ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/01.3001.0012.4793

TECHNICAL AND ECONOMIC ANALYSIS OF VARIOUS SOLUTIONS OF FUEL SUPPLY SYSTEMS IN MARINE DIESEL ENGINE OF SHIPS SAILING IN THE CONTROL EMISSION AREAS (ECA)

Rafał Krakowski

Gdynia Maritime University, Faculty of Marine Engineering
Morska Street 83, 81-225 Gdynia, Poland
tel.: +48 58 5586398
e-mail: r.krakowski@am.gdynia.pl

Abstract

In the article, legal norms regarding the reduction of sulphur content limits in exhaust gases in special areas were presented. Then an overview of various solutions for supplying the marine engine with heavy fuel, distillation fuel and gas was made. In addition, the problem of using low-sulphur fuels in internal combustion engines was described. The presented solutions are a response to the latest provisions being part of the VI Annex of the MARPOL Convention, which entered into force on 01.01.2015. These provisions constitute that sulphation of fuel used in Emission Control Areas (ECAs) may not exceed 0.1%. Then, to meet the requirements, the conditions of using heavy fuels for supplying diesel engines were presented. Individual solutions such as the use of low-sulphur fuels, exhaust gas scrubber assembly, and the supply of liquefied natural gas (LNG) from the technical side were shown. Besides, the advantages and disadvantages of each of them were also indicated. In the following part, the economic analysis of the selected ship was made. Its purpose was to evaluate economically in the assumed time of operation, and then select the optimal solution for a given unit. For the comparative analysis, the use of low-sulphur fuels was used; the assembly of the scrubber, as well as the adaptation of the unit to use liquefied natural gas (LPG). The article was finished with conclusions; the most important of them is that the use of fuels with reduced sulphur content is the most expensive solution for the selected ship. The cost of the remaining solutions is at a comparable level, but they require greater interference in the ship's construction.

Keywords: *environmental protection, sulphur compounds, power engines, marine scrubbers, shipping*

1. Introduction

The development of the fleet and an increasing number of vessels moving ports around the world and the fact that the increase of toxic substances into the atmosphere causes an increasingly rapid degradation of the natural environment. To prevent this, at the MARPOL convention in 1997 Annex VI, containing provisions on the prevention of air pollution by ships was adopted and entered into force on 19.05.2005. Annex VI to the MARPOL Convention contains, first and foremost, restrictions on emissions from sulphur and nitrogen oxides as well as substances that deplete the ozone layer, particulates matter (PM) and volatile organic compounds (VOC). The visible consequence of the growing requirements and increasing restrictions in the area of emissions from ships was the introduction of special Emission Control Areas (ECA), where on 01.01.2015 the fuel parameters were changed from 1% of sulphur content to 0.10%.

2. Legal norms

2.1. Arrangements VI of the MARPOL Convention Annex

Annex VI to MARPOL 73/78 concerns provisions on the prevention of air pollution by ships. It was found that emissions of NO_X, SO_X and solid pollutants from seagoing vessels contribute to the increase of air pollutants in cities and coastal areas around the world. The adverse effects on public health and the environment related to air pollution include premature mortality, circulatory diseases, lung cancer, chronic respiratory diseases, acidification, and eutrophication. Annex VI to the MARPOL Convention contains, first and foremost, restrictions on emissions from sulphur and nitrogen oxides as well as substances that deplete the ozone layer, particulates matter (PM) and volatile organic compounds (VOC). One of the most spectacular limitations of the annex is the introduction of sulphur content limits in marine fuel. The change of marine fuel parameters (Fig. 1) is extremely radical and significantly affects its price [7].

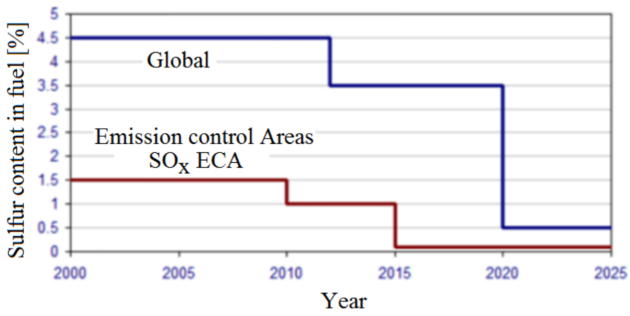

Fig. 1. Permissible sulphur content in fuel according to Annex VI MARPOL [4]

Fig. 2. Emission Control Areas (ECA) [11]

Fuel costs are the main element of the ship's operating costs. Therefore, tightening the requirements has meant that ship owners now consider conversion to Liquefied Natural Gas (LNG) as an alternative fuel, or installing scrubbers, but this is associated with installation costs. A very far-reaching limitation is also the introduction of Emission Control Areas (ECA), i.e. marine areas, where the emission of sulphur oxides is subject to particularly strict control and general sulphur content limits in fuel are more stringent than in other sea areas. Among other things, the Baltic Sea (Fig. 2) has been designated as such an area [7].

3. Overview of applied solutions for powering the marine engine with heavy fuel, distillation fuel and gas

The requirements of Annex VI of MARPOL 73/78 Convention, which reduces the acceptable sulphur content limits in exhaust gases, force ship owners to look for effective solutions to reduce SO_x emissions to the atmosphere. SO_x emission in the exhaust gas can be limited by the reduction of the sulphur content in the fuel – the use of low-sulphur fuels or by the use of flue gas desulphurisation methods – the treatment of exhaust gases using scrubbers. An alternative to liquid fuel can be the adaptation of marine diesel engines to LNG natural gas (Liquefied Natural Gas). Natural gas is considered an ecological fuel because its exhaust gases contain much less harmful components of the environment than from liquid fuels [2, 3].

3.1. Problems of using low-sulphur fuels in internal combustion engines

The first of the possible methods of fulfilment SOx emission conditions to the atmosphere is the change from the heavy residual fuel (HFO) used so far to the low-sulphur residual (LSFO/ULSFO) and distillation fuels (LSMGO). This solution is not without disadvantages and has an impact on the correct operation of marine diesel engines. Residual low-sulphur fuels are LSFO with sulphur content below 1% and ULSFO with sulphur content below 0.1%. Subjecting the fuel to desulfurization leads to a decrease in aromaticity, which results in a decrease in its stability. This has an impact on its ability to mix with heavy fuel (HFO) during a fuel changer. The desulfurization process can also lead to difficulties with ignition and combustion of fuel. Furthermore, when an LSFO ship used in ECA areas is interchangeably used with HFO, MARPOL Annex VI requires that the storage and treatment facilities are separate for each. On existing ships, there may be a need for changes in pipelines of transport installations [1].

Problems occurring during operation of marine engine systems with fuel that has a reduced sulphur content result mainly from the physical and chemical properties of such fuels and phenomena that occur in the transport, dosing and fuel injection devices. The main effects of fuel desulfurization include the reduction of lubricating properties, viscosity and density.

The advantages of desulfurized fuels are undoubtedly the reduction of all types of emissions of harmful substances into the air, including solid particles, which allows meeting the limits of ECA areas without the need to install additional installations to reduce SO_x and PM emissions. They also eliminate the need to install fuel-processing equipment on board and significantly reduce the amount of waste generated in the engine room.

3.2. Using heavy fuels to power diesel engines

The basic type of fuel currently used in slow-speed and medium-speed diesel marine engines are residual type fuels, called heavy fuels. Annex VI to the MARPOL Convention allows the continued use of these fuels despite sulphation of up to 3.5%. At the same time, however, it requires technological solutions so that the SO_x emission level does not exceed the set values. Such a solution is the installation of flue gas scrubbers, whose main task is to remove sulphur oxides from exhaust gases.

Exhaust gas scrubbers are an alternative solution for desulphated fuels that ship owners can use on their ships to meet the conditions of movement in ECA areas. Exhaust gas cleaning technology for SO_x reduction using flue gas scrubbers has been used on land since 1930. Currently, companies such as Wärtsilä, Hamworthy and MAN are working on adapting this technology for ships. So far, the first such installations have been developed and have successfully passed the verification and obtained the certificate of some classification societies (including DNV or GL) [6].

The cost of installing scrubber on a ship is dependent on the type of ship and engine power, however, the estimated value of the investment fluctuates between 2-4 million euros.

Generally SOx flue gas scrubber can be divided into two types:

– wet scrubbers that use seawater or fresh water as a rinsing medium,
– dry scrubbers, in which dry chemical agents are used, so-called sorbent.

Next, we divide wet scrubbers into:

– open loop scrubbers, where the irrigation factor is seawater,
– closed loop scrubbers, where the rinsing agent is fresh water with additives increasing alkalinity,
– scrubbers in a hybrid system, which are a combination of the two above.

3.3. Liquefied natural gas LNG in shipbuilding

Currently, manufacturers of diesel engines propose the use of natural gas for marine engines. These are dual fuel engines that can burn both natural gas and heavy or light liquid fuels. Such engines are particularly useful on LNG tankers (Liquefied Natural Gas Carriers) for the transport of liquefied natural gas, where a boiled load – BOG (Boil off Gas) is used. Natural gas before entering the engine requires heating to ambient temperature and compression to a pressure of 0.3-0.5 MPa for medium-speed engines and as much as 25 MPa for low-speed engines. The use of natural gas as a fuel for diesel engines increases the life of the engine and also reduces the emission of harmful substances (NO_x, SO_x) which contributes to the protection of the environment. Therefore, the use of marine engines powered by natural gas is becoming more and more common not only on gas carriers, but also on other types of ships, such as ferries, container ships, tugboats and passenger ships. Dual Fuel technology is most easily used in four-stroke, medium-speed and high-speed engines of both main propulsion and generator sets [2].

In the case of using gaseous fuel to supply marine engines, all its advantages are preserved (above all high efficiency), supplemented with other benefits, such as:

- reduced emission of toxic exhaust components and less deposits of carbon deposits in the combustion chamber,
- no dilution of lubricating oil with fuel,
- significant limitation of sulphur corrosion,
- better combustion from the point of view of the ease of mixing gas with air, and thus ensure the homogeneity of the fuel-air mixture,
- reduction of thermal loads of engine components.

Gas engines, especially dual fuel engines, alternatively powered with either liquid or gaseous fuel or both fuels at the same time, are increasingly used in shipbuilding [8].

4. Economic analysis of various solutions of fuel supply systems

To create an example cost estimate in which the costs of individual technical solutions were compared, the ship m/f WAWEL was chosen. It is a passenger and car ferry, currently in operation. It supports the line Gdansk (Poland) – Nynäshamn (Sweden).

Length: 163.96 [m],
Width: 27.63 [m],
Draft: 6.5 [m],
Contract speed: 18 [kn],
Mechanical drive: 2 x SULZER 7RLA56,
2x6600 = 13,200 [kW],
Ship power plant: 3 x Bergen Diesel BRG-6,
Power: 2500 [kW] / 3125 [kVA].

Fig. 3. M/F WAWEL and selected ferry data [13]

The m/f WAWEL ferry operates on the Gdansk (Poland) – Nynäshamn (Sweden) line, the distance between the ports is 286 nautical miles [14], while the one-way trip lasts 18 hours. The unit flows this route every day with a six-hour stopover after arriving at the port (unloading/ loading). A 10-year period for each of the selected solutions was adopted for the need to calculate.

4.1. The use of low-sulphur fuels

Actual specific fuel consumption

The LSMGO fuel with a sulphur content of 0.1% and a density of ρ_{15} = 863.4 kg/m^3, which is used in the ECA zones, was accepted for the calculations. The value of the specific fuel consumption of the SULZER 7RLA56 engine, which results from the technical and operational documentation, is g_e = 178 g/kWh. The actual specific diesel consumption was calculated from the formula [5]:

$$g_e^{on} = \beta \cdot g_e \cdot \frac{w_d^u}{w_d^{on}} \text{ [g/kWh]}, \quad (1)$$

where:

β – coefficient of limiting fuel consumption above the normative value, given and guaranteed by the engine manufacturer, β = 1.03 was assumed,

g_e [g/kWh] – specific, nominal consumption of contractual fuel given by the manufacturer of the engine,

w_d^u [kJ/kg] – calorific value of contractual fuel given by the manufacturer of the engine, w_d^u = 42707 kJ/kg,

w_d^{on} [kJ/kg] – assumed calorific value of diesel oil, w_d^{on} = 42600 kJ/kg.

After inserting data into formula (1), actual specific diesel consumption was obtained:

$$g_e^{on} = 183.80 \ \frac{\mathrm{g}}{\mathrm{kWh}}.$$

The actual specific fuel consumption of auxiliary engines is calculated from a similar formula and is:

$$g_{ep}^{on} = 189.74 \ \frac{\mathrm{g}}{\mathrm{kWh}}.$$

Auxiliary engines like the main ones are supplied with LSMGO desulfurized light fuel with a sulphur content of 0.1% and density ρ_{15} = 863.4 kg/m^3. The calorific value of the contractual fuel given by the engine manufacturer is w_d^u = 42650. Whereas the value of specific fuel consumption given in the technical and operational documentation is g_e = 184 g/kWh. Other data accepted as above.

Fuel consumption during the cruise

Nominal consumption of light fuel by the main engine (G_g^{on}) and auxiliary engines (G_p^{on}) within an hour are determined respectively by the formulas:

$$G_g^{on} = g_e^{on} \cdot N_n^* \cdot 10^{-6} \ [\mathrm{t/h}], \tag{2}$$

$$G_p^{on} = g_{ep}^{on} \cdot N_{np}^* \cdot 10^{-6} \ [\mathrm{t/h}], \tag{3}$$

where:

g_e^{on} – actual specific light fuel consumption by the main engine (g_e^{on} = 183.80 g/kWh),

g_{ep}^{on} – actual specific light fuel consumption by the auxiliary engine (g_{ep}^{on} = 189.74 g/kWh),

N_n^* – nominal power of the main engine (N_n^* = 6600 kW),

N_{np}^* – nominal power of the auxiliary engine (N_{np}^* = 2500 kW).

After inserting into the formula (2) and (3), the nominal fuel consumption is respectively:

$$G_g^{on} = 1.21 \ \frac{\mathrm{t}}{\mathrm{h}}, \quad G_p^{on} = 0.47 \ \frac{\mathrm{t}}{\mathrm{h}}.$$

Assuming that during the ferry cruise two main engines and one of the three generator sets operate, the hourly fuel consumption will be as follows:

$$G_{gip}^{on} = 2 \cdot 1.21 \ \frac{\mathrm{t}}{\mathrm{h}} + 0.47 \ \frac{\mathrm{t}}{\mathrm{h}} = 2.89 \ \frac{\mathrm{t}}{\mathrm{h}}.$$

With information that this ferry is on the route 18 hours a day, you can count the daily consumption:

$$G_{gip}^{on} = 18 \cdot 2.89 \ \frac{\mathrm{t}}{\mathrm{h}} = 52.02 \ \frac{\mathrm{t}}{24\mathrm{h}}.$$

Due to the fact that the ferry operates this route 6 times a week and the year consists of an average of 52 weeks, you can estimate the fuel consumption for a year:

$$G_{gip}^{on} = 52.02 \ \frac{\mathrm{t}}{24\mathrm{h}} \cdot (6 \cdot 52) = 16230.24 \ \frac{\mathrm{t}}{\mathrm{year}}.$$

Suppose that the ferry will sail for 10 years, the LSMGO fuel consumption has been calculated for this period:

$$G_{gip}^{on} = 16230.24\,\frac{\mathrm{t}}{\mathrm{year}}\cdot 10 = 162302.4\,\frac{\mathrm{t}}{10\ \mathrm{years}}.$$

Assuming the world price of low-sulphur fuel is fixed and amounts to USD 500 per ton [18] it is possible to estimate the cost of fuel consumed for a given period (10 years):

$$162302.4\cdot 500 = 81151200\ \$.$$

Both main engines and auxiliary units are adapted to the combustion of this type of fuel, so there is no need to replace the installation (including fuel pumps or injectors). Therefore, investment costs for this solution are virtually negligible and the cash input depends mainly on the fuel price.

Installation of exhaust gas scrubber

The ferry route, which is entirely in the Emission Control Area (ECA), has a decisive influence on the selection of an appropriate exhaust gas scrubber, namely a wet scrubber in a closed circuit. This solution does not require the discharge of water from the exhaust gas scrubber directly into the sea in contrast to ones that operate in the open circuit. In addition, the use of a wet scrubber in a closed circuit reduces the nitrogen oxides from exhaust gases to a sufficient degree, so there is no need to install SCR devices. It would be necessary if the choice fell on a dry scrubber, this way you can avoid further costs. The disadvantage of this type of scrubber is the costs associated with passing of sludge formed during the rinsing process to specialized pickup points ashore. The cost of purchasing sodium hydroxide (NaOH) – the agent necessary for the operation of the scrubber and proper exhaust gas cleaning is in the range of 50-250 $\$/m^3$, which means that the average cost of using the scrubber is 20-50 \$ per metric ton of burnt fuel. The price of the scrubber, depending on the manufacturer, is about 3 to 4 million USD. Shipbuilding costs must also be added to the investment (assembly and adaptation of the ship's structure). These costs depend on contractors and the degree of interference in the construction, one source gives a price of 1 million USD [10], other ones even 3 million USD [11]. For the economic analysis of this solution, the total costs of the scrubber and shipbuilding of 4.5 million dollars were accepted.

The investment cost will be added to the purchase price of heavy fuel used to supply main and auxiliary engines during ten-year operation, along the route of the m/f WAWEL ferry.

Actual specific fuel consumption

Calculations were made for IFO 380 fuel. It is one of the most popular heavy fuels. IFO 380 fuel density: $\rho_{15} = 942.9\ \mathrm{kg/m^3}$ [5]. The actual specific fuel consumption for main engines was calculated from the formula [5]:

$$g_e^{oo} = \beta\cdot g_e\cdot\frac{w_d^u}{w_d^{00}}\ [\mathrm{g/kWh}], \tag{4}$$

where:

β – coefficient of limiting fuel consumption above the normative value, given and guaranteed by the engine manufacturer, $\beta = 1.03$ was assumed,

g_e [g/kWh] – specific, nominal consumption of contractual fuel given by the manufacturer of the engine, for the SULZER 7RLA56 engine it is $g_e = 178$ g/kWh,

w_d^u [kJ/kg] – calorific value of contractual fuel given by the manufacturer of the engine, $w_d^u = 42707$ kJ/kg was assumed,

w_d^{00} [kJ/kg] – assumed calorific value of diesel oil. $w_d^{00} = 41600$ kJ/kg was assumed.

The selected values were inserted into the formula (4):

$$g_e^{oo} = 188.22\,\frac{\mathrm{g}}{\mathrm{kWh}}.$$

Actual specific consumption of heavy fuel by the auxiliary engines is calculated with the following formula:

$$g_{ep}^{00} = \beta \cdot g_{ep} \cdot \frac{w_d^u}{w_d^{oo}} \text{ [g/kWh]}, \tag{5}$$

where:
β – coefficient of limiting fuel consumption above the normative value, given and guaranteed by the engine manufacturer, β = 1.03 was assumed,
g_{ep} [g/kWh] – specific, nominal consumption of contractual fuel given by the manufacturer of the engine, g_e = 184 g/kWh was assumed,
w_d^u [kJ/kg] – calorific value of contractual fuel given by the manufacturer of the engine, w_d^u = 42650 kJ/kg was assumed,
w_d^{oo} [kJ/kg] – assumed calorific value of diesel oil, w_d^{on} = 41600 kJ/kg was assumed.

Using formula (5) the following was calculated:

$$g_{ep}^{oo} = 194.3 \frac{\text{g}}{\text{kWh}}.$$

Fuel consumption during the cruise

Nominal consumption of heavy fuel by the main engine and auxiliary engines within one hour is determined by formulas [5]:

$$G_g^{oo} = g_e^{oo} \cdot N_n^* \cdot 10^{-6} \text{ [t/h]}, \tag{6}$$

$$G_p^{oo} = g_{ep}^{oo} \cdot N_{np}^* \cdot 10^{-6} \text{ [t/h]}, \tag{7}$$

where:
g_e^{oo} – actual specific consumption of heavy fuel by the main engine (g_e^{oo} = 188.22 g/kWh),
g_{ep}^{oo} – actual specific consumption of heavy fuel by the auxiliary engine (g_{ep}^{00} = 194.3 g/kWh),
N_n^* – nominal power of the main engine (N_n^* = 6600 kW),
N_{np}^* – nominal power of the auxiliary engine (N_{np}^* = 2500 kW).

The selected values were inserted into the formulas (6), (7) and the following was calculated:

$$G_g^{oo} = 1.24 \frac{\text{t}}{\text{h}}, \quad G_p^{00} = 0.49 \frac{\text{t}}{\text{h}}.$$

As in the case of light fuel calculations, we assume that both main engines and one of three generator sets work during a ferry cruise. Hourly fuel consumption will be:

$$G_{gip}^{oo} = 2 \cdot 1.24 \frac{\text{t}}{\text{h}} + 0.49 \frac{\text{t}}{\text{h}} = 2.97 \frac{\text{t}}{\text{h}}.$$

During the ten-year exploitation, fuel consumption by the ferry will be (assuming the same as in the previous case):

$$G_{gip}^{00} = 16679.52 \frac{\text{t}}{\text{year}} \cdot 10 = 166795{,}2 \frac{\text{t}}{10 \text{ years}}.$$

Assuming that the global fuel price is fixed and is \$ 320 per tonne, you can approximate the fuel cost during the ten-year operation of the ferry:

$$166795.2 \cdot 320 = 53374464 \text{ \$}.$$

The operating costs must include the average cost of using the scrubber, which is \$ 20-50 per metric ton of burnt fuel. The costs of using the scrubber include the purchase of sodium hydroxide (NaOH) and the disposal of sludge in the port. The average value of the costs of servicing the scrubber, \$ 35 per ton of burnt fuel, will be assumed. The costs of using a scrubber will be:

$$166795.2 \cdot 35 = 5837832 \text{ \$}.$$

When calculating the total value of the investment along with the ten-year exploitation period for the previously calculated costs incurred for the purchase of fuel as well as the use of the scrubber, we must add the purchase price for the scrubber in the amount of \$ 4.5 million:

53374464 \$ + 5837832\$ + 4500000\$ = 63712296 \$.

4.3. Adaptation of the unit to use liquefied natural gas (LNG)

The selected ferry is designed to burn only liquid fuel, in order to adapt it to work on liquefied natural gas it will be necessary to replace main engines and auxiliary engines for dual fuel engines. The Wärtsilä 8L50DF main engine was selected for the economic analysis. When the engine is running in the "dual fuel" mode, i.e. when natural gas and a pilot fuel dose are used to power the engine, the gas consumption is given in [kJ/kWh]. To determine the cost of gas for the engine supply, you need to calculate the gas consumption in [m^3], using the gas consumption indicator provided by the engine manufacturer (heat rate):

$$7412\ \frac{\mathrm{kJ}}{\mathrm{kWh}} \cdot 7800\ \mathrm{kW} = 57813600\ \frac{\mathrm{kJ}}{\mathrm{h}}$$

or:

$$57813600\ \frac{\mathrm{kJ}}{\mathrm{h}} = 57813.6\ \frac{\mathrm{MJ}}{\mathrm{h}} \cdot$$

Natural gas consumption was calculated for the heating value of 34.43 MJ/m^3 for GZ-50 gas [9] under normal conditions (temperature 0ºC, pressure 101.3 kPa).

Hourly gas consumption in one main engine: Natural gas consumption was calculated for the heating value of 34.43 MJ/m^3 for GZ-50 gas [9] under normal conditions (temperature 0ºC, pressure 101.3 kPa).

Hourly gas consumption in one main engine:

$$\frac{57813.6\ \frac{\mathrm{MJ}}{\mathrm{h}}}{34.43\ \frac{\mathrm{MJ}}{\mathrm{m^3}}} = 1679.16\ \frac{\mathrm{m^3}}{\mathrm{h}}.$$

Then the auxiliary engine was selected. The ferry is equipped with three generating sets consisting of Bergen Diesel BRG-6 engines, each with a power of 2500 kW. Motors of similar power were selected from the manufacturer's table. A suitable two-fuel auxiliary engine is 6L34DF.

As with main engines, calculate the gas consumption of auxiliary engines:

$$7387\ \frac{\mathrm{kJ}}{\mathrm{kWh}} \cdot 2880\ \mathrm{kW} = 21274560\ \frac{\mathrm{kJ}}{\mathrm{h}}$$

or:

$$21274560\ \frac{\mathrm{kJ}}{\mathrm{h}} = 21274.56\ \frac{\mathrm{MJ}}{\mathrm{h}} \cdot$$

The hourly natural gas consumption was calculated for the heating value of 34.43 MJ/m^3 for gas GZ-50 [9] under normal conditions:

$$\frac{21274.56\ \frac{\mathrm{MJ}}{\mathrm{h}}}{34.43\ \frac{\mathrm{MJ}}{\mathrm{m^3}}} = 617.91\ \frac{\mathrm{m^3}}{\mathrm{h}} \cdot$$

During the gas combustion, dual-fuel engines use a certain amount of liquid fuel in the form of a pilot dose. This amount will be included in the calculation.

The consumption of liquid fuel by the main engine and the auxiliary engine within one hour is determined by the following formulas:

$$G_g^{on} = g_e^{on} \cdot N_n^* \cdot 10^{-6}\ [\mathrm{t/h}], \tag{8}$$

$$G_p^{on} = g_{ep}^{on} \cdot N_{np}^* \cdot 10^{-6}\ [\mathrm{t/h}], \tag{9}$$

where:
g_e^{on} – specific fuel consumption of the main engine in dual fuel mode (g_e^{on} = 1 g/kWh),

g_{ep}^{on} – specific fuel consumption of the auxiliary engine in dual fuel mode (g_{ep}^{on} = 1.9 g/kWh),
N_n^* – nominal power of the main engine (N_n^* = 7800 kW),
N_{np}^* – nominal power of the auxiliary engine (N_{np}^* = 2880 kW).

The assumed values have been inserted into formulas 8 and 9:

$$G_g^{on} = 0.0078\,\frac{\mathrm{t}}{\mathrm{h}},\quad G_p^{on} = 0.0055\,\frac{\mathrm{t}}{\mathrm{h}}\cdot$$

When both main engines and one of three generating sets are working during a ferry cruise, the hourly natural gas consumption is:

$$G_{gip}^{np} = 2\cdot 1679.16\,\frac{\mathrm{m}^3}{\mathrm{h}} + 617.91\,\frac{\mathrm{m}^3}{\mathrm{h}} = 3976.23\,\frac{\mathrm{m}^3}{\mathrm{h}}\cdot$$

The total hourly fuel consumption of the pilot dose is:

$$G_{gip}^{on} = 2\cdot 0.0078\,\frac{\mathrm{t}}{\mathrm{h}} + 0.0055\,\frac{\mathrm{t}}{\mathrm{h}} = 0{,}02\,\frac{\mathrm{t}}{\mathrm{h}}\cdot$$

During the 10 years of operation of the unit, the demand for gaseous and liquid fuel will be (assuming the same as in the previous case):

$$G_{gip}^{ng} = 22330507.68\,\frac{\mathrm{m}^3}{\mathrm{year}}\cdot 10 = 223305076.8\,\frac{\mathrm{m}^3}{10\ \mathrm{years}},$$

$$G_{gip}^{on} = 112.32\,\frac{\mathrm{t}}{\mathrm{year}}\cdot 10 = 1123.2\,\frac{\mathrm{t}}{10\ \mathrm{years}}\cdot$$

Due to the fact that the price of natural gas is variable and depends on the place of purchase, and the ferry uses ports in the Baltic Sea Region, the price of fuel from this area will be used for calculations. The price of gas in Europe in July 2017 is 5.20 \$/mm BTU, with the unit mmBTU (1 million British Thermal Unit), approximately 27.096 m^3. Therefore, one cubic meter of natural gas costs \$ 0.19. The cost of fuel, as in the previous calculations, is \$ 500 per ton.

$$223305076.8\cdot 0.19 + 1123.2\cdot 500 = 42989564.59\ \$.$$

The cost of conversion of the selected passenger-car ferry is difficult to evaluate. Exchanges are subject to, among others, two main engines, three auxiliary engines, tanks and auxiliary equipment, and shipbuilding costs has to also be added. Based on the example solutions [8], the estimated investment in the conversion of the ferry will be \$ 25 million.
The cost of ship conversion and ten-year operation will be:

$$42989564.59 + 25000000 = 67989564.59\ \$.$$

4.4. Summary

The estimated total cost during the 10-year operation of the ferry, depending on the chosen solution, is presented in Tab. 1.

Tab. 1. Comparison of costs during the ten-year operation of the ferry

SOx emission reduction method	Estimated cost [MUSD]
The use of low-sulphur fuel	81
Installation of flue gas scrubber + HFO	64
LNG liquefied natural gas supply	68

The ship-owner should decide which of the emission reduction methods presented in the article the optimal solution is. The choice of one of them should be influenced by, among others: the route covered by that vessel, environmental conditions, the ability to adjust the structure, the age of the ship, and in the case of liquefied natural gas, the availability of fuel. In addition to the main advantage of all methods, which is to reduce the emission of toxic compounds to the atmosphere, each of them has some disadvantages that ship-owners should take into account.

5. Conclusions

As it results from the work, both the use of low-sulphur fuel, liquefied natural gas to power the ship's engine or the assembly of a scrubber allows compliance with restrictive standards of toxic gas emissions to the atmosphere. However, the conducted analysis proves that the use of fuels with a reduced sulphur content is the most expensive solution for the selected ferry. The cost of the remaining solutions is at a comparable level, but they require greater interference in the ship's construction, and the system elements take up more space compared to the low-sulphur fuel installation.

In the case of the m/f WAWEL ferry, when we assume a ten-year service life, the cost incurred for the conversion of the unit to the combustion of liquefied natural gas and the assembly of the scrubber will be returned. The cost of using fuel with reduced sulphur content will be 81 [MUSD]. The calculations show that in the case of assembly of the gas scrubber in a given period, savings will amount to 17 [MUSD], while the conversion cost for burning liquefied natural gas – 13 [MUSD]. It should be remembered that the calculated costs have an estimated value depending on the global fuel price and may change over time.

For ships that are in operation, conversion to one of the cheaper methods may be difficult or even impossible. Therefore, the only alternative is to use fuel with reduced sulphur content. However, in the case of the construction of new vessels, orders of units based on LNG combustion or with built-in scrubbers are increasingly often found, such solutions are future-proof and allow reducing the cost of operation.

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Manuscript received 03 July 2018; approved for printing 04 October 2018