh)
Diesel	123.74	1690.2	9.90	0.5028	168.0
Residual fuel	121.51	1655.1	9.44	0.5073	176.1
Ethanol	106.00	1407.7	6.38	0.5088	260.4
RME	117.92	1597.7	8.76	0.5061	190.0
LNG	131.47	1810.9	11.47	0.4863	145.0

Table 4. Indicated combustion parameters, when $m = 1.3$; $\varphi = 50$.

Fuel	$m = 1.3$; $\varphi_{CD} = 50$				
	P_z, bar	T_z, K	p_{mi}, bar	η_i	G_i, g/(kWh)
Diesel	110.15	1749.7	10.23	0.5196	162.5
Residual fuel	108.17	1709.7	9.76	0.5243	170.4
Ethanol	95.04	1422.6	6.60	0.5261	251.9
RME	105.06	1643.2	9.05	0.5234	183.7
LNG	117.08	1885.6	11.86	0.5028	140.2

Table 5. Indicated combustion parameters, when $m = 1.3$; $\varphi = 110$.

Fuel	$m = 1.3$; $\varphi_{CD} = 110$				
	P_z, bar	T_z, K	p_{mi}, bar	η_i	G_i, g/(kWh)
Diesel	80.32	1367.1	8.26	0.4196	201.3
Residual fuel	80.09	1330.1	7.88	0.4230	211.2
Ethanol	75.70	1083.5	5.31	0.4232	313.1
RME	79.75	1273.5	7.30	0.4221	227.8
LNG	81.22	1494.5	9.59	0.4066	173.4

The simulation results show that under the conditions of equal cyclic fuel supply differences indicated efficiency for different fuel are in the range 0.04–5%. Interesting to note that the differences indicated efficiency for an inefficient process with lengthy heat release $m = 1.3$, $\varphi_{CD} = 110$ is reduced to 4%. Indicated efficiency has the greatest value for ethanol, the lowest for LNG. Given trend seen for all combinations of form factor and duration of combustion. However, a significant difference is observed in the indicated power of various fuels due to lower calorific value of ethanol received less power. In comparison with a diesel, indicated power, when using ethanol, decreases by 35%.

To solve practical problems related to the operation of the engine is more interesting second case of study – the achievement of the same indicated power. To perform the similar efficient work for different fuel types, the cylinder cyclic fuel portion has been changed respectively for the used fuels. Also, according to Equation (1) are estimated CO_2 emissions. Data are presented in Table 6.

The best η_i is obtained for heavy fuel – 0.5272, while for ethanol 1.7% lower – 0.5179. The table shows that the least CO_2 is released from LNG, not so environmentally friendly fuel – residual fuel, at 1 kWh produced 534.49 g of CO_2, as well as due to the presence of sulfur in the fuel, during combustion SO_2 is formed. The use of LNG released almost 2 times less CO_2 than from residual fuel, when the η_i lower 2.5%.

Maximum pressure and temperature at identical indicated power for different fuels are approximately at the same level. Hereby, the results of the research show that even with the same heat dissipation characteristic differences in chemical composition leads to a change in indicated efficiency of up to 5%.

Further research is planned simulation engine indicator process using a model of a higher level of reproducing the injection parameters, evaporation, and the foundations of the kinetics of fuel combustion.

Table 6. Workflow parameters when p_{mi} = 10.32 bar.

Fuel	$m = 0.5$; $\varphi_{CD} = 50$						
	P_z, bar	T_z, K	p_{mi}, bar	η_i	G_i, g/(kWh)	Fuel c. p., g	CO_2, g/(kWh)
Diesel	135.94	1861.0	10.32	0.5244	161.0	0.1800	513.59
Residual fuel	136.08	1861.3	10.32	0.5272	169.5	0.1892	534.49
Ethanol	135.28	1824.4	10.32	0.5179	255.8	0.2858	487.73
RME	135.81	1852.7	10.32	0.5237	183.6	0.2050	521.73
LNG	135.37	1857.2	10.32	0.5142	100.8	0.1530	277.38

5. Conclusions

1. Study and optimization of the physicochemical properties of marine fuels are important components in the work in order to improve energy efficiency and reduce toxic emissions from marine diesel engines. Analysis shows that the different elemental composition affects the fuel calorific value and consequently the operating parameters of the engine.
2. When duration of combustion shorter, the efficiency is higher and when parameters of forms are getting higher the workflow become softer. Under the conditions of equal cyclic fuel supply differences indicated efficiency for different fuel are in the range 0.04–5%. Indicated efficiency has the greatest value for ethanol, the lowest for LNG. Given trend seen for all combinations of form factor and duration of combustion.
3. A significant difference is observed in the indicated power of various fuels due to lower calorific value of ethanol received less power. In comparison with a diesel, indicated power, when using ethanol, decreases by 35%. In the same indicated power the best indicated efficiency is obtained for heavy fuel – 0.5272, while for ethanol 1.7% lower – 0.5179. Maximum pressure and temperature at identical indicated power for different fuels are approximately at the same level.
4. The least CO_2 is released from LNG, not the most environmentally friendly fuels – residual fuel, as well as due to the presence of sulfur in the fuel, during combustion SO_2 is formed. The use of LNG released almost 2 times less CO_2 than from residual fuel.

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