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Full Length Article

Performance of marine diesel engine in propulsion mode with a waste oil-based alternative fuel

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ABSTRACT

Marine diesel engines are one of the most representative fossil fuels consumers on the planet. These engines are responsible for a large amount of air pollutants, including greenhouse gas emissions. This concern led to the adoption of new regulations and policies for shipping, which involved more intensive restrictions for airborne emissions. This scenario, in addition to the finite fossil fuel reserves, the fluctuating price of fossil fuel and its share of the annual costs of ships, has boosted the development of new alternative fuels for marine diesel engines from traditional ones. It is known that waste oils are one of the most abundant residues generated within the industry. This study assesses the technical suitability of an alternative fuel oil, obtained from recycled waste automotive lube oil, in comparison with traditional fuels, complying with the ISO 8217 for distillate fuel oils. The alternative fuel was tested on a full scale marine diesel engine test bench, simulating real operating conditions for marine diesel engines and electric diesel generators in steady loads. To this end, the engine was cooled with sea water and coupled to a hydraulic brake, which allowed tests to be undertaken in different engine loads and propulsion modes, such as controllable and fixed pitch propeller propulsion systems. The results demonstrated that the alternative fuel burns rapidly but with a delay at the end of combustion, which should be expected for this type of fuel. Additionally, the energy efficiency of the diesel engine is comparable to the distillate fuel commonly used by the fishing fleet; however, due to its higher heating value, the alternative fuel presents lower fuel consumption. According to the emissions, the alternative fuel exhibits lower NO_x and CO_2 emission levels but slightly higher CO emissions and smoke opacity levels than common fuels, with the sulphur content in the fuel below the maximum level being allowable by more stringent marine rules. Hence, waste oil-based alternative fuel oils are acceptable for use in marine diesel engines operated on-board a ship under real conditions and meet the rules applicable to marine environments for burning fuel oils.

1. Introduction

Despite being immersed in the de-carbonisation era, shipping is still heavily dependent on fossil fuels. However, diesel engines are considered as outstanding power plants due to its fuel efficiency, strength and durability [1]. Marine diesel engines burn approximately 60 million barrels of crude oil every year [2]. This represents an annual emission of almost one thousand million tonnes of CO_2 equivalents, more than 20 million tonnes of NO_x, more than 10 million tonnes of SO_x and more than one million tonnes of particulates [3]. The seaborne trade is worth in the order of 9.84 billion tonnes of volume (data from 2014) and is one of the few players that maintained a steady growth in the recent economic crisis [4]. In addition, according to global estimates, the trend is upwards for the forthcoming years. Therefore, air pollution and its effect on climate change will worsen unless new alternative fuels or energy efficient measures are widely implemented.

For decades, the maritime sector has tried to develop environmentally friendly strategies [5], such as the development of alternative fuels [6,7], hybrid propulsion [8,9], energy auditing [10], engine waste heat recovery [11,12], speed and voyage optimisation [13,14], and slow steaming and wind-powered propulsion [15,16], as shown in the series of conferences on Low Carbon Shipping and

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Nomenclature

AFO	alternative fuel oil
ATDC	after top death centre
BP	brake power
BSFC	brake specific fuel consumption
BTE	brake thermal efficiency
CO	carbon monoxide
CO_2	carbon dioxide
CPP (XX)	controllable pitch propeller, at XX% engine load
DFO	distillate fuel oil
ECA	emission control area
EOC	end of combustion
FOC	fuel consumption
FPP (XX)	fixed pitch propeller, at XX% engine load
HC	hydrocarbons
IMO	international maritime organization
ISO	international organization of standardization
I (XX)	mass burned fraction at XX% (of total fraction)
LHV	low heating value
NO_x	nitrogen oxides
P100	engine full load (100%)
SOC	start of combustion
SO_x	sulphur oxides

Shipping in Changing Climate [17]. Biodiesels have been considered as a potential substitute for conventional marine fuels. Large and exhaustive research has been undertaken that focuses the combustion and engine performance on broad biodiesel types and blend configurations [18–20] and injection characteristics [21], mainly for inshore applications. In contrast, the use of biodiesel in shipping or fishing alike presents more challenging conditions than land-based uses due to its higher density and viscosity compared with distillate fuel oils and long-term storages in humid environments, which could lead to stability problems. These challenges have hampered the progress of biodiesel use in shipping [22]. Likewise, other difficulties include biodiesel's feedstock costs dependence [23] and higher production, the incompatibility with some plastic and metallic materials for fuel feeding systems, low temperature fluidity and the high quantity of biomass feedstock required to cope with a representative fleet [24].

One of the solutions for shipping is to use mineral origin alternative oils, such as recycled waste oils. Waste oils are abundant residues with the production of 24 million metric tonnes a year [25]. The recovery of valuable energy content coproducts, such as waste plastics, waste cooking oils, or waste lube oils may represent an important feedstock for energy conversion plants [26]. However, contributions on mineral origin waste oils concerning their application in diesel engines are less abundant than plant origin fuels. Initially, authors such as Mani et al have been developing research studies based on waste plastic oils [27,28]; likewise, Arpa et al. have been studying engine performance and exhaust emissions characteristics with alternative fuel from waste oils by pyrolysis process [29,30]. However, recent studies on waste lubricating oils are boosting new research studies with different producing processes and engine performance assessments fuelled with such waste oils [31,32].

Marine fuel specifications are determined by the ISO 8217 regulation [33,34]. The IMO (International Maritime Organization) has intensified its maritime environmental regulations with restrictions on fuels (maximum sulphur content 0.1% for fuels beginning 2015 within the Emission Control Areas and a cap of 0.5% beginning 2020 globally); shipping operations (the control of greenhouse gas emissions through the reduction of CO_2 emissions via energy efficiency measures, such as, Ship Energy Efficiency Management Plan, Energy Efficiency Design Index and Energy efficiency Operational Index); and diesel engines (NO_x emissions restrictions for marine diesel engines with Tier III regulation for new ships beginning 2016 in NO_x Emission Control Areas) [35,36].

By 2020, 10% of the transport fuel in European countries is required to come from renewable sources such as biofuels. Moreover, fuel suppliers must reduce the CO_2 emissions intensity of the European fuel mix by 6% in comparison to 2010 [37,38]. In addition, the Paris Agreement has recently set out a global action plan to keep the increment of the global average temperature well below 2 °C [39].

This study assesses the suitability of a waste oil-based alternative fuel (now onwards "alternative fuel oil", AFO) for real scale marine diesel engines.

This contribution is the follow up to a precedent contribution, which assessed the suitability of the same waste-oil for a laboratory scale small high speed single cylinder diesel engine test (presented in Gabiña et al., 2016) [40]. It concluded that further assessments were feasible; thus, full scale marine diesel engine test bench was developed for fuel testing. The higher scale marine diesel engine is the better operates with high viscosity fuels; thus, test bench provides higher similarity with real testing conditions on board a vessel.

The process used to obtain AFO is not part of the scope of this work, although it is worth to mention that the AFO used is a high viscosity mineral origin fuel, produced from recycled and post-processed automotive lubricating oil through a distillation process; the fuel could be used directly in medium speed marine diesel engines, thus, the authors assumed that it was produced by a desulfurization process, too. Likewise, there are several waste oil regeneration and re-refining processes in the market; although fuel production from waste oil is a small amount of total consumed fuel oil of any kind considering the ratio of oil used with fuel oil burned in internal combustion engines [41]

Different propulsion systems were simulated and different engine loads were considered. Engine efficiency and performance properties, combustion and injection patterns and emission characteristics were assessed. All tests were carried out with the AFO and a distillate fuel oil (DFO) to compare the suitability between both fuels.

2. Materials and methods

Engine tests were carried out on a 400 kW multi-cylinder diesel engine test bench adapted to simulate the real performance of a marine diesel engine on board a ship. The engine, Baudouin DNP 12ST, was coupled to a hydraulic brake, Zollner Kiel model 6N29, to manage the engine load and brake-power. The test bench was cooled with sea water, thus, sea water was pumped from the sea, to cool the brake and the engine's cooling systems.

The engine was configured to have two independent fuel circuits. One was used for a conventional distillate fuel oil (DFO), the other for the AFO. Based on Gabiña et al., 2016, the AFO was preheated between 65 and 70 °C to reduce its viscosity and to avoid jeopardising the injection process of the engine and supply the fuel oil to the engine with a viscosity value accepted by most engine manufacturers. The key physical and chemical properties of the AFO and DFO are listed in Table 1 (shown in Gabiña et al., 2016 [40]). The test bench lay-out is shown in Fig. 1.

The diesel engine is a 12-cylinder turbocharged 4-stroke V–type engine. The cylinders are aligned on two separate planes, 6 cylinders per plane with a centred direct injection pump. The mechanical characteristics of the engine are indicated in Table 2 and its monitoring is represented in the Supplementary Material. The engine performance was monitored by different sensors and instruments to control and assure the correct functioning of the whole system (Table 3).

Two cylinders (1 and 7) were mechanised for installing the combustion pressure sensors and their respective injection pipes were