APPLICATION OF BIODIESEL DERIVED FROM OLIVE OIL PRODUCTION WASTES AT MARINE DIESEL ENGINE AND EVALUATION OF GASSEOUS EMISSION TRENDS

by

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As a carbon neutral fuel, biodiesel is one option in future IMO scenarios for reducing carbon intensity in shipping sector, and at same time reducing emission of pollutants. Some oily wastes, such as waste from olive oil production, might be used for production of second-generation biodiesel. The current study looks into the effect of biodiesel on the characteristics of gaseous pollutant emissions of NO_x and CO from slow-speed two-stroke marine Diesel engines that do not have any after-treatment devices or engine control technology installed to reduce gaseous pollutant emissions. While the ship was berthed in the harbor, tests were performed on two separate loads at 210 rpm. The engine was powered by diesel fuel and blends of 7%, 20%, and 25% v/v of biodiesel derived from oily wastes generated during olive oil processing. For biodiesel production in lab conditions, base-catalyzed transesterification was implemented. According to the findings, there are tendencies of reduced gaseous emissions when utilizing blended fuels.

Key words*: biodiesel made of wastes from olive oil production, marine Diesel engine, gaseous pollutants*

Introduction

Total maritime transport sector has increased its CO_2 (GHG) emission from 962 million tonnes in 2012 to 1056 million tonnes in 2018, or from 2.76% in 2012 to 2.89% in 2018 of total anthropogenic global emission [1]. During same period, the carbon intensity of shipping operations decreased by around 11%, although efficiency gains were outpaced by increased activity [1].

Aside from GHG emission, maritime transport sector releases significant amounts of pollutants such as NO_x and SO_x, and in smaller amount CO and HC, as well. From 2014 to 2018, NO_x emissions climbed from 19 million tons to 20.9 million tons, while SO_x emissions increased from 10.2 million tons to 11.3 million tons, according to statistics [2].

The International Maritime Organization (IMO) regulates shipping air pollution and greenhouse gas emissions through MARPOL and Annex VI of the International Convention

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for the Prevention of Pollution from Ships. The Convention's Annex VI sets limits on NO_x and SO_x emissions from ship exhausts, prohibits deliberate emissions of ozone-depleting substances, regulates shipboard incineration and emissions of volatile organic compounds from tankers, and specifies variety of measures for improving the energy efficiency of new and existing ships (EEDI and SEEMP) [3]. In 2018, the IMO developed the strategy for reducing GHG emissions from ships [4]. The initial GHG strategy calls for a reduction in international shipping's carbon intensity (to reduce CO_2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, with a goal of 70% by 2050, compared to 2008) and a reduction in total annual GHG emissions from international shipping of at least 50% by 2050, compared to 2008. An updated strategy is set to be released in 2023 [4]. Over the next few decades, policy changes and stakeholder participation will push ship owners to find, evaluate, and adopt technology, fuels, and solutions that help them decarbonize their ships, cut energy use, and meet other environmental goals. The need for decarbonization in global industrial value chains will also drive logistics optimization, including measures like greater fleet utilization and speed reductions [5].

While the particular solutions available to different ship segments may differ, decarbonization of shipping will necessitate the use of carbon-neutral fuels to replace fossil fuels. A range of energy sources or energy systems that have no net GHG emissions or carbon footprint are referred to as carbon-neutral. Sustainable biofuels may be a good fit for replacing oil-based fuels in the existing ship fleet. Hydrogenated vegetable oil, biomass-to-liquids, and fatty acid methyl ester (FAME) are all types of biofuels. The FAME is not a drop-in fuel because the international standard ISO 8217:2017 limits the allowed blending concentration at 7%. Still, the IMO study concludes that low blends of biodiesel of up to 20% (B20) could be used without any fuel system modifications [6].

Biodiesel is a long-chain fatty acid mono-alkyl ester made from animal fats or vegetable oils. The most common way of manufacturing biodiesel is by an esterification reaction [7]. As a catalyst, a short-chain alcohol such as methanol (or acid or base) is used in the reaction [7].

The main disadvantages of biofuels are a scarcity of raw materials and high production costs. Because biodiesel is derived from animal fats or vegetables, its use is controversial due to food competition. Using oils from waste materials is a viable strategy for lowering the cost of raw materials for biodiesel production without competing with food.

Although practical experience with the use of biodiesel in the shipping industry is very scarce [7], several research activities [2, 7-9] and demonstration projects [10, 11] have been conducted to assess the technical feasibility of different biofuels.

The aim of this study was to produce biodiesel from local wastes and use it as fuel for marine Diesel engines. It was followed by characterizing the biodiesel properties and comparatively assessing the effects of diesel and biodiesel blends on diesel engine performance and exhaust emission trends under various loads. For the study, a reversible two-stroke, low-speed, cross-flow scavenging, four-cylinder marine Diesel engine was used. The engine was fuelled with pure diesel fuel and blends containing 7%, 20%, and 25% of the biodiesel produced in laboratory conditions using oily wastes from olive oil extraction. Base-catalyzed transesterification was implemented for biodiesel production.

Experimental procedure

A marine Diesel engine was used in this experiment. It was a reversible two-stroke, four-cylinder marine Diesel engine with cross-flow scavenging, type ALPHA 494 R, manufactured under Burmeister license by LITOSTROJ Ljubljana, Slovenia, tab. 1. The engine is classified as a low-speed engine because its maximum speed is 320 rpm and it produces 390 kW of power. Because it was an old-style marine Diesel engine, no after-treatment devices or engine management systems to limit pollutant emissions were fitted. In fact, a circumstance like this is ideal for studying the direct effects of biodiesel on exhaust emissions from marine Diesel engines. After the last overhaul, the engine has been operating for 8600 hours with no alterations made for this experiment.

Table 1. Marine Diesel engine specifications

Engine producer	Engine model	Working principle	Max power	Cylinder No.	Stroke/Bore
Burmeister	Alpha 494-R	two-stroke	390 kW at 320 rpm	4	490 mm/290 mm

The direct propulsion system of the ship comprises of the engine, propeller shaft connected to the output coupling, and a fixed-pitch propeller. Tests were conducted when the ship was berthed in harbour and during the same day – in order to have the identical atmospheric conditions. At the engine crankshaft speed of 210 rpm, two modes of load were achieved, the first with the rudder in the zero position (midship) and the rudder turned to the far left, which achieves an increased load for the same number of revolutions (designated as 210 and 210N, respectively).

During the engine operation, power is constantly changing depending on the connected consumer. In the conditions of operation of the vessel, engine power that is transmitted to the fixed pitch-propeller depends on the number of revolutions, pitch and propeller diameter. Effective power that is delivered to the propeller could be expressed via the torque which is transmitted from the engine crankshaft, via coupling, to the propeller shaft and propeller, where it reverses the angular velocity, ω. The recorded average torque and shaft speed data can be used for engine effective power estimation in accordance to the formula below [12]:

$$P_e = M\omega = \frac{M\pi n}{30} \text{ [kW]} \tag{1}$$

where M [kNm] represents measured torque [kNm] and n [rpm] represents engine-propeller rotational speed .

As for the set of engine speeds and different testing fuels, measurements of propeller shaft torque and power were conducted by means of strain gauges. This method establishes a functional connection between the elastic angular deformation of the propeller shaft and engine torque/power. Measurements of the propeller shaft torque and power were conducted by installing two pairs of strain gauges (type XY21-6/350), connected in Wheatstone bridge, onto the propeller shaft. The strain gauges were mounted at an angle of 180° relative to one another. Power was delivered to strain gauge from a 9 V source. Measuring signal from the Wheatstone bridge was delivered to the radio transmitter, allowing transfer of data to the receiver. A power source, transmitter and antenna were mounted on a ringed disc made of plastic, placed on the propeller shaft, with a view to eliminate noise. Next to the shaft, a signal receiver and a speed sensor were placed, fig. 1. The signal receiver and the speed sensor were connected to an electronic measuring device – Spider 8. The

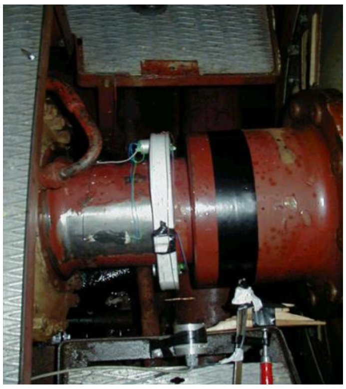

Figure 1. Strain gauges mounted on the propeller shaft

Spider 8 was connected to a personal computer. The software for data processing was *Catman 3.0*. The equipment listed was produced by hottinger baldwin messtehnik.

Fuel consumption (FC) was measured directly during experiment, while the brake specific fuel consumption (BSFC), and brake thermal efficiency (BTE) were calculated based on the known equations.

The hourly fuel consumption was measured for each engine speed and fuel type. The volumetric method of fuel consumption measurement was employed for fuel mass-flow estimation according [12]:

$$FC = \frac{V_f \rho_f}{t} \tag{2}$$

where FC [kgh^{-1}] represents fuel mass-flow, V_f [m^3] represents fuel volume consumed during the measurement time, ρ_f [kgm^{-3}] represents fuel density, and t [hours] represents the time period of measurement.

The BSFC [gr per kWh] is defined as the ratio of fuel mass-flow to the engine power. It is calculated by [13]:

$$BSFC = \frac{m_f 10^3}{P_e} \tag{3}$$

where m_f [kgh^{-1}] is the fuel consumption and P_e [kW] – the engine power.

The BTE [%] is the ratio of engine power to the thermal energy released by fuel combustion under unit of time. It is calculated by [7]:

$$BTE = \frac{P_e 3600}{m_f H_d} 100 \text{ [\%]} \tag{4}$$

where m_f [kgh^{-1}] is the fuel consumption, P_e [kW] – the engine power, and H_d [kJkg^{-1}] – the lower heating value of the tested fuel.

Exhaust emission analyser Testo, model 350-MARITIME, was used in the experiment for measuring gaseous concentrations in the engine exhaust. Testo model 350-MARITIME has Germanischer Lloyd (DNV GL) and Nippon Kaiji Kyokai (Class NK) certificates according to MARPOL Annex VI and NOx Technical Code 2008 [14]. The specifications of the emissions analyzer are cited in tab. 2. The instrument itself was located on the engine room's gallery, about two meters above the engine. The probe was inserted into an opening in the exhaust gases collector above the engine (which was designed for such experiments). The lower section of the exhaust gasses collector from the engine exhaust to the point of probe insertion was not cooled. Once the engine parameters were stabilized, the exhaust emission measurements were performed for each engine's speed regime for the same exhaust gas flow. Each running step was held for 10 minutes until exhaust emissions were stabilized and maintained while each parameter was measured and recorded, during the last 5

Table 2. Specification of exhaust emission analyser Testo, model 350-MARITIME [14]

Parameter	Measuring range	Accuracy
°C, flue gas	–40 up to 1000 °C	max ±5K
O_2	0 … 25 vol.%	According to to MARPOL Annex VI and NO_x technical code
CO	0 … 3000 ppm	
NO	0 … 3000 ppm	
NO_2	0 … 500 ppm	
SO_2	0 … 3000 ppm	
CO_2	0 … 40 vol.%	
Pabs	600 … 1150 hPa	±5 hPa at 22 °C ±10 hPa at –5 °C up to 45 °C

minutes of each running step. Measurements were taken on the same day to ensure that the atmospheric conditions were nearly identical in each test. Figure 2 depicts the exhaust emission test schematic.

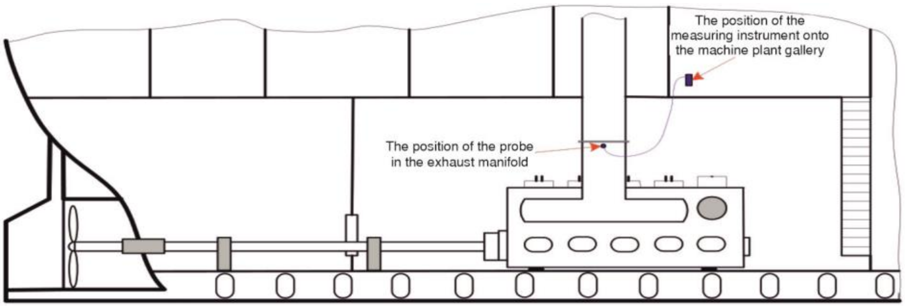

Figure 2. The position of exhaust emission testing equipment

An outside tank supplied fuel to the engine. The fuel lines were cleaned after each fuel type change, and the engine was left running for at least 20 minutes to stabilize under the new conditions. Separate fuel samples were prepared and poured into separate tanks that were connected to the suction side of the engine fuel pump. Excess fuel was pumped back into the same tank. The tanks were placed on the gallery in the engine room, about 2 m above the engine, so that the fuel was delivered to the fuel pump by gravity. In addition, a glass burette of known volume was attached to the tank and used to measure fuel consumption.

Given that the marine Diesel engine was running for 8600 hours after the last overhaul and that there were no adjustments of the engine for this experiment, the purpose of performed measurements was to give trends of gaseous emissions in relation to different types and content of the second-generation biodiesel in the blends for the marine diesel engine in service.

Results and discussion

Test fuel parameters

The engine was powered by diesel fuel and blends containing 7%, 20%, and 25% v/v of the FAME. None of the blends required any adjustments to the marine Diesel engine for this experiment [5]. The diesel fuel was a typical fuel used by the Montenegrin fleet in territorial waters, with a flash point above 60 °C. The FAME was produced in the lab conditions using oily wastes from olive oil extraction (olive pomace) collected from Montenegro's local olive oil producers. The FAME was produced using base-catalyzed transesterification. Table 3 shows the basic test fuel properties, with letter D representing pure diesel fuel with no biodiesel addition, DO representing blends of diesel fuel and biodiesel made of olive pomace oil. In the case of blended fuels, a percentage of biodiesel in the blend is added to the initial letters. Because the tests were carried out during the summer, the poor low temperature properties of biodiesel were avoided.

Table 3. Test fuels basic properties

Parameters	Units	D	DO7%	DO20%	DO25%
Density at 15 °C	kg/m^3	833.4	837.8	846.1	849.2
Viscosity at 40 °C	mm^2/s	2.92	3.02	3.21	3.28
Cetane number	–	51.3	53.8	55.1	55.4
Sulfur content	mg/kg	8.6	8.0	7.1	6.7
Total aromatics	% m/m	22.8	21.2	18.2	17.1
Lower heating value	MJ/kg	43.98	43.41	42.34	41.93
FAME content	v/v	0	7	20	25

Engine parameters

The FC, BSFC, and BTE at each operation condition are further discussed.

With an increase in engine speed, torque and effective shaft power increased as well, as shown in tab. 4. For the constant engine parameters, fuel consumption increased along with the increase in biodiesel share in the blends, as shown in tab. 4, which is due to lower calorific value of biodiesel compared to diesel fuel.

Table 4. Dependence of engine speed on torque, effective power, and fuel consumption

Engine speed [rpm]	Torque [Nm]	Effective power (propeller), [kW]	Fuel consumption, [kgh^{-1}]			
			D	DO7	DO20	DO25
n210	7643	168	36.20	37.2	38.1	38.65
n210N	8371	184	38.60	39.95	41.05	41.45

As it can be observed, biodiesel blends have greater fuel consumption and BSFC than diesel fuel under the same engine operation circumstances, fig. 3. Furthermore, when the biodiesel blended ratios grow, so does the fuel consumption and BSFC. The fundamental reason is that biodiesel and consequently fuel mixes have a lower heating value than pure diesel fuel. Some studies have also stated that the decrease in biodiesel fuel heating value is the most significant component resulting in enhanced BSFC for biodiesel fuels [2, 7]. As a result, in order to maintain the same engine output under the same conditions, the fuel injection volume is increased in fuel blended mode, resulting in an increase in FC and BSFC.

Viscosity and density, in addition to the heating value, have important roles in raising BSFC [7]. Biodiesel has a greater viscosity, it has a lower fluidity, which might cause pressure oscillations in the fuel supply pipeline at low temperatures. At low-load engine operations, this might result in poor atomization during combustion resulting in partial combustion. Because of the increased in-cylinder temperature, the influence of kinematic viscosity on BFSC may progressively diminish as the engine load increases.

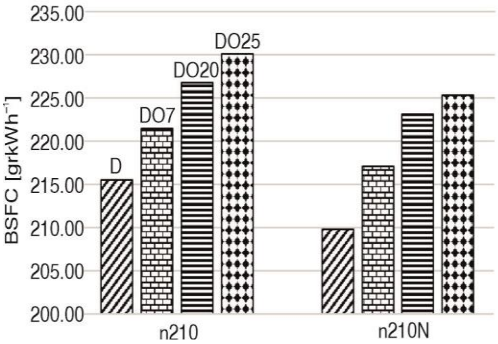

Figure 3. The BSFC for diesel fuel and biodiesel blends with different engine load conditions

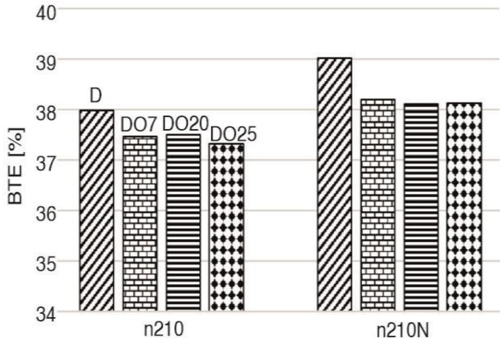

Figure 4. The BTE for diesel fuel and biodiesel blends with different engine load conditions

The BTE rises as engine speed and load increases, although it has minimal association with biodiesel blend ratios. In comparison to diesel fuel, the oxygenated character of biodiesel aids in the improvement of the combustible mixture and the promotion of complete combustion. However, in terms of BTE performance, incomplete combustion due to poor atomization and low calorific value of biodiesel blends have a larger influence in the reduction of BTE. Similarly, [2, 7] achieved comparable findings, fig. 4.

Exhaust emission

Carbon monoxide

Diesel engines always operate with fuel lean mixtures [15]. In this case, CO concentration in the exhaust varies little with the air/fuel ratio [15].

Figure 5 shows that CO emission concentrations rose as engine loads increased due to a drop in air/fuel ratio. In addition, with increasing engine speeds and loads, more fuel has being injected. In works of [7, 13, 16-18] similar patterns was shown.

There is a trend of decreasing CO emissions with increasing biodiesel content in test fuels. This is feasible due to the oxygenated nature of biodiesel fuel. When biodiesel blends are used, the local air/fuel ratio increases during combustion, resulting in lower CO emissions from biodiesel blends. [7, 13] reported on this tendency.

The greater likelihood of being converted to CO_2 resulted in a reduction in CO emissions [7]. Furthermore, because biodiesel fuel has lower carbon content than diesel fuel, it emits less carbon oxides.

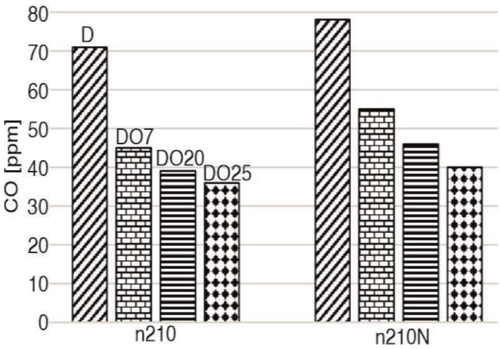

Figure 5. Exhaust emission of CO for different fuels and engine loads, [ppm]

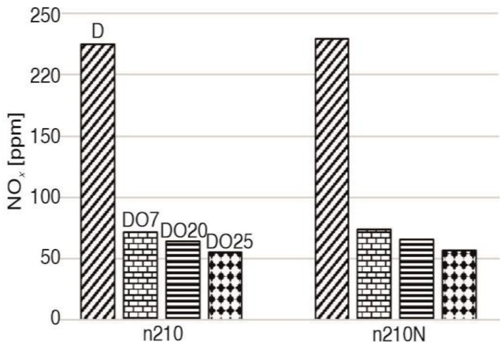

Figure 6. Exhaust emission of NO$_x$ for different fuels and engine loads, [ppm]

Oxides of nitrogen

It can be observed from fig. 6 that the amount of NO_x slightly increased with an increase in engine load. The reason for this is a higher combustion temperature, because NO_x generation inside engine cylinders is temperature-dependent [19].

At both engine loads, there is a trend of decreasing NO_x emissions with increasing biodiesel content in test fuels, fig. 6. Higher cetane numbers and lower aromatic concentrations in biodiesel blends compared to diesel fuel might be explanations for NO_x reduction. In literature, higher cetane levels in biodiesel blends are typically linked with reduced NO_x emissions when compared to diesel fuel [13, 20, 21]. Higher cetane number reduces the size of the premixed combustion by shortening the ignition delay, resulting in lower NO_x formation rates as the combustion pressure rises more slowly, allowing more time for cooling via heat transfer and dilution and resulting in lower localized gas temperatures [20, 22].

Aromatic and poly-aromatic hydrocarbons, in particular, are responsible for increased NO_x emissions [20, 23-25]. This is most likely because aromatic compounds produce greater flame temperatures. By lowering the aromatics, the flame temperature falls, resulting in a decreased NO_x generation rate. As a result, adding biodiesel, which does not include aromatic compounds, reduces NO_x emissions from engines. Because aromatics have a high carbon-hydrogen ratio, fuels with lesser aromatics produce less CO_2 and more H_2O when compared to highly aromatic fuels. Since H_2O has a lower tendency to dissociate at high temperatures (compared to CO_2), this leads to low aromatic fuels having lower concentrations of $O^\bullet$ radicals, which further reduces the kinetic production of NO [20]. The same trend was also reported by [20, 26, 27].

According to [2], decreased NO_x emissions with biodiesel might be attributed to its lower fuel nitrogen concentration and lower mean in-cylinder temperature.

Others reported an increase of NO_x emission with an increase in biodiesel proportion in blended fuels owing to the increasing oxygen content of biodiesel fuels [8, 16, 28].

Conclusion

The effect of biodiesel (FAME) generated from oily wastes following olive oil manufacturing on the characteristics of gaseous emissions from a slow-speed, two-stroke marine Diesel engine was studied. The engine was run on pure low sulfur diesel fuel as well as blends comprising 7%, 20%, and 25% of such biodiesel. The findings might lead to the following conclusions.

- Biodiesel blends have greater fuel consumption and BSFC than pure diesel fuel under the same engine operation circumstances due to its lower heating value and increased injection volume for the same engine output. At low loads, higher viscosity of biodiesel blends might result in poor atomization. With increasing load, influence of viscosity is diminished due to increased in-cylinder temperature.
- The BTE rises as engine speed and load increase, although it has minimal association with biodiesel blend ratios.
- There is a tendency toward lower CO emissions with increasing biodiesel content in blended fuels, which might be attributed to their oxygenated nature, which results in leaner combustion.
- There is a tendency toward lower NO_x emissions with increasing biodiesel content in blended fuels, which might be attributed to their greater cetane number and reduced aromatic content of blended fuels, offsetting their oxygenated nature in this particulate engine.

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