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Research article

# Waste oil-based alternative fuels for marine diesel engines

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ABSTRACT

Fossil fuels are the main energy source used in the world. However, environmental concerns, over-consumption, and fluctuating price rates are boosting efforts in the development of alternative fuels. This study presents the technical suitability of an alternative fuel for its use in marine diesel engines, as assessed through laboratory and engine performance tests. The alternative fuel assessed is based on waste oil obtained from used automotive lubricating oil. Tests were conducted for the alternative fuel and a distillate fuel, commonly used in the fishing fleet, to compare their performance. The effects of injection timing on their energy efficiency, combustion analysis and emission characteristics have been studied. Here, we show that the alternative fuel met the requirements of ISO 8217 regulations for distillate oils, with the exception of the viscosity, which was 1.9 times higher, thus requiring heating the alternative fuel before its use. The combustion period was shorter than that of residual heavy fuels but longer than that of ISO-F category distillate fuels. Better combustion properties were obtained with advanced injection timing. With such timing, the distillate fuel presented slightly better energy efficiency characteristics (specific energy and fuel consumption) than the alternative fuel, and carbon emissions were drastically reduced in both fuels. $NO_x$ emissions were lower for the alternative fuel than for the distillate fuel. The good performance of the alternative fuel indicates feasibility for use in medium-speed diesel engines commonly used, for example, in fishing vessels.



## 1. Introduction

Shipping is fuel dependent. Thus, the cost of fuel is one of the main concerns in the shipping industry. Fuel represents nearly 60–70% of a ship's operating costs [1]. In the specific case of fishing vessels, which are fitted with high- and medium-speed engines burning distillate fuels, the cost can represent 50% of their total annual costs [2].

It is estimated that marine diesel engines burn 60 million barrels of crude oil annually [3], which accounts for the annual emission of 961 million tonnes of $CO_2$ equivalents, 20.9 million tonnes of $NO_x$, 11.3 million tonnes of $SO_x$ and 1.4 million tonnes of particulates for shipping [4].

Because of that, environmental maritime regulations are becoming stricter. Since 2015, the IMO has intensified its work in regulating emissions from ships. The key outcomes are the restriction on the use of fuels with a maximum sulphur content of 0.1% from 2015 within the Emission Control Areas (North America coastlines, and the North Sea and the Baltic coastlines) and a cap of 0.5% from 2020 for the global sphere; the control of greenhouse gas emissions through the energy efficiency design index (EEDI), the energy efficiency operational indicator (EEOI) and the ship energy efficiency management plan (SEEMP); and the new $NO_x$ emissions restrictions with the Tier III IMO regulation (beginning in 2016, for $NO_x$ Emission Control Areas), involving reductions of allowable emissions from marine diesel engines in new vessels (by 75% of reductions from the Tier II regulation) [5,6]. These regulations are driving an increase in energy efficiency strategies in the shipping industry.

Increasing energy efficiency can result in potential cost savings and environmental improvement. Several strategies have been developed with that aim. On-board energy audits are considered as the first screening to be set out and facilitate viable decision making. Best available technology is often implemented on board, such as energy management systems, fuel consumption indicators, or route optimization systems, enabling 10–20% fuel savings [2]. The preceding strategies are based on operational actuations, such as reducing the navigation speed—in other words, slow steaming [7]—and condition-based maintenance (CBM) for diesel engines that also contribute to energy efficiency and cost reductions [8,9].

Other strategies are based on the improvement of the combustion characteristics in diesel engines; different research studies have been undertaken with fuel and oil additives or fuel treatments devices (such as magnetic devices, about which contradictory results have

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**Table 1**
MINSEL M430 single-cylinder engine characteristics.

| Engine parameter | Value | Units |
|---|---|---|
| Maximum speed | 3000.00 | rpm |
| Indicated power | 5.00 | kW |
| Compression ratio | 19.3:1 | – |
| Diameter | 85.00 | mm |
| Stroke | 75.00 | mm |
| Fuel injection valve opening pressure | 220.00 | bar |
| Fuel injection timing | −14.00 | ° ATDC[a] |
| Suction valve opening | −22.00 | ° ATDC |
| Suction valve closing | 54.00 | ° ABDC[b] |
| Exhaust valve opening | −54.00 | ° ABDC |
| Exhaust valve closing | 22.00 | ° ATDC |

Key:
[a] ATDC: After Top Dead Centre.
[b] ABDC: After Bottom Dead Centre.

been found in the literature [10,11]). New fuel concepts are also gaining relevance to replace the use of conventional fuels. Research on different diesel fuels was initially focused upon the use of biofuels. However, their higher density and viscosity compared with distillate fuel oils [12], stability problems—especially when used in the presence of high humidity—and necessity of long-term storage on board ships have jeopardised their progress in marine applications [13,14].

With a production of 24 million metric tonnes a year, waste oils are considered to be the most abundant pollutant residues currently generated [15]. The present study presents the technical suitability of an alternative fuel oil (AFO) for use in marine applications. The AFO used is a mineral origin fuel, produced from recycled and post-processed automotive lubricating oil. The process used to obtain AFO is not part of the scope of this work, although it is worth to mention that the process contains a distillation process. Hence, the AFO could be considered a distilled fuel oil. Fuel consumption characteristics, combustion performance, injection patterns and exhaust gas emissions have been assessed. Two injection timing conditions were also assessed—one as received from the manufacturer, and the second advancing the injection timing. All tests were undertaken with AFO and a commercial distillate fuel oil (DFO), commonly used in the fishing fleet, to compare their differences.

## 2. Material and methods

### 2.1. Laboratory tests

Two laboratory tests were undertaken for each of the fuels studied—i.e., AFO and DFO—prior to the engine tests. The analytical tests defined the physicochemical characteristics and combustion properties of the AFO. The first screening served to certify the fuel properties, such as, density, viscosity, flashpoint, cetane number, low heating value, and sulphur, carbon, hydrogen and nitrogen contents. Those parameters were compared with a local DFO following the ISO 8217 specifications of marine fuels. Any fuel for general marine applications must comply with Regulation 4 of Annex 13 of the Marine Environment Protection Committee of the International Marine Organization at its 58th Session [16]. Analytical tests were carried out at the TEKNIKER, SGS and EKONOR laboratories.

The combustion properties were evaluated by the mean of the FIA-100FCA instrument for heavy fuel oils. The test consisted of injecting fuel to a constant volume combustion chamber heated to 500 °C and pressurized to 45 bar. During the combustion of the fuel, the pressure increase was measured and registered in a computer, for further computational analysis. The measured properties also included ignition delay; main combustion delay; estimated cetane number; pre-combustion period; end of main combustion; main combustion period; post-

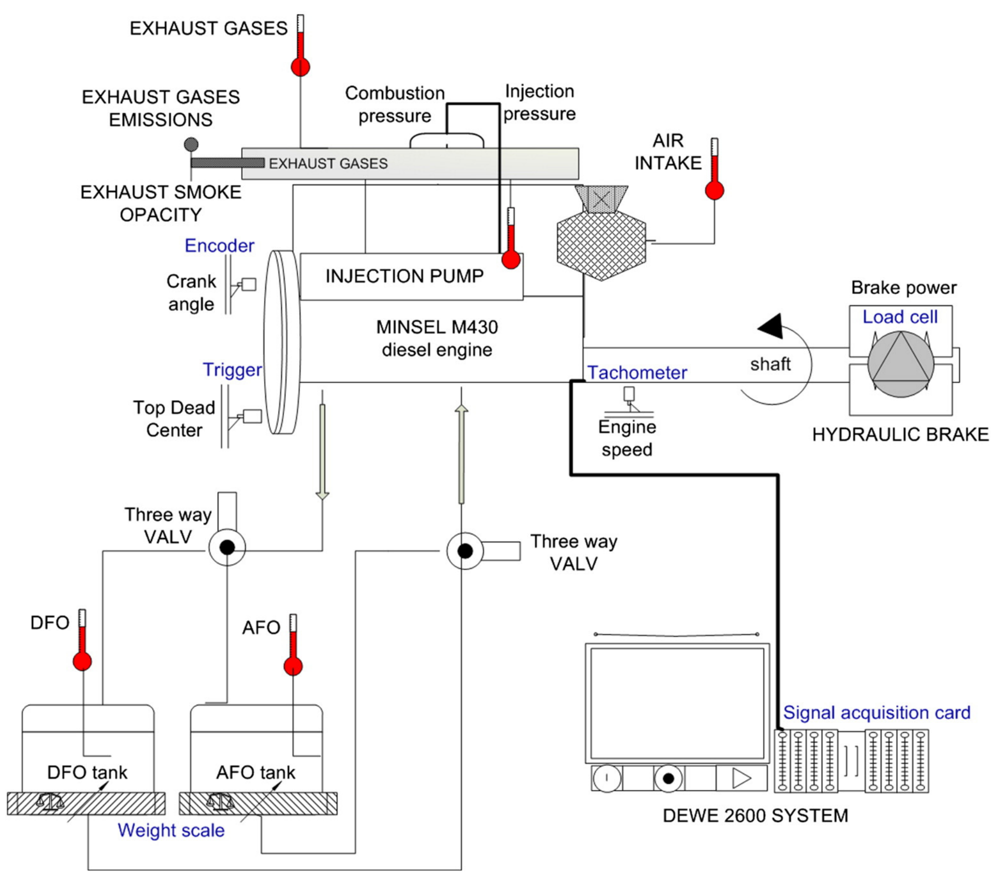


**Fig. 1.** Engine test bench layout.