DETERMINATION OF CO_2 MASSES IN THE EXHAUST GASES OF THE MARINE DIESEL ENGINES

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Abstract:

Currently, reducing CO_2 emissions that contribute to the greenhouse effect is currently under attention of the relevant international bodies. In the field of maritime transport, in 2011 International Maritime Organization (IMO) has taken steps to reduce emissions of CO_2 from the exhaust gases of marine diesel engines on ships, by imposing their energy efficiency standards.

In this regard, we conducted a laboratory study on a 4-stroke diesel engine naturally aspirated by using to power it diesel and different blends of biodiesel with diesel fuel. The purpose of the study was to determine the formulas for calculating the mass flow rates of CO_2 from exhaust gases' concentrations experimentally determined. Determining the mass flow of CO_2 is necessary to calculate the energy efficiency coefficient of the ship to assess the energy efficiency of the board of the limits imposed by the IMO.

Keywords: IMO, EEDI, CO_2 emissions.

1. Introduction

In 2011 IMO (International Maritime Organization) by resolution MEPC.203 (62) introduced an amendment to Chapter 4 of Annex VI to Marpol, which imposes certain energy efficiency standards for all vessels in order to reduce greenhouse gas emissions resulting from fuel combustion by power devices on board [1].

The energy efficiency standard imposed by the IMO is the energy efficiency design coefficient (EEDI - Energy Efficiency Design Index) determined for each category of vessel, depending on its type and tonnage [2]. EEDI is expressed in grams of carbon dioxide (gCO_2) per ships' carrying capacity (dwt) and distance (nautical miles) [3].

Increasing the energy efficiency on operating vessels can be obtained by taking measures to reduce fuel consumption and / or use of alternative fuels to run on the motors on board. Such measure to increase energy efficiency on board ships is the use of biodiesel blended fuels to power the marine diesel engines on board.

The study described below aims at determining formulas for calculating the mass of CO_2 emissions in the exhaust gas of a diesel engine with direct injection that is powered by biodiesel mixtures in diesel.

We have not found in the literature studied an approach to transforming CO_2 concentrations in mass flow, for the diesel engines powered with biodiesel in different diesel mixtures.

2. Method

To determine the mass flow of the CO_2 emissions we used concentrations of CO_2 obtained experimentally in the exhaust gas of a 2 kW four-stroke, single cylinder diesel engine, which was powered by diesel and biodiesel mixtures in different concentrations (10%, 15%, 20%, 25%, 30%, 40%, and 50%) in diesel fuel. The resulting fuels were marked for identification, depending on the raw material used, as follows: M (100% fossil diesel); B10;

B15; B20; B25; B30; B40; and B50 (biodiesel mixed with fossil diesel); There were used in the tests, a proportion of biodiesel mixtures with more than 50%, because, due to the high viscosity of diesel fuel, engines must bear certain modifications to the fuel supply system.

Measurements were carried out both for engine's run without load and with load (8 Nm) and also for intermediate loads (3 Nm, 4 Nm, 5 Nm, 7Nm).

The engine features that the tests were carried out on are shown in Table 1.

Table 1. Engine features

Engine name	Hatz 1B20-6
Engine manufacturer	GUNT Germany
Engine type	Diesel in 4 strokes
Speed [1/min]	2500
Power [kW]	2
Cylinder number	1 cylinder
Suction type	naturally aspirated
Cooling type	Air cooling
Type injection	direct injection
Torque	8 Nm/2500l/min
Compression ratio	21:1

Table 2. The main characteristics of fuels

Fuel Type / Chemical Properties	Diesel EFIX 51	Biodiesel
Density 15 grd (ISO 3675) [Kg/m^3]	842,7	879.30
Viscozity at 40 ^{o}C (ISO 3104) [mm^2/s]	3,1294	5,13
Cetane number	51,5	60,1
Carbon Concentration [%]	85.7	77
Hydrogen Concentration [%]	13.3	12
Oxygen Concentration [%]	0.923	11
Sulf Concentration (ISO 8754) [%]	0.077	0.0024
Content of fatty acid methyl esters [%]	5.6	100

For the measurement of exhaust emissions components of NO, CO, HC and CO_2 from the exhaust gases of the engine and the other engine parameters we used the Gunt CT 159 modular stand and a HM 365 universal load and braking device, which was connected to a computer with a dedicated data collection program conducted on the core platform and LabView. An MGT5-type exhaust gas analyzer connected to a printer was attached on the stand.

For testing it was used EFIX 51 diesel (containing at least 5% biodiesel) and biodiesel made from field mustard seeds, which were supplied by the Rompetrol Midia - Năvodari refinery. The main characteristics of fuels used for the tests are shown in Table 2.

In order to obtain a formula for determining the mass flow of CO_2 we used two methods of determination of the mass concentrations of CO_2 emissions from engine exhaust gases:

• Analytical calculation method - the stoichiometric method;

• Calculation method based on experimental data - carbon balance method for determining the exhaust gases mass.

2.1. Stoichiometric method

To obtain a formula for calculating the mass flow of CO_2 from the exhaust gases of a diesel engine, we used the stoichiometric chemical equation of oxidation of the carbon in the fuel composition by burning [4, 5].

The formation mechanism of CO_2 emissions from burning one kilogram of fuel is

$$C+O_2 \rightarrow CO_2+406.45MJ \quad (1)$$

where: C - carbon mass in the fuel; [kg C/ kg comb]; O_2 – the oxygen content of the air supply [kg O_2/kg air]; Qc – the resulting heat energy from the chemical reaction [Mj/Kmol].

The above stoichiometric oxidation equation is expressed usually in kilomoles:

$$1kmol\ C+1kmol\ O_2 \rightarrow 1kmol\ CO_2+406.45MJ/kmol \quad (2)$$

The reaction of formation of carbon dioxide can be converted from kilomoles to kg by taking into account the molecular weight of carbon and oxygen as follows:

$12[kg\ C]+32[kg\ O_2]\rightarrow[44\ kg]CO_2$ (3)

or $$1[kgC]+\frac{32}{12}[kg\ O2]\rightarrow\ \frac{44}{12}[kgCO2]$$ (4)

For an amount of carbon burned "c" [kg C / kg comb] from fuel the combustion equation will be:

$$c\ [Kg\ C]+\frac{32\ c}{12}[Kg\ O2]\rightarrow\frac{44}{12}\ c\ [Kg\ CO2]$$ (5)

Therefore, the mass of carbon dioxide resulting from the combustion of the c mass of carbon in the fuel quantity is:

$$mCO2=\frac{44}{12}\times c\text{ , for 1 kg of fuel}\quad [Kg\ CO2]$$ (6)

Where, for a given quantity of fuel consumed in a given period of time, the above equation can be written as:

$$mCO2=\frac{44}{12}\times c\times Ch\quad [(Kg\ CO2)/h]$$ (7)

where: C_h- hourly fuel consumption [kg comb/h]; c- carbon contents in fuel.

2.2. Carbon balance method for determining the exhaust mass.

To determine the masses of the specific emissions of CO_2 we used the calculation algorithm of the Technical Code on controlling emissions of nitrogen oxides (NOx) for marine diesel engines, that use the carbon balance method to determine the mass flow rate of the exhaust gas [6]. This method uses the concentrations of components in the exhaust gases which have been determined on the basis of experimental measurements carried out.

Therefore, the formula for calculating the mass flow rate of the exhaust emissions is:

$$q_{me\_w}=C_h\cdot\left\{\left[\frac{\dfrac{1.4\cdot(C\cdot C)}{\left(\dfrac{1.4\cdot C}{f_c}+H\cdot 0.08936-1\right)\dfrac{1}{1.293}+f_{fd}}}{f_c\cdot f_c}+C\cdot 0.08936-1\right]\cdot\left(1+\frac{H_a}{1000}\right)+1\right\}$$ (8)

where: C_h – hourly fuel consumption of the engine [kg comb/h]; C – carbon in fuel [%]; H – the hydrogen content of the fuel [%]; H_a – the absolute humidity of the supply air [g water/kg air]; N – nitrogen content of fuel [%]; O – the oxygen content in the fuel [%]; f_{fd}– fuel specific constant; f_c– carbon factor [6].

The mass flow rate of the specific CO_2 emissions of exhaust gases was determined by the formula:

$$q_{CO2} = u_{CO2} \cdot c_{CO2\_w} \cdot q_{me\_w} \quad [\text{kg } CO_2/\text{h}] \tag{9}$$

in which: u_{CO2} – CO_2 ratio of component density and density of exhaust gas; c_{CO2_w} – wet concentration of CO_2 in the exhaust gas component [ppm]; q_{me_w} – wet exhaust gas mass flow rate [kg/h]; [6]

3. Results

Determining the mass flow rate of the CO_2 emissions in the exhaust gases of the engine by the two methods described above was carried out by using a program developed by Microsoft Excel. The program can be used for both diesel engines and turbocharged natural intake. CO_2 mass flow rate values obtained from calculations made by the two methods are presented below in graphical form (Fig.1-8). The diagrams were done according to the load and type of fuel that has powered the engine (M, B10, B15, B20, B25, B30, B40, and B50).

From the graphs above it can be seen that for loads ranging from 0-50%, values of the CO_2 mass flow rates determined through the experimental method are approximately equal to those determined by the analytical method, both for gas oil and mixtures of diesel biodiesel. For loads between 50-100% CO_2 the mass flow rate values determined by the carbon balance method are lower than those obtained by analytical method, both for diesel powered engine and supply of different diesel with biodiesel mixtures. The maximum difference in case of full load for diesel fuel supply is 8.47%. These differences result from analytical and determined mass flow rates determined by the carbon balance method can be explained by the influence of atmospheric moisture it was accounted for in determining CO_2 mass flow rates through the second method.

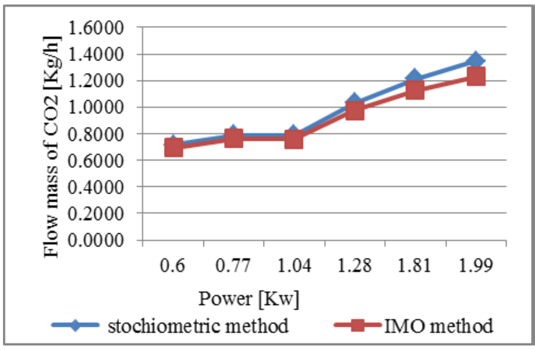


Fig.1. Mass flow rate variation of CO2 – diesel

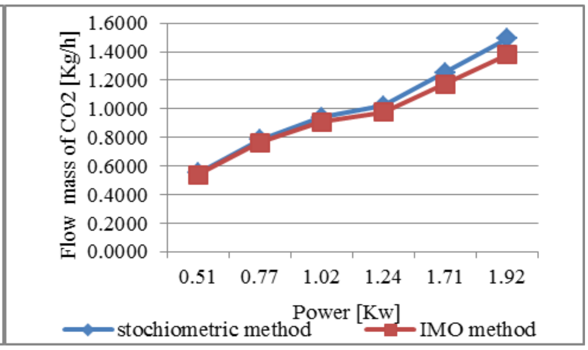


Fig.2. Mass flow rate variation of CO2 – B 10

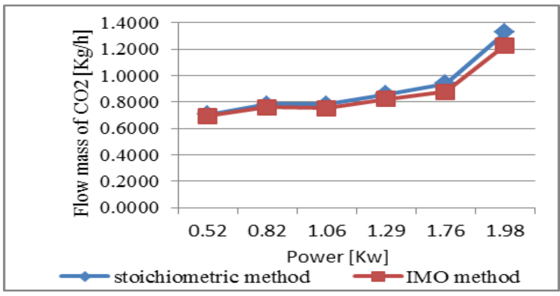


Fig.3. Mass flow rate variation of CO2 – B 15

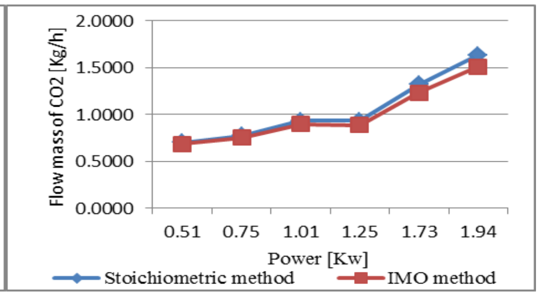


Fig. 4. Mass flow rate variation of CO2 – B 20

Therefore, since these percentage differences of CO_2mass flow rate is less than 10%, mass flow rates of CO_2 emissions for any diesel engine can be determined using the calculation formula obtained by the analytical method:

$$mCO2 = 3{,}666 \times c \times Ch \;\; [(Kg\ CO2)/h] \qquad (10)$$

From the above graphs it can be seen that the variation of the mass flow rate of CO_2 has the lowest values for the mixture of 15% biodiesel in the diesel fuel. Since the composition of diesel under study is a rate of about 5% biodiesel and diesel naval contains no biodiesel, the formula determined above may be used to study the situation of a 20% biodiesel mixture in naval diesel. This percentage of biodiesel blends in naval diesel is also recommended in the references [7, 8].

In order to implement the measures on board vessels in service, ship management should first make a study on the performance of energy efficiency. Since at this stage it is not known the hourly consumption of marine engines fueled with biodiesel blended in diesel, Eq. (10) cannot be applied for determining the mass flow rate of CO_2 emissions.

In this situation, to estimate the EEDI coefficient we used experimental data to determine a formula for calculating the mass of CO_2 for the B15 mixture, according to the carbon emissions if supplied with diesel. The mass of CO_2 emissions for diesel can be determined using Eq. (10) as the fuel consumption of engines on board naval diesel is known.

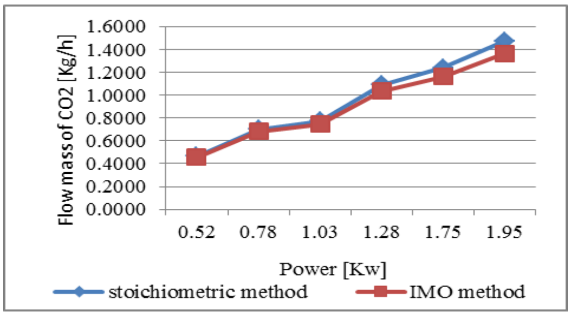


Fig. 5. Mass flow rate variation of CO2 – B 25

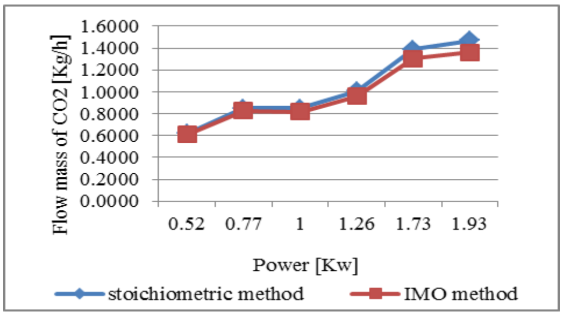


Fig. 6. Mass flow rate variation of CO2 – B 40

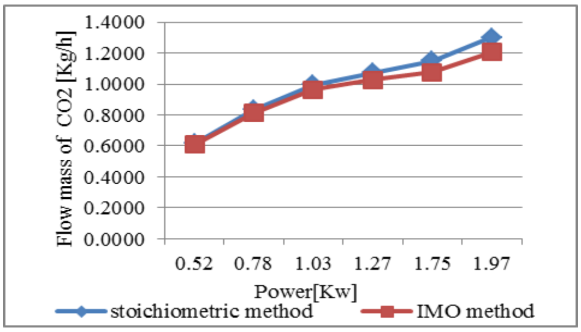


Fig. 7. Mass flow rate variation of CO2 – B 30

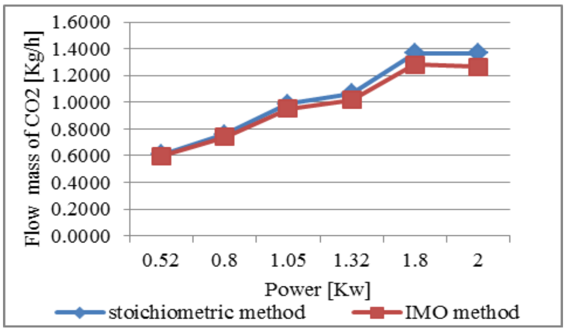
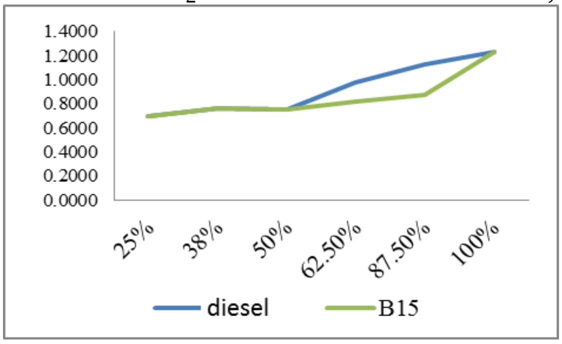


Fig. 8. Mass flow rate variation of CO2 – B 50

Thus, in figure 9 we depict the comparison between the change in mass of CO_2 depending on load, if powered with diesel and 15% biodiesel blend in diesel (B15). From the figure it shows that for engine loads between 0-50% there is no difference between the masses of CO_2 for B15 versus diesel.

Therefore the formula to compute the mass of CO_2 if the mixture is determined for B15 engine loads between 50-100%. In Figure 10 it is plotted the percentage difference between mass flow of CO_2 for diesel and B15 mixture, for loads ranging from 50-100%.



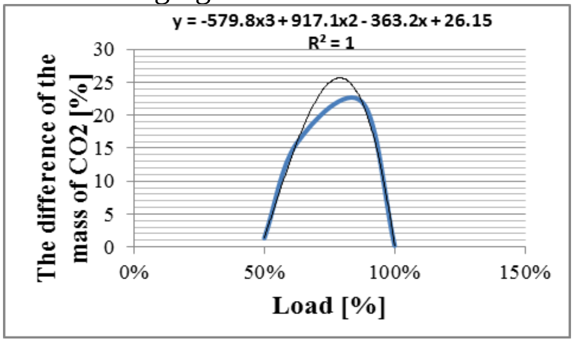


Fig.9. CO_2 mass flow rate variation diesel and B15 Fig. 10. CO_2 mass difference between diesel and B15

By using the mathematical regression method applied in Excel, *we determined* the following calculation equation of the estimated mass of CO_2 for a 15% biodiesel mixture in diesel fuel, depending on the CO_2 mass of diesel, for loads between 50-100%:

$$m_{CO2B15} = m_{CO2Diesel}(1 - y\%)[Kg\ CO_2] \quad (11)$$

where: $y = 579{,}8*(s\%)^3 + 917{,}1*(s\%)^2 - 363{,}2*(s\%) + 26{,}15$ [%] and s- engine load percentage.

4. Conclusions

Reducing of the CO_2 emissions from ships is one of the current problems facing the management of vessels in service. Using the mixture of biodiesel for in naval fuels represents a method of reducing CO_2 emissions.

Using the experimental data obtained from a diesel engine with direct injection and two methods of calculating the mass flow rate of CO_2 emissions, we determined a formula for calculating the mass emissions of CO_2, both for diesel oil and mixtures of biodiesel in diesel depending on the hourly fuel consumption. This calculation formula for determining the mass flow rate of CO_2 from the exhaust gases can be used for diesel engines with direct injection both naturally aspirated and supercharged because the parameters of the air supply (pressure, temperature, humidity) influence insignificantly the amount of CO_2 emissions. It has to be further studied whether this formula can be applied to modern diesel engines with a Common Rail-type assisted injection system.

In the event that it is not known the consumption per hour of the mixture of 20% biodiesel in diesel oil, we determined a formula for calculating the mass of CO_2 for a mixture of 20% biodiesel in diesel depending on the CO_2 emissions mass of diesel for loads ranging between 50-100%.

These formulas are needed by the management of the vessels in service in order to study the effectiveness of the measure of replacement of the classical fuels with the mixture of 20% biodiesel in diesel by calculating the energy efficiency design coefficient (EEDI) for any vessel under various loading conditions and for any speeds.

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