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Waste lube-oil based fuel characterization in real conditions. Case study: Bottom-trawl fishing vessel powered with medium speed diesel engine

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ABSTRACT

The high-fuel dependency of the shipping industry and its corresponding pollutant emissions need to be addressed within the new de-carbonisation era. Concurrently, the waste-to-energy concept arises to drive sustainable initiatives for energy production. In that sense, in the present study, the feasibility of an alternative fuel oil (AFO) based on recycled-waste lubricating oil was assessed. Tests were conducted on board a bottom-trawler fishing vessel, under real operating conditions. The fishing activity was monitored, and the engine performance, the combustion and injection properties, and the emissions characteristics were studied. The vessel performance when operating on the AFO was compared with that when operating on standard distillate diesel oil (DFO). The results showed that the AFO required preheating up to 70 °C owing to its higher viscosity value, which is considerably higher than the allowed by the ISO 8217 standard for distillate fuels. Therefore, a heating module was installed on board the vessel to ensure optimal performance with the AFO. The fuel consumption was slightly lower for the AFO; however, owing to its higher low-heating value, the engine efficiency was higher when using the DFO. The AFO presented lower combustion pressure than the DFO and a longer combustion period; however, its ignition process occurred earlier. The results suggested that the AFO contained light components which caused the early ignition of the fuel, as well as heavy components, which delayed the end of the combustion. The NO_X emissions were considerably reduced with the AFO by 15%; the CO_2 emissions were slightly reduced as well; however, CO emissions were higher for the AFO by 15%. By operating under the usual conditions while burning the AFO throughout a year, the vessel would consume 8 t of fuel less, and would emit 21 t of greenhouse gases less. The vessel burnt a total of 40,000 L of AFO, for approximately 300 h, without any operational issue. The results demonstrate that the distillate fuel obtained from lubricating oil is suitable for marine medium-speed engines and enables satisfactory performance.

1. Introduction

Fossil fuels are the largest energy sources worldwide; however, they trend to become depleted [1]. Waterborne transportation is highly fossil-fuel dependent; in the past years, the seaborne trade volumes reached approximately 10×10^{12} t per year, and presents a growth tendency, despite the crisis context [2,3]. Marine diesel engines consume 60×10^6 t barrels of crude oil in a year [4], implying additional emissions of 961×10^6 t of greenhouse gas, 20.9×10^6 t of NO_X, 11.3×10^6 t million tonnes of SO_X, and 1.4×10^6 t of particles in the atmosphere [5]. In this context, the lack of prevention measures may cause an increase of 20–60% of greenhouse emissions by the year 2050 [6]. Thus, being aware of this situation, the International Maritime Organization (IMO) has dictated several environmental measures and restrictions for maritime transport [3,7,8].

Moreover, fuel price is one of the main concerns of the shipping industry. The fuel price is volatile [9]. The crude-oil barrel price depends on operational costs; however, it principally depends on external factors, such as structural geopolitical matters which directly influence the fuel market [10]. The fuel cost may represent 60–70% of the total operational costs of the vessel [11]. In the case of fishing vessels, which are equipped with high- and medium-speed diesel engines, the fuel cost

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may represent 50% of the total operational costs of the vessel [12]. Regarding large fishing vessels, annually, a tuna freezer fleet may consume a total amount of 3 billion litres of fuel [13], and a bottom-trawl vessel may consume approximately 1 million litres of fuel [12]. Practically, the entire fuel burnt in fishing vessels is high-quality distillate diesel oil. It is expected that the IMO regulation on sulphur content will increase the distillate-oil demand in the marine environment, which would consequently lead to an increase in the price of the marine distillate diesel oil.

Considering the above-mentioned facts, through the present study, we aim to assess technically the possibility of using an alternative fuel in marine diesel engines and reduce their dependence to actual conventional fuels. In the present study, we assessed a recycled-waste lubricating oil (AFO). Residual oil is the main waste product generated worldwide (24 million tonnes), and waste lubricating oils represent 60% of the aforementioned waste oils [14]. Their management is highly complex and expensive [15,16]; therefore, to recycle and to reuse them is the optimal waste management practice. The circular economy is a new concept that considers waste as an element that is worth transforming into a new, able product.

Furthermore, biofuels may be generated from recycled waste [17,18]. In the past decades, several research works have been focused on biofuels [19–23]. In a similar manner, several engine and emissions tests have been conducted with such alternative fuels [24–26]; however, the studies that have been conducted in real conditions are scarce [27]. In contrast, biodiesel fuels present severe difficulties regarding their use in a ship, i.e. storage problems, fuel stability problems under moisture conditions, and feedstock limitations; thus, the use of biodiesel fuels in marine applications is not guaranteed in the near future [28,29]; this fact, encourages the possibility of assessing the use of mineral origin alternative fuels, such as a waste lubricating oils.

Its principal difference with distillate fuels is its high viscosity [30]. Practically, the alternative fuel oil (AFO) may be considered as a low-viscosity heavy fuel. Fishing vessels are principally equipped with four-stroke engines, high-speed and small (100–500 kW) engines, and medium-sized medium-speed (500–5000 kW) engines. The present study is focused on medium-speed diesel engines. Owing to their combustion properties and adaptability characteristics, they are able to burn several types of fuels, such as heavy fuels, distillate fuels, and gas fuels at dual cycles [31]. In addition, research works on mineral-origin alternative fuels maybe found; however, they are less than those on biodiesel fuels. There are fuels obtained from lubricating oils [14,32–34], pneumatic tyre wheels [35–38], and plastic recycled oils [39–42].

In the present work, we assessed the suitability of an AFO generated from waste lubricating oils. The injection, combustion, engine performance, and emission characteristics were studied in actual operating conditions. All tests were conducted on board a fishing vessel in normal operation. The work represents the culmination of a series of works related to the feasibility of using an alternative fuel for marine diesel engines, which had been tested with different equipment at different laboratory conditions [30] and marine diesel engines [43].

2. Materials and methods

The suitability of the AFO was studied for medium-speed diesel engines; for the testing, 40,000 L of the AFO were burnt. In a similar manner, the standard distillate fuel oil (DFO), which is commonly used in the vessel, was burnt in the same engine and vessel continuously, and both fuel performances were compared. The AFO was produced by a distillation process from recycled and post-processed automotive waste lubricating oil from automotive applications. The physiochemical characteristics are listed in Table 1.

The engine employed for the test was a four-stroke marine diesel engine, currently used on board a bottom-trawl fishing vessel. The tests were conducted under real operation conditions. The fishing vessel operates non-stop, for six days per week (144 h/trip), and for 42 fishing trips a year. The main engine of the vessel which is used for ship propulsion and energy generation consisted of a four-stroke, direct injection, turbo-compressed, and water-cooled diesel engine, namely the YANMAR 8N21A-UN. It has eight cylinders in line and an independent plunger-and-barrel type injection pump, one per cylinder. The injection system is the traditional helix profile plunger and barrel injection system with no special configuration and is representative of injection systems used in four stroke medium speed engines used in marine application.

Table 1
Physical and chemical properties of the AFO compared with those of the DFO.

Parameter	Standard method	Units	AFO	DFO
Density at 15 °C	ASTM D-1298-99(05)	kg/m^3	850.3	836.6
Viscosity[1] at 40 °C	ASTM D-445-09	mm^2/s	20.8	2.9
Flashpoint	ASTM D-5950-02	°C	310.0	68.0
Cetane number	ASTM D-613-08	–	56.8	53.0
Low heating value	ASTM D-420	kJ/kg·K	46,649.0	44,935.0
Sulphur content	PE-TQ.021 Rev5	ppm	58.0	22.0
Carbon content	ASTM D-5291-5	%	85.9	86.2
Hydrogen content	ASTM D-5291-5	%	14.1	13.6
Nitrogen content	ASTM D-5291-5	%	< 0.1	< 0.1

Key:
[1] Viscosity at 100 °C, AFO: 4.2 mm^2/s.

The injection system regulation and functioning is totally mechanical. The injection timing is mechanically adjusted in each fuel injection pump using a nut and bolt system with a maximum combustion pressure measurement as reference. The injector opening pressure is adjusted using a counter nut system. All the injectors were adjusted prior to the test and fuel injection valves were renewed. The fuel injection pumps remained the same except one unit that was installed new in order to have possibility of comparison between new and used pumps with AFO after tests in event of any mechanical problem in fuel injection pumps [44].

The engine in generator application is able to burn heavy fuel oil with a viscosity value up to 700 mm^2/s at 40 °C with minor modifications in injection system.

The engine meets the IMO NO_x Tier I emissions limit. The propulsion system consisted of a one speed gear box driving a fixed-pitch propeller (FPP). The vessel and engine characteristics are listed in Table 2.

Two fuel circuits were fixed on board; there was one for the testing of the AFO and another for the normal DFO (Fig. 1). To overcome the challenges which would occur from the high viscosity of the AFO [30], a fuel heating module with a temperature and viscosity control unit was installed. Thus, AFO was heated prior to being burnt in the engine.

A fuel booster unit was manufactured and installed on board. The AFO was pumped from the daily tank to the booster unit. The AFO was heated with two heating resistances, and was then delivered to the recirculation and de-aeration tank. The fuel circulated within the booster unit until it reached the appropriate temperature (which was in a range of ~65–75 °C) for the viscosity setting in the control unit; considering the possibility of uncertainties in viscosity monitoring in real conditions (error: ± 2%). The fuel viscosity was continuously monitored and value used as control signal in the heating system to supply the fuel to the engine in the acceptable viscosity range (10–15 mm^2/s), with the set point at 11 mm^2/s. This viscosity values were according to the instruction from engine maker.

Then, the AFO circuit would manually open, hence allowing the AFO to be burnt in the diesel engine. A de-aeration tank was used to eliminate the formation of bubbles from the heated fuel and the injection process, thus preventing the entrance of fuel and air bubbles into the injection system. The engine pump suctioned fuel from the de-aeration and circulating tank, and the excess fuel returned to the de-